Hand Function

A Practical Guide to Assessment

Mehmet Tuncay Duruöz
Editor

Second Edition

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To my excellent mother, Servet, and wonderful father, Talat, my heartfelt thanks infinitely for your never-ending love, support, and selfless help.
I am incredibly thankful to my wife, Evrim, and my son, Mustafa Can, for their lovely distinguished support.

Preface from 1st Edition

The hand is extremely involved in our daily lives because of its vital and sophisticated functional role. With the growing expectation in society of a life without disability and handicap, hand function has become increasingly important over the past decades. The accurate assessment of hand function is very important for establishing strategies to maximize functional potential and evaluating treatment and the progress of disease. The evaluation of hand function is of critical importance in determining the extent of functional loss in patients with many rheumatic and neurologic diseases and traumatic injuries and in assessing the outcome of some surgical and rehabilitative procedures. Thus, the clinical assessment of hand function remains complex and controversial. This book of practical information will be very useful in physicians' and in healthcare professionals' daily practice. There are four main sections in this book: Basic principles of hand function, hand function assessment in clinical assessment, hand function and imaging outcomes, and appendices. The authors approach their subjects in an especially practical dimension. Because hand assessment is performed in the daily practice of many areas, such as rheumatology, physical and rehabilitation medicine, orthopedic surgery, plastic and reconstructive surgery, and neurology, this book is written by a multidisciplinary team with adult and pediatric rheumatologists, physiatrists, physiotherapists, occupational therapists, hand therapists, neuroscientists, and neurologists.

Many clinicians and healthcare practitioners insist on the evaluation of outcomes based on questionnaires for the functional status of patients. Questionnaires provide us with better information on what our patients truly experience in their daily lives. The appendices of this book include seven famous and practical scales for hand assessment, all of which were validated in many different kinds of hand disorders, such as rheumatoid arthritis, osteoarthritis, systemic sclerosis, psoriatic arthritis, geriatric and pediatric hand disorders, hand tendon injuries, stroke, tetraplegia, diabetes mellitus, carpal tunnel syndrome, and hemodialysis patients.

The goal of this book is to present recent practical information to assess hand function in daily practice and scientific research. I hope it will help in accurate and practical evaluation of hand function and the interpretation of functional outcomes in clinical practice. I wish to thank the chapter authors assembled in this book for graciously giving their time and sharing their experiences.

Istanbul, Turkey — Mehmet Tuncay Duruöz, MD

Preface for 2nd Edition

The hand is one of the most sophisticated instruments that its functional status plays a significant role in our quality of life. To increase the functional capacity of the hand, we should evaluate its all dimensions carefully and accurately. Besides the development of some rehabilitation and surgical methods to regain the functional ability of the hand, the prosthesis has taken their places rapidly to facilitate the daily life of humankind. Although technology is far from replicating human hand dexterity, the new generation of robotic hands offers incredible functions of the natural hand.

Each chapter in the present edition of *Hand Function: A Practical Guide to Assessment* has been extensively reviewed, and most of them were updated to include advancements of recent years, and six crucial chapters were added. We purposed to provide practical information to assess the hand function for physicians, healthcare professionals, and bioengineers. At the same time, we already purpose to give hope and to look new horizons with chapters about the sports and recreational adaptations, robotic hands, and assistive devices. The disability and the handicap should not be the destiny of persons with hand disorders.

I would like to express my gratitude of the authors assembled in this book for generously giving their time and sharing their experiences.

I hope that the reader finds the *Hand Function: A Practical Guide to Assessment*, Second Edition, both useful and enjoyable in daily practice.

Istanbul, Turkey — Mehmet Tuncay Duruöz, MD

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Section I

Basic Principles of Hand Function

Functional Anatomy and Biomechanics of the Hand

1

Ton A. R. Schreuders, J. Wim Brandsma, and Henk J. Stam

The Hand: A Beautiful but Complex Instrument

> The human hand is so beautifully formed; it has so fine a sensibility, that sensibility governs its motions so correctly, every effort of the will is answered so instantly, as if the hand itself were the seat of the will; its action are so powerful, so free, and yet so delicate, as if it possessed quality of instinct in itself, that there is no thought of its complexity as an instrument, or of the relations which make it subservient to the mind. [1]

Introduction

The complexity of the hand is evident, its anatomy efficiently organized to carry out a variety of complex tasks. These tasks require a combination of intricate movements and finely controlled force production. The close relationship between different soft tissue structures contributes to the complex kinesiology of the hand. Injury to any of these even very small structures can alter the overall function of the hand and thereby complicate the therapeutic management [2].

Rehabilitation of the hand is different from other parts of the body not only because of the hand's complexity but also the delicate surgery that is involved in repairing the different tissues and consequently also the rehabilitation. However, the hand is well accessible for examination.

All the joints, together with the tendons, ligaments, nerves, and skin, move smoothly, minimally resisting the gliding movements between the various structures. Following trauma, the delicate structures between the tissues might adhere, lose their ability to unfold or stretch, generating restricted lengths and limited free motion in the healing process of the body repairing the tissues. Therefore, after trauma or surgery, the tissues that need to glide and stretch should be moved as soon as possible to prevent adhesions, shortening, and/or stiffness.

Adhesions are the number one enemy of the hand, resulting in a stiff joint resulting in reduced range of motion(s) affecting overall hand function.

We describe the different structures with relevant pathokinetics in this chapter:

1. Skin and connective tissue
2. Joints and ligaments
3. Muscles and tendons
4. Nerves and innervations

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Skin and Connective Tissue

The skin provides a protective and sensitive covering, which is highly innervated volarly for efficient tactile sensibility. The volar surface is endowed with fixed fat pads in addition to numerous sweat glands. The various lines or creases of the skin follow the normal stresses imposed by the movements of the hand (Fig. 1.1). Important creases are distal, palmar, and thenar crease. These lines need to be observed, e.g., when making splints.

There are important differences in the structure of the volar and dorsal skin of the hand. The dorsal skin is loose and has little connection with the subcutaneous tissues like the tendons or bones. The skin of the palm is much thicker and has many connections through fascicular tissue with the bones and palmar fascia, thus making the skin of the palm protects the tissues on the volar side, and is able to transfer forces to the bones and fascia. In extensive trauma to the palm of the hand, a full-thickness graft is sometimes performed for skin closure which often results in the inability to open a tight jar because the skin is too loose.

The transverse structures within the hand create a fibrous skeleton for the nerves, blood vessels, tendons, and muscles (Fig. 1.2). The walls of the compartments are not very elastic.

Clinical Relevance: Example

Trauma could result in compartment syndromes similar to Volkmann's contracture [3]. Swelling in the hand and lower arm therefore are a threat

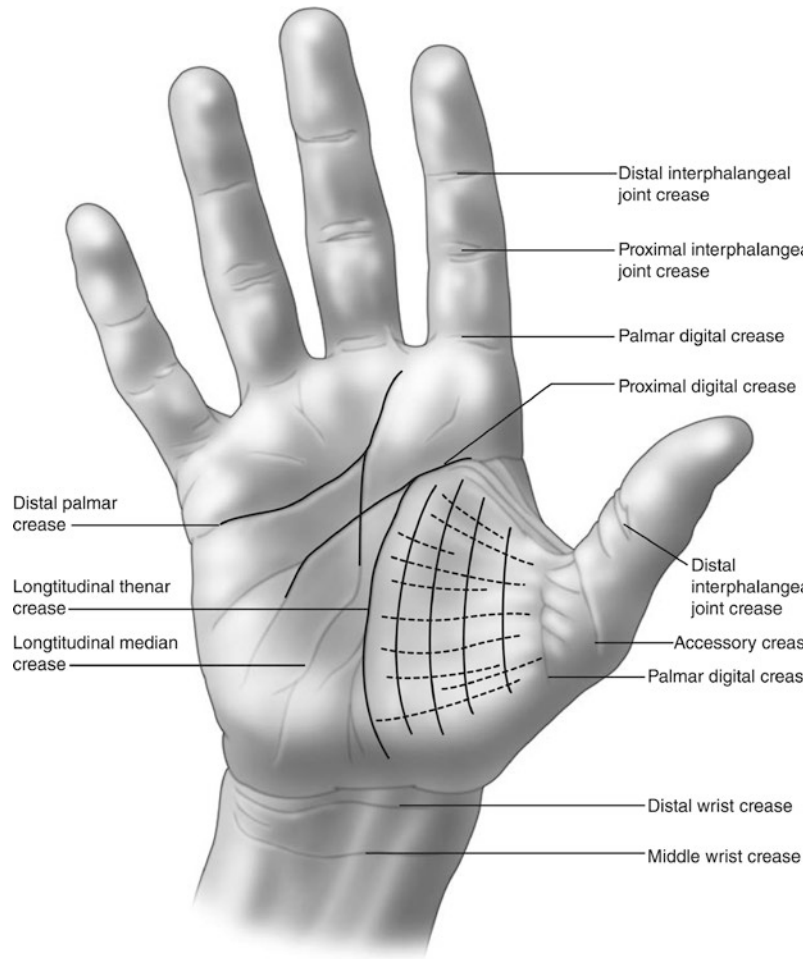

Fig. 1.1 Palmar creases of the hand and wrist

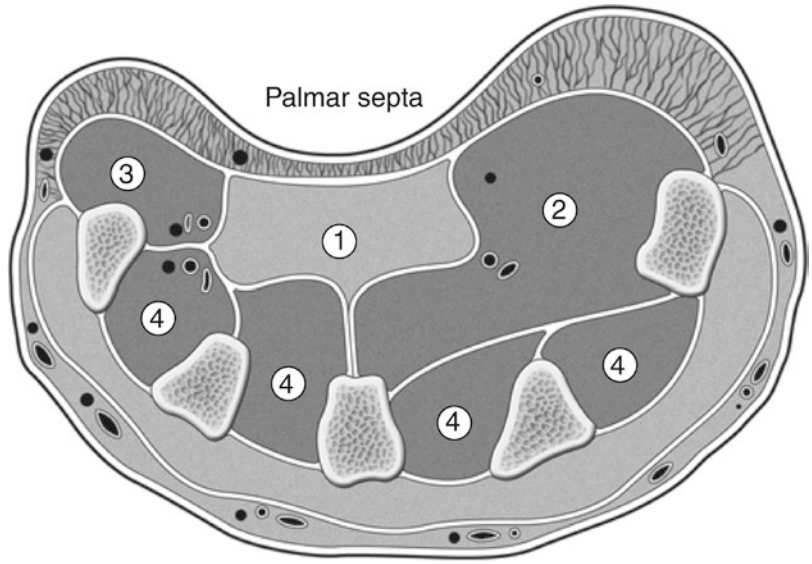

Fig. 1.2 Transverse view of the hand with the fibrous skeleton-forming compartments

of developing such pathology and must be treated immediately.

Extensibility and innervation of the skin are important for the ultimate function of the hand. The hand is innervated volarly by the median and ulnar nerves; dorsally, it receives innervation from all three nerves. On the volar surface, the thumb and the index and long fingers are innervated by the median nerve. The ulnar nerve supplies sensation to the ring and little fingers. The sensory division between ulnar and median nerves is usually given as going across the ring finger, but this dividing line can be very variable.

Clinical Relevance: Example

On the palmar side of the hand, Dupuytren's disease can be the cause of flexion contractures of the MCP and IP joints and is especially common in the fourth and fifth fingers and the thumb.

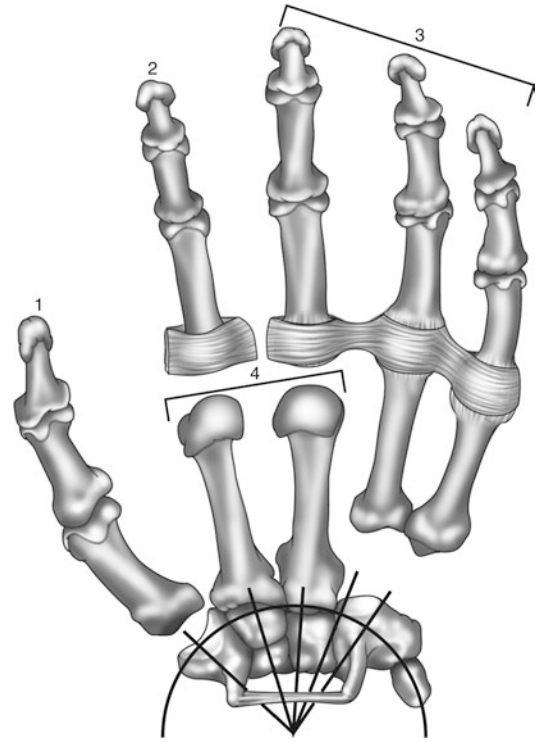

Fig. 1.3 The architectural components of the hand are divided into four separate elements: the central rigid unit (4) and the three mobile units (1, 2, and 3)

Joints and Ligaments

There are three arches of the hand which are known as the distal transverse, longitudinal, and proximal transverse arch. The proximal transverse arch is more rigid, while the distal transverse and longitudinal arches are mobile (Fig. 1.3). The intrinsic muscles are important in the formation of the arch of the hand. In grasping,

the arches provide a postural base to the hand and have a role in the production of finger joint movements and the assurance of a stable grasp. The arches form a hollow cavity that changes its shape during hand pre-shaping and grasping according to the object to be grasped. The contraction of thenar and hypothenar muscles plays a role during hand shape modulation [4].

The distal transverse arch is formed by the transverse intermetacarpal ligament (TIML) and the metacarpal heads. The TIML is attached to and courses between the volar plates at the level of the metacarpal heads along the entire width of the hand.

Carpometacarpal (CMC) Joints

The CMC of the thumb will be discussed later. The CMC joints of the fingers are incongruous joints and have only one degree of freedom. However, the fifth CMC joint is often classified as a semi-saddle joint with conjunctional rotation [5], allowing more movement in the fourth and fifth ray compared to the index and middle finger CMC joints. The forward/backward movement of the fourth and fifth ray makes cupping of the hand possible which can be observed when holding an object like a hammer in a diagonal position or when scooping up water.

The hand has a secure grip and maximum contact area because of the ability to "fold" the hand around the object. In addition, abduction and rotation of the proximal phalanges are regulated in an approach to an object and adjusted by the phalangeal-inserting interossei muscles. This permits spatial adjustment to a large spherical object by wide abduction and rotation of the fingers from the central ray or to a cylindrical grip with variable flexion and rotation from the ulnar to the radial fingers [6].

Clinical Relevance: Example

Loss of mobility after fracture or loss of muscle power after ulnar nerve lesion results in loss of the ability of cupping the hand and consequently in less powerful grip.

Metacarpophalangeal (MCP) Joints

The MCP joints are ellipsoidal or condylar joints with two degrees of freedom, but it also allows for conjoint rotation, e.g., in pinch grip, the index finger can rotate to a certain degree. The place of the collateral ligament of the MCP joint and the prominent condylar shoulders that the collateral ligaments must cross causes the ligaments to be tight in the flexed position, making it almost impossible to abduct and adduct in MCP-flexed position and abduct the fingers when in flexion.

In the extended position, the ligaments are at its maximum relaxed position (Fig. 1.4) which can be observed in a swollen hand where the hand tends to adapt the position of injury: MCP extension and IP flexion.

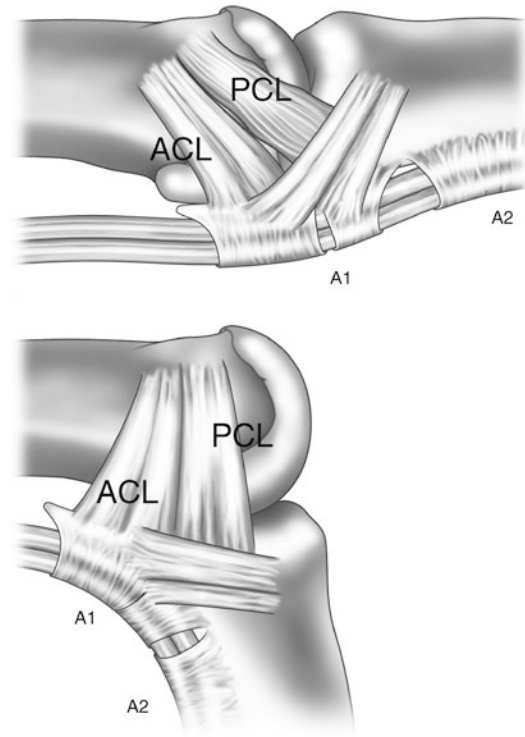

Fig. 1.4 The metacarpophalangeal (MCP) joint with its collateral ligaments. In MCP joint extension (top), the proper collateral ligament (PCL) is somewhat relaxed allowing for abduction and adduction. In flexion (bottom), both the PCL and the accessory collateral ligaments (ACL) are tight. Both A1 and A2 pulleys are noted in figure

Clinical Relevance: Example

There is a danger of (adaptive) shortening of the MCP collateral ligaments when left in extension. If the MCP joint is immobilized, it is preferred to have the MPs splinted in flexion to prevent shortening. For the IP joint, this is extension.

The collateral ligaments are obliquely orientated and resist palmar translator forces induced by the flexors and intrinsics [6]. The enfolded distal component of the collateral ligament, which becomes increasingly taut during full flexion, helps resist proximal subluxation.

Clinical Relevance: Example

In rheumatoid arthritis (RA), the volar luxation of the proximal phalanges is seen as one of the first signs of the progressive deformation of the fingers. Sometimes it is the first symptom in a cascade of superimposed deformities: volar luxation, tendency to move in intrinsic plus position, shortening of intrinsic muscles, more volar luxation, etc.

The metacarpal condylar surface is somewhat asymmetrical. As a result, this articular configuration plays a role in ligamentous orientation and subsequent movements of the joint. This is a variable when studying pathological conditions such as ulnar drift [7]. The volar plate attachments at the MCP joint are capsular rather than bony as in the PIP joints, which permits hyperextension.

Proximal Interphalangeal (PIP) Joint

The PIP joint differs from the MCP in that an intact volar plate and its check rein ligaments effectively restrict hyperextension. The volar plate is attached to the accessory collateral ligament (ACL) which is tight in extension, thus pulling the volar plate against the phalanges and together with the proper collateral ligaments (PCL) completely stabilizes the PIP joint. No ulnar or radial deviation is passively possible. In some flexion, the PCL is still tight and helps in stability of the PIP joint.

The volar plate is a fibro-cartilaginous structure attached to the check rein ligament, a swallowtail-like structure (Fig. 1.5). The volar plate serves as a volar articulating surface and is an additional confining structure for synovial fluid. Lesion or laxity can result in swan neck deformity. Bowers et al. identified a bony attachment of the PIP joint's volar plate that provides greater joint stability. In their analysis of joint ruptures, they observed that the static resistance to hyperextension is offered by the lateral insertion of the volar plate-collateral ligament at the margin of the phalangeal condyle.

Clinical Relevance: Example

Combining the tendency after a trauma of the MCP and PIP joint to adopt an extended and

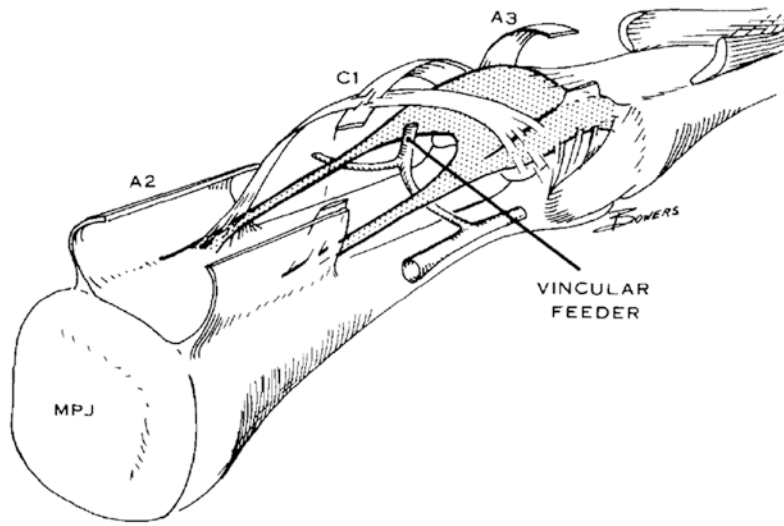

Fig. 1.5 The volar plate (gray) of the proximal interphalangeal (PIP) joint with check reins and the vinculum between the two check reins and the pulleys cut open for better view

flexed position, respectively, the splint with MCP in flexion and IPs extended is a protective splint counteracting the tendency of the ligaments to cause undesirable contractures. This is also a position in which minimal muscle and joint function is needed to regain a pinch and some hand function, another reason to choose for such a position when immobilizing the hand. Given the anatomy of the MCP and PIP joints with the inherent tendency to move in extension and flexion, respectively, the hand should, when needed, be immobilized in MCP flexion and just short of full extension in the PIP joints.

PIP and DIP Move Interdependently

In the extended finger, it is impossible to flex the DIP without also flexing the PIP joint unless the PIP joint is blocked in extension. The main reason is the oblique retinacular ligament (ORL) or Landsmeer's ligament [8] which passes volar to the axis of the PIP joint and attachment at the distal joint on the dorsal side [9] and allows transfer of tension between the dorsal aspect of the DIP joint and the palmar aspect of the PIP joint. This couples the movement of the two joints because increased tension in the terminal tendon simultaneously increases tension in the ORL, thereby adding a flexion moment at the PIP joint. The ORL acts as a passive tenodesis assisting in DIP extension as the PIP joint is extended and relaxing with PIP flexion to allow full DIP flexion [10]. It has been calculated that on average, every 1 ° of PIP joint flexion results in 0.76 ° of DIP joint flexion [11].

Clinical Relevance: Example

Under pathological conditions, like a central slip lesion (Boutonniere deformity), but also in Dupuytren's contracture and in a chronic claw hand, the ORL may become contracted which may show in a hyperextended DIP joint.

Thumb

The CMC joint of the thumb is a saddle joint exhibiting with reciprocally convex–concave surfaces

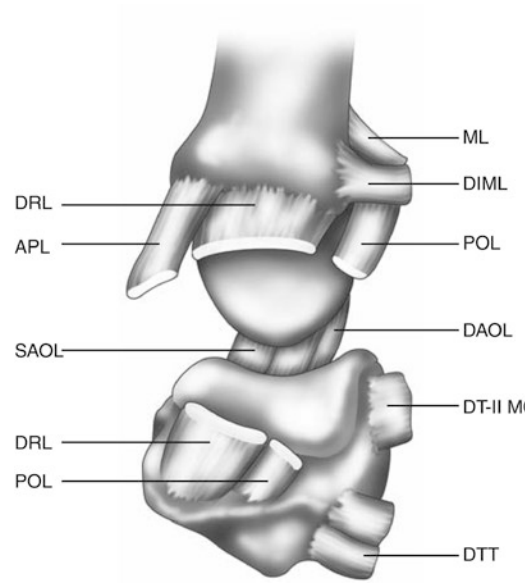

Fig. 1.6 Dorsal to palmar view of the interior of CMC joint of the thumb showing the position of the ligaments. *DAOL* deep anterior oblique ligament (beak ligament), *DIML* dorsal intermetacarpal ligament, *DT-IIMC* dorsal trapezio-second metacarpal ligament, *DTT* dorsal trapeziotrapezoid ligament, *SAOL* superficial anterior oblique ligament. (Adapted from Fig. 1.1. Mayo Foundation for Medical Education and Research)

which permits the motions of flexion and extension (concave–convex), abduction and adduction (convex–concave), and conjunctional rotation. The joint capsule is a fibrous structure composed of irregular, dense connective tissue that accepts stress and permits stretch in all directions of that joint's motion. Within the joint capsule is contained the synovial membrane from which synovial fluid is produced for these joints. The deep anterior oblique ligament (Fig. 1.6; DAOL) or beak ligament has been seen as important in preventing subluxation of the metacarpal bone of the trapezium. However, controversy exists as to the primary thumb carpometacarpal joint stabilizers. The beak ligament in a more recent study was found to be more structurally consistent with a capsular structure than a proper ligament [12].

The three dorsal ligaments of the deltoid ligament complex compared with the anterior oblique ligament were found to be uniformly stout and robust, the thickest morphometrically and the greatest degree of sensory nerve endings.

The anterior oblique ligament (beak) was thin and variable in its location [13].

The configuration of the joint surfaces makes full rotation only possible in the maximum palmar abducted position.

An acute injury to the ulnar collateral ligament of the MCP joint of the thumb is called a Skiers thumb. Not only seen in skiers falling but also in all situations, people fall on their thumb especially when holding an object like a stick. If the ligament lesion is complete, the adductor aponeurosis can get in between the two ends of the ligament and prevent repair. This is called a Stener's lesion and needs surgical repair. If the lesion is partial, a number of weeks, immobilization will be sufficient. A Gamekeeper's thumb is a similar impairment but is due to chronic laxity of the collateral ligament caused by breaking the necks of game. In modern times, musician playing the saxophone can suffer from this problem.

Loss of MCP mobility (artrodesis) often results in no loss of function.

The thumb MCP joint is similar to the finger MCP joints arthrokinematically. The thumb IP joint's articulating condyles also display an unevenness, resulting in an obliquity of the axis of motion of 5–10°.

Clinical Relevance: Example

When the hand is immobilized for surgical or traumatic reasons, the tissues in the thumb web; muscle and capsule, will adaptively shorten in the immobilized position, preventing normal motion of the articular surfaces later; therefore, the maximum palmar abducted position of the thumb is preferred.

Wrist Carpal Bones

The carpal bones can be divided into a proximal and distal carpal row, based on their kinematic behavior during global wrist motion. The distal carpal row (trapezium, trapezoid, capitate, and hamate) is tightly bound to one another via stout intercarpal ligaments, and motion between them can be considered negligible. Similarly, the nearly rigid ligamentous connection of the capitate to the index and middle metacarpals and lack of motion between these bones allow us to consider the distal row functionally as part of a fixed hand unit that moves in response to the musculotendinous forces of the forearm. The scaphoid, lunate, and triquetrum can be described as an intercalated segment because no tendons insert upon them and their motion is entirely dependent on mechanical forces from their surrounding articulations. The motions of these bones are checked by an intricate system of intrinsic, or interosseous, and extrinsic carpal ligaments [14].

The distal row is more arched than the proximal row with a deep concave volar surface which makes the trapezium lie more palmar compared to the capitate. The ulnar side is deepened by the hook of hamate which produces a deep carpal groove, which accommodates the flexor tendons and the median nerve as they pass into the hand through the carpal tunnel [15].

Distal Radioulnar Joint (DRU)

The DRU joint is most lax in the midrange of pronation and supination. Rotating the wrist into full pronation and supination results in tightening either of the volar or dorsal components of the TFCC, respectively. This stabilizes the DRU. Laxity on ballottement in full rotation is abnormal and indicates loss of the stabilizers of the distal ulna.

Triangular Fibrocartilage Complex (TFCC)

This is a homogenous structure composed of an articular disc, dorsal and volar radioulnar ligaments, a meniscus homologue, the ulnar collateral ligament, and the sheath of the ECU. The best place to palpate the TFCC is between the ECU and the FCU, distal to the styloid and proximal to the pisiform. In this soft spot of the wrist, there are no other structures than the TFCC. Pressure at this point causes pain in cases of TFCC pathology (ulnar fovea sign test) [16].

The TFCC acts as a cushion or trampoline for the ulnar carpus and carries 18–20% of the axial load across the wrist in the neutral position. The TFCC also extends the gliding surface of the radius ulnarly for carpal motion and stabilizes the ulnar carpus. The most important function, however, is as a stabilizer of the distal radioulnar (DRU) joint [17].

Another provocative test, the ulnar grind test, involves some dorsiflexion of the wrist, axial load, and ulnar deviation or rotation. If this maneuver reproduces the patient's pain, a TFCC tear should be suspected.

Scapholunate (Interosseous) Ligament (SL)

The scaphoid and lunate are bound together by a strong interosseous SL ligament. This is C shaped and attaches along the dorsal, proximal, and volar margins of the articulating surfaces. The three parts of the SL ligament have different properties, of which the dorsal component is regarded as the thickest, strongest, and most critical of the scapholunate stabilizers.

Normal kinematics of the scapholunate joint are tightly governed by the SL ligament and by an envelope of surrounding extrinsic ligaments, oriented obliquely to the primary axis of wrist motion (flexion–extension).

The scaphoid, lunate, and triquetrum rotate collectively in flexion or extension depending on the direction of hand motion. As the hand flexes or turns into radial deviation, mechanical forces from the distal carpal row drive the distal scaphoid into flexion, and the lunate follows passively into flexion through the strong SL ligament [18]. These ligaments are the most frequently injured of the wrist ligaments [14].

To test for SL ligament injury, Watson's test or the scaphoid shift maneuver is used. The examiner's thumb is placed firmly on the tubercle of the scaphoid, and the wrist is moved into radial deviation. If the SL ligament is disrupted, the proximal pole of the scaphoid remains on the dorsal rim of the radius until it suddenly pops back into place. If this elicits pain, Watson's test is positive.

The Dart-Throwing Motion (DTM)

The plane of the DTM can be defined as a plane in which wrist functional oblique motion occurs, specifically from radial extension to ulnar flexion. During a DTM, there is less scaphoid and lunate motion than during pure flexion–extension or radioulnar deviation. Clinically, a DTM at the plane approximately 30–45° from the sagittal plane allows continued functional wrist motion while minimizing radiocarpal motion when needed for rehabilitation [19].

Clinical Relevance: Example

Most activities of daily living are performed using a DTM. Scaphotrapeziotrapezoidal anatomy and kinematics may be important factors that cause a DTM to be a more stable and controlled motion.

Muscle and Tendons

To study the anatomy and kinetic chains of the hand and the interplay of more than 40 muscles that control its movements requires an appreciation of the biomechanics of the hand and its dexterity [6]. The muscles of the lower arm and hand can be conveniently arranged according to innervation and localization (Table 1.1). Usually the muscles are divided into extrinsic, where muscles have their origin proximal to the hand, and intrinsic muscles, which have their origin and insertion within the hand (Fig. 1.7). In general, each finger has six muscles controlling its movements: three extrinsic muscles (two long flexors and one long extensor) and three intrinsic muscles (dorsal and palmar interosseous and lumbrical muscles). The index and small fingers have an additional extrinsic extensor.

Table 1.1 Innervation of all the extrinsic and intrinsic muscles of the forearm and hand arranged by nerve and main joints involved

	Extrinsic				Intrinsic	
	Forearm	Wrist	Fingers	Thumb	Fingers	Thumb
Ulnar		FCU	FDP (dig 4, 5)		Interosseous dorsal (4)	AdP
					Interosseous palmer (3)	FPB (part)
					Lumbricals dig 4, 5	
					Hypothenar muscles	
Median	PT	FCR	FDP (dig 2, 3)	FPL	Lumbricals dig 2, 3	APB
		PL	FDS (dig 2–5)			OpP
		PQ				FPB (part)
Radial	BR	ECRL	EDC	APL		
	Supinator	ECRB	EDQ	EPB		
		ECU	EIP	EPL		

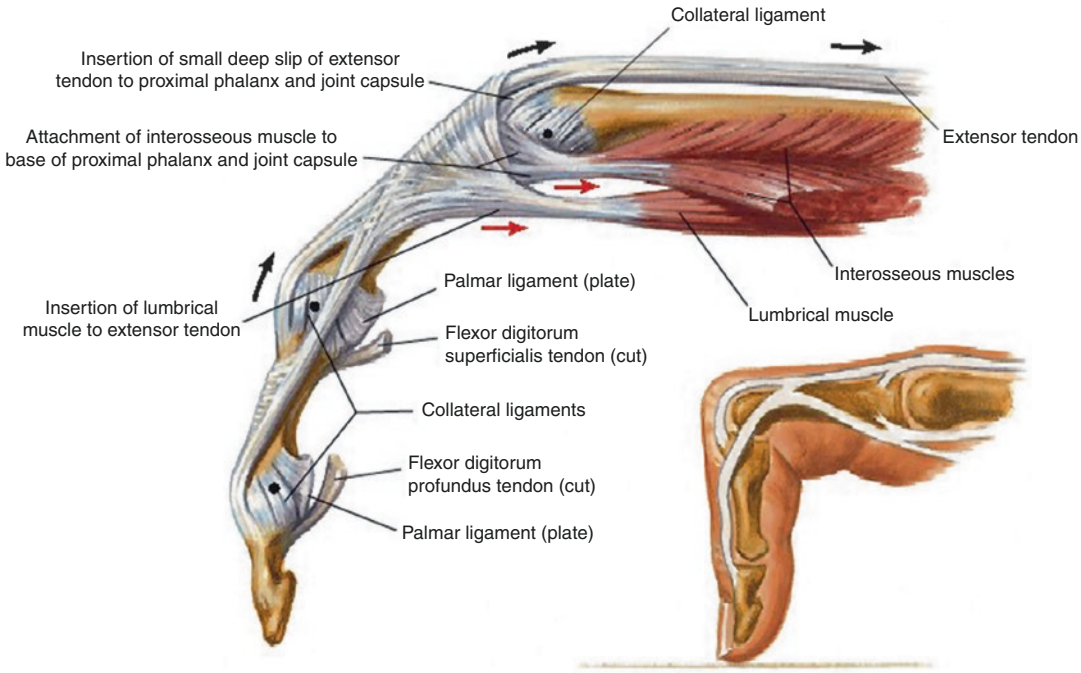

Fig. 1.7 Intrinsic muscles of a finger contribute to the extensor apparatus (mechanism) of the finger

Intrinsics of the Finger and Thumb

Sterling Bunnell [3] wrote that "the intrinsic muscles of the hand, though tiny, are important because, with the long extensors and long flexors, they complete the muscle balance in the hand." Referring to the intrinsic muscles as tiny or small muscles of the hand is true for some muscles like the lumbricals or third palmar interosseous muscle but not for the first dorsal interosseous (1DI) and the adductor pollicis muscle; they have a cross-sectional area similar to extrinsic muscles [20].

Many valuable studies have been published about the anatomy [9], mechanics [6, 8, 20], and architectural design [21] of the intrinsic muscles of the hand.

Clinical Relevance: Example

There is a considerable decrease in functional efficiency in hands with loss of intrinsic muscle function, often referred to as the claw hand or intrinsic minus hand [22]. Besides the inability to manipulate smaller objects, the loss of holding and gripping large objects is sometimes more evident. Key pinch can be very weak in case the 1DI and/or adductor pollicis is paralyzed.

Clinical Relevance: Example

Strength testing for the interosseous muscles is often done by testing abduction and adduction; however, the more important function to test is the test in intrinsic plus position: pushing against the volar proximal phalanx or PIP joint in attempt to extent this joint (Fig. 1.8). A weak 1DI and adductor pollicis muscle also result in a weak pinch because the MCP joint of the thumb cannot be stabilized; the FPL creates a flexion force for this which results in IP flexion of the thumb, called a Froment sign [20].

The strongest activity of the 1DI is in key pinch when the thumb is pressed against the mid-phalanx of the index finger. The 1DI is also active in tip pinch, when the tip of the thumb is pressed against the tip of the index finger. In that case, the main action is as a flexor at the metacarpophalangeal (MCP) joint. The first palmar interosseous (1PI) muscle is also active in tip pinch activities and produces some supination of the index finger to get good approximation with the pulp of the thumb. Without interosseous muscles, the finger is unstable and will collapse into the intrinsic minus position of (hyper) extension of the MCP joint and flexion of the IP joints when loaded. The primary function of the interosseous is MCP flexion/stabilization allowing extension of the (IP) joints (Fig. 1.9).

Intrinsic Tightness

Shortening of the interosseous muscles is called intrinsic tightness (IT) and is often caused by trauma of the hand. The interossei are situated in rather tight compartments (Fig. 1.2). Therefore,

Fig. 1.8 The manual muscle strength test for the intrinsic muscles of the fingers combined in its action to flex the MCP joint and extend the IP joints. Pressure is applied upward at the volar side of the PIP joint

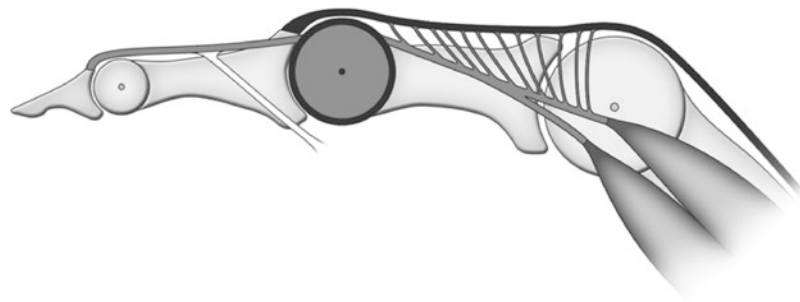

Fig. 1.9 Schematic drawing of extensor apparatus showing the action of the interosseous and lumbrical muscles in producing flexion of the MCP and extension of the PIP joint

swelling will cause an increase in pressure in these compartments, resulting in anoxia and muscle fiber death, with subsequent fibrosis of the muscle and shortening. This process is identical to the cause of Volkmann's ischemic contracture in the forearm [23]. The IT test consists of two parts. First, the range of passive PIP flexion is tested with the MCP joint extended. Next, passive PIP flexion is tested with the MCP joint flexed. Intrinsic tightness is present if there is a large difference in PIP flexion between the two MCP positions (Fig. 1.9).

This test is sometimes called the Bunnell intrinsic tightness test [3]. Intrinsic muscle tightness may also play an important role in the pathogenesis of MCP joint subluxation in rheumatoid arthritis.

Clinical Relevance: Example

The long-term complications of IT can result in decreased MCP extension and a swan neck finger, i.e., hyperextension of the PIP joint with secondary DIP joint flexion. A long-standing swan neck deformity might result in a painful snapping of the lateral bands at the PIP level when the finger moves into flexion.

The lumbrical muscles are unique muscles in several aspects. They connect two extrinsic antagonistic muscles. Proximally the lumbricals are attached to the FDP, and distally they are inserted into the lateral band of the extensor tendon. The third and fourth lumbricals also connect, by their bi-penal origin, two adjacent FDP tendons. The effect of the lumbrical muscles upon MCP joint flexion is somewhat controversial. Brand suggested that the lumbrical muscles are not important for MCP flexion [20]. Nonetheless, independent MCP joint flexion is possible when the lumbricals are functioning and the interosseous muscles are paralyzed [8]. There is no controversy, however, regarding the effect of the lumbrical muscle on proximal and distal interphalangeal joint extension. The lumbricals are more efficient for IP extension than the interosseous.

Leijnse and Kalker [24] concluded that the lumbricals are in an optimal position for proprioceptive feedback regarding PIP–DIP joint movements. The unique properties of the lumbricals indicate that they are probably important in fast, alternating movements, e.g., in typing and playing musical instruments [25].

Clinical Relevance: Example

In low median nerve injuries, the lumbrical muscles of the index and middle finger are paralyzed. In these hands, it is difficult to discover any problems in the motion of these fingers. A mildly diminished extension of the DIP joint has been noticed in a few patients, which might be explained by the decreased extension force on the extensor apparatus.

Lumbrical Plus

The "lumbrical plus" sign is a situation in which there is an FDP tendon rupture distal of the lumbrical origin. It is also present in the situation where a graft in tendon reconstruction has been used that was too long. The FDP now pulls through the lumbrical muscle rather than through its tendon, causing PIP extension [26].

Fingers Flexing: The Flexors and Pulleys

Often anatomical textbooks present the flexor tendons as simple homogenous cords with all the same diameter, well ordered in one position. Looking in more detail, the FDP tendon has certain curvatures according to the contact areas with the FDS [27]. Recent studies found that the flexor tendons change position and shape when moving [28].

Pulleys

Flexor tendon sheaths, with four annular and three cruciate pulleys, not only serve as a protective housing for the tendons but also provide a smooth, gliding surface by virtue of their synovial lining and an efficient restraint system that holds the tendons close to the digital bones and joints [29] (Fig. 1.10).

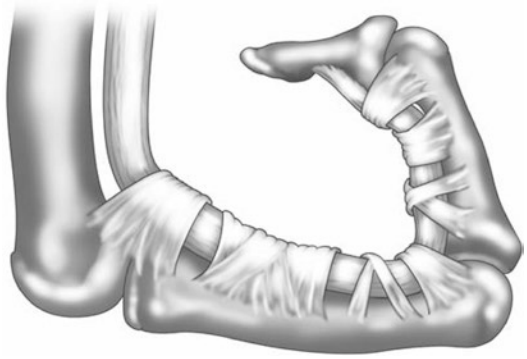

Fig. 1.10 A finger pulled in flexion; the pulleys maintain the close arrangement of the flexor tendon to the bone and prevent bowstringing

Clinical Relevance: Example

Loss of pulley especially the A4 and A2 results in bowstringing and as a result loss of a certain degree of flexion of the involved finger.

Flexor Digitorum Profundus (FDP) Quadriga: Linkage of Tendons

In the carpal tunnel, anatomical interconnections between the tendons of the FDP are consistently present. These interconnections limit the mutual tendon displacements, which decrease finger independence; this is sometimes called the Quadriga phenomena [25] or Verdan's quadriga syndrome [30]. Another reason why the FDP cannot move independently is the common muscle belly [31].

Clinical Relevance: Example

The clinical relevance of this phenomenon can be observed in FDS test, dystonia, grip strength, PIP arthrodesis, flexor tendon injury exercises, and tip finger amputation [32].

The index finger can sometimes be flexed independently from the other fingers, but sometimes, the FDP of the index finger has an anomalous tendon connection with the FPL first described by Linburg–Comstock [33]. An incidence as high as 60–70% has been reported [34]. In case of intertendinous connection between index FDP and FPL, thumb IP flexion may also result in DIP index finger flexion.

Flexor Digitorum Superficialis (FDS)

The FDS is not normally activated until firm grasp is required or the wrist is in flexion [6]. FDS of the little finger is absent bilaterally in 4.5% and absent unilaterally in 3%, and has a dependent function with ring finger FDS is present in 38% [35].

If in isolated little finger flexion the PIP joint is flexing, then an independent FDS is present. If there is only flexion of that joint with simultaneous flexion of the ring finger, then the two FDS tendons are most likely connected. If no flexion occurs and the ring finger is allowed to flex, the little finger will flex which shows that the FDS 5 is present but connected to FDS 4.

Congenital absence of flexor digitorum superficialis has implications for assessment of little finger lacerations [36]. For above reasons, FDS of the little finger is also not a suitable "donor" in tendon transfer surgery.

FDS Chinese Finger Trap: Tendon Locking Mechanism

The "finger trap" can be observed when making a hook fist: flex IPs and extend MCP. When holding your middle finger in that position actively and extending the other fingers, the DIP can maintain the flexed DIP position. This is due to the FDS squeezing the FDP at Camper's chiasm. Now passively extend DIP (you might feel a little resistance) and see that it keeps an extended position, and you cannot actively flex it (Quadriga) or extend it. The changes in tendon shape and the lateral and anteroposterior forces produce a "compression" mechanism on the FDP tendon by the FDS slips, resulting in a smaller diameter of the FDS loop and altering frictional resistance.

This tendon locking mechanism is more apparent in animals like bats [27]. They can hang on the branch of a tree without active muscle contraction.

Clinical Relevance: Example

Tendon lesion at this level is difficult to repair and has a great risk of adhesions and needs special care to regain gliding of the two tendons.

Finger Extension: The Extensors

Extensor Tendons

The extensor tendons do not have a synovial sheath system, but at the wrist level (Zone 7), the extensors are restricted by the extensor retinaculum that forms six fibro-osseous compartments within which 12 extensor tendons pass. Adhesion formation after extensor tendon injuries is not uncommon, but because the requirement of tendon gliding excursion is low and adhesions form under largely moveable skin, adhesions often do not pose an important problem for function of the extensor tendons. Metacarpal fractures, however, including surgical repair, may often result in adhesions.

The extensor retinaculum at the dorsum of the wrist functions as a pulley, keeping the wrist and finger extensor tendons near the axis of the wrist during motion.

Clinical Relevance: Example

Extensor tendon lesions at the extensor retinaculum location (Zone 7) often result in dense adhesions between retinaculum and the tendons and often hinder gliding/excursion of the extensor tendons.

The principal function of the sagittal bands of the MCP joints is to extend the proximal phalanx. They lift the phalanx through their attachments to the volar plate and the periosteum of the proximal phalanx. In addition, the sagittal bands help to stabilize the extensor tendons at the mid-line of the dorsum of the joint. They prevent bow stringing of the extensor tendons dorsally. When the MCP joint is fully extended, they may also contribute to its lateral stability.

The manner in which the sagittal bands extend the proximal phalanx is worthy of particular attention. Since the extensor tendon is not tethered to the proximal phalanx (except for occasional articular slips), its excursion may be transmitted to more distal joints if MCP hyperextension is prevented. If hyperextension is not prevented, the excursion and force of the extensor tendons are directed principally through its sagittal bands to the volar plate, and little or none of its excursion or force will be transmitted more distally. The interphalangeal joints will then fall into flexion unless they are extended by other muscle–tendon units, i.e., intrinsic extensors, lumbricals, and interossei.

Clinical Relevance: Example

Loss of sagittal bands may occur with rheumatoid synovitis of the metacarpophalangeal joints. Swelling within these joints may gradually stretch and thin the sagittal bands. The extensor tendon will no longer be kept at the dorsal midline of the joint and will be free to dislocate. With finger flexion, the fourth and fifth metacarpals descend volarly, and the extensor tendons have a tendency to be pulled ulnarly through the intertendineal fascia and the juncturae tendinae. Dislocation of the extensor tendons may then occur. Furthermore, with stretching of the sagittal bands, the link between the extensor tendon and the volar plate is weakened. The dislocated extensor tendon will only poorly be able to extend the proximal phalanx. If the tendon had dislocated ulnarly, it may cause the finger to deviate ulnarly.

The dorsal apparatus of the fingers (Fig. 1.11) consists of the two conjoined lateral bands at the dorsolateral aspect of the proximal interphalangeal joints, converging more distally at the dorsum of the middle phalanx to form the terminal tendon which is inserted at the dorsal lip of the base of the distal phalanx. The conjoined lateral band is dorsal to the axis of motion of the proximal interphalangeal joint. It is held dorsally by the triangular ligament. This “ligament,” actually a sheet of transversely oriented fascia, is bounded proximally by the insertion of the central slip and of the medial interosseous bands at the base of the middle phalanx, laterally by the conjoined lateral bands, and its apex, distally, is at the terminal tendon.

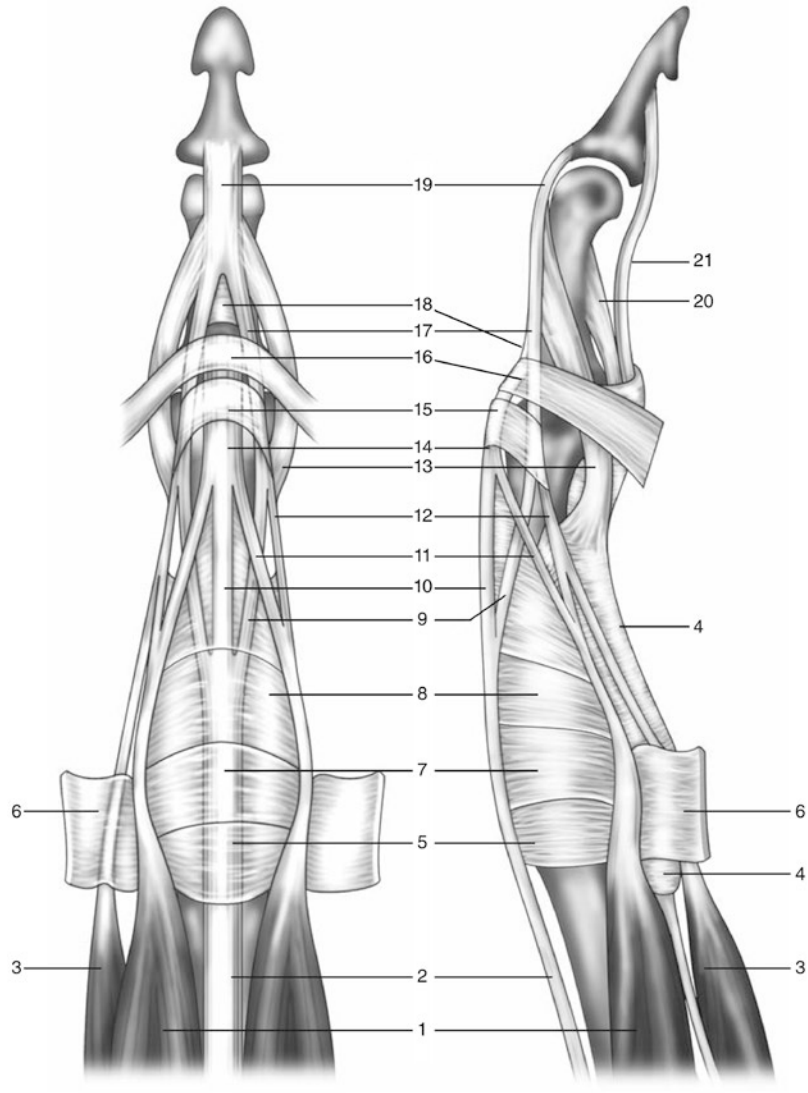

Fig. 1.11 The extensor apparatus of the finger. (1) Interosseous muscle. (2) Extensor communis tendon. (3) Lumbrical muscle. (4) Flexor tendon fibrous sheath. (5) Sagittal bands. (6) Intermetacarpal ligament. (7) Transverse fibers of extensor apparatus. (8) Oblique fibers of the extensor apparatus. (9) Lateral band of extensor tendon. (10) Central or middle band/slip. (11) Central or middle band of interosseous tendon. (12) Lateral band of interosseous tendon. (13) Oblique retinacular ligament (Landsmeer's ligament). (14) Middle extensor tendon. (15) Spiral fibers. (16) Transverse retinacular ligament. (17) Lateral extensor tendons. (18) Triangular ligament. (19) Terminal extensor tendon. (20) Flexor superficialis tendon. (21) Flexor profundus tendon

The conjoined lateral bands are prevented from dislocating too far dorsally by the transverse retinacular ligaments. These structures extend volarly and proximally from the lateral edges of the conjoined lateral bands to the pulley of the flexor tendons on either side of the proximal interphalangeal joint.

In the normal finger, the lateral bands of the dorsal apparatus (or extensor mechanism) at the PIP level shift dorsally and toward the central position of the finger when the PIP joint is extended, whereas when flexing the PIP joint, the dorsal apparatus needs to allow the lateral bands to move volarly toward the flexion–extension axis of movement at the PIP joint.

If the extensor tendon to the middle or ring finger is lacerated proximal to the juncturae tendinae, the finger may still fully extend as was noted above. If the central slip itself is lacerated, there may still be full extension of the middle phalanx through the ateral bands. If these, too, are lacerated and if the triangular ligament is torn, the lateral bands subluxate laterally and a Boutonniere deformity results. If the terminal tendon is divided, the distal joint falls into flexion: a Mallet finger.

Clinical Relevance: Example
When this dorsal expansion is elongated, the lateral bands are too much volarly, resulting in a loss of PIP joint extension; consequently, the ORL is slack most of the time and will adjust to this new situation by shortening, and this may result in hyperextension of the DIP joint. In Boutonniere deformity, the ORL is shortened [20].

The characteristic Boutonniere deformity is not usually present at the time of injury because extension of the PIP joint is still possible via the lateral slips of the extensor tendon. Consequently, a rupture of the central slip of the extensor tendon can easily be missed. Early diagnosis is essential to start treatment as soon as possible to prevent deformity [37, 38].

EIP and EDC of Index Finger

The EDC strength test is for testing the MCP extension without PIP extension of the fingers. Without the intrinsic, you cannot extend all the joints of the fingers simultaneously because the EDC has too little excursion, that is, insufficient proximal movement of the EDC when contracting. When you block the MCP (e.g., with a knuckle bender splint), all the excursion is now used at the IP joints of the fingers, and you can extend the IPs without intrinsic muscle action.

Clinical Relevance: Example
When there is a subluxation of the EDC at the MCP level possible due to rheumatoid arthritis or sagittal band lesion, the EDC tendon can become a flexor and ulnar deviator.

It has been shown that extension of the index finger is possible without the EIP apparently because the loose connection between EDC index and middle finger allows this [39].

Thumb Muscles

Extensor Pollicis Longus (EPL)

The EPL together with the FPL are strong adductors of the thumb. Even in ulnar palsy, the adduction can be quite strong. Because EPL and FPL contribute to adduction, an isolated strength of this muscle cannot be done and should be tested in pinch grip, e.g., with a dynamometer.

The best way to test the function of the EPL is by putting the hand flat on the table and asking for elevation of the thumb [39]. The EPL is a positioning muscle and does only need strength to lift the weight of the thumb. IP extension of the thumb is in radial palsy possible through the intrinsics (FPB and adductor) similar to lumbricals–interossei in the fingers.

Clinical Relevance: Example
Froment sign is a sign of adductor weakness, e.g., seen in ulnar nerve paralyses.

Extensor Pollicis Brevis (EPB)

Weakness of the EPB will result in weaker MCP extension of the thumb, which is rarely seen after injury but is more often seen in a congenital deformity called the clasped thumb.

Clinical Relevance: Example
The EPB and the APL are the tendons involved in Quervain tendinitis in the first extensor compartment at the wrist.

Abductor Pollicis Longus (APL)

It is a strong muscle close to the abduction–adduction axis of the CMC. The main function is to stabilize the CMC joint where the metacarpal bone is held firmly against the trapezium.

Clinical Relevance: Example
In CMC arthritis, the trapezium is tilted, and pulling on the APL will cause a deforming force by pulling the metacarpal off the trapezium.

When the APB is weak, patient will move the wrist in flexion, allowing the APL to have a better moment arm at the CMC joint and assist in palmar abduction of the thumb.

Similarly, when testing for abduction strength of the thenar muscles, e.g., in carpal tunnel

syndrome, keep the wrist in extension. This will prevent the APL from moving volarly, thus assisting in abduction [40]. Brand called this the bow stringing of the APL [41].

Nerves and Innervations

Sensibility tests include different modalities, e.g., touch and temperature. Although a number of tests are useful in diagnosis or describing the location of nerve injury, quantitative tests are more appropriate as outcome measures. Sensibility testing with Semmes-Weinstein monofilaments (SWMF) has become one of the most commonly used quantitative measures in hand rehabilitation. Advantages of SWMF include the ability to assign numbers to sensory touch thresholds, regulation of force variations, and translation of forces obtained into functional levels. The Weinstein Enhanced Sensory Test (WEST) instrument has five filaments with consistent head sizes across filaments.

Tactile discrimination is frequently measured using two-point discrimination (2PD). This test is said to reflect the quantity or innervation density of innervated sensory receptors. The smallest distance that the patient can correctly discriminate one from two probes is recorded. Normal values within the range of 4–7 mm for the finger tips have been reported.

With low ulnar nerve palsy, all interossei and the ulnar two lumbricals are paralyzed. Flexor profundus and flexor superficialis work normally. Abduction and adduction of all the fingers are lost. Grip is weakened because of interosseous paralysis. The ring and little fingers may claw, particularly if the volar plates of the MCP joints are lax since the proximal phalanx will become an "intercalated bone." Overt clawing of the index and middle fingers is usually not present as the lumbrical will continue to extend the interphalangeal joints and may achieve flexion of the metacarpophalangeal joints (Fig. 1.12).

Latent hidden or functional clawing is usually present in functional activities because the two primary flexors of these fingers are paralyzed.

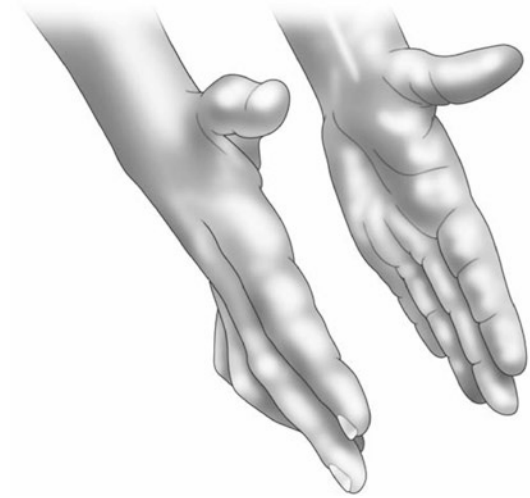

Fig. 1.12 Typical claw hand in an early stage after ulnar nerve lesion. The ring and little finger cannot be fully extended at the PIP joint and often show hyperextension at the MCP joint

The main deformity to prevent is PIP flexion contractures by splinting and exercises.

With high ulnar nerve palsy, if the ulnar nerve is lacerated above the site of innervations of the flexor digitorum profundus to the ring and little fingers, these muscles will be paralyzed along with all the interossei and the ulnar two lumbricals. Abduction and adduction of all the fingers will be lost. The power of finger flexion will be decreased by as much as 50% as the contribution toward MCP joint flexion by the interossei will be lost. Flexion of the ring and little fingers will be weakened as both the profundus and interossei are paralyzed.

There will be only mild clawing of the ring and little fingers since the loss of their profundus tendons will somewhat balance the weakness of extension which follows lumbrical and interosseous paralysis of these digits. Ring and little finger flexion will occur at the proximal interphalangeal joints. In addition, grip strength loss also occurs because of loss of antepulsion of the fourth and fifth rays, causing a decreased ulnar opposition and less secure grip.

When the nerve recovers from proximal to distal, the long flexors first regenerate which causes a more pronounced flexion of the fingers

and clawing; more attention toward preventing PIP flexion contractures must be initiated.

With low median nerve palsy, the main problem is the loss of sensation in the radial side of the hand and the loss of median innervated thenar muscle action. It must be noted that in median nerve palsy, especially when the FPB is entirely ulnar innervated, there is still a good palmar abduction possible [40].

In some patients with weak thenar muscles, a trick movement of flexing the wrist to activate the APL is adopted [20]. The loss of lumbricals on the index and middle finger does have little effect. Sometimes, a slight diminished extension of the DIP can be observed. The main deformity to prevent is adduction contracture of the thumb.

With a low median and ulnar nerve palsy, all interossei and lumbricals are paralyzed. All abduction and adduction of the fingers are lost. Flexion power is weak because of the loss of interosseous muscles as MCP joint flexors. Secondary flexion of the metacarpophalangeal joints occurs through the flexor profundus and superficialis.

With high median nerve palsy, often the so-called Preachers Hand is shown, but this does not describe what is seen in clinical practice. The MCP can still flex because of the ulnar innervated interosseous muscles, and the middle finger will often flex because of the connections between the FDP tendons of the ring and middle finger and the common muscle belly. This represents a pointing finger (Fig. 1.13), which is a much better name. Sometimes this is called the orator's hand posture in which the patient has been asked to make a fist. The hand is held in an "orator's hand" posture [42].

With high median and ulnar nerve palsy, all the profundi and the superficialis tendons and all the interossei and the lumbricals will be paralyzed. The only motors still functioning within the fingers will be the (extensor digitorum communis, extensor indicis proprius, and the extensor digiti quinti proprius) finger extensors. Full extension will probably be possible at all three joints since the weakened extension at the interphalangeal joints will not be antagonized by the normal viscoelastic forces of the long flexors. Flexion of the fingers will be impossible, however.

With radial nerve palsy, extension at the metacarpophalangeal joints will be lost. There will still be full flexion at all three joints and often complete extension of IP joints through the intrinsics.

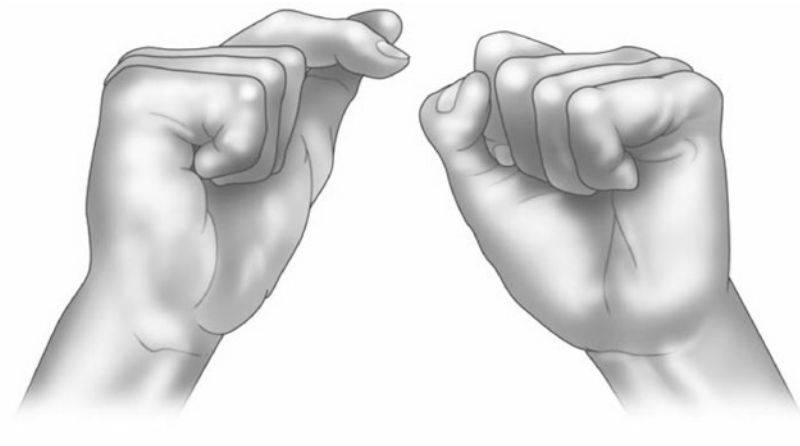

Fig. 1.13 A "pointing finger" as a result of a median nerve lesion at elbow level (high median nerve) in an attempt to make a full fist. The index finger cannot flex at the IP joint due to paralyses of the FDP and FDS, while the interosseous muscles flex the MCP joint. The middle finger is flexed due to attachments between FDP tendons of the middle and ring finger (Quadriga phenomenon)

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Physical Examination of the Hand

2

Fitnat Dinçer and Gülbüz Samut

Introduction

Hand is one of the most complex anatomical structure in human body. It is said that hand is the mirror of the brain. Especially evolutionary specialization of thumb as an opposing digit makes it the most important digit in a way providing exceptional motor abilities. Because of these complex functions, injuries to the hand severely compromise a patient's well-being, although they are rarely life-threatening. So immediate evaluation and accurate diagnosis of hand injuries carries great importance. With a thorough history, systematic examination, and knowledge of disease process of hand, it is possible to make the clinical diagnosis with a considerable accuracy. Radiographs, electrodiagnostics [1, 2], and specialized laboratory test will only be ancillary tool to confirm the diagnosis. However, recording the clinical findings is also important in order to demand the necessary diagnostic tools and in the patient follow-up.

In this chapter, an approach to clinical examination of the hand will be outlined as in order: patient history, inspection, palpation, assessing range of motion, neurological examination, and specific tests.

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Patient History

Patient history [3] is the key point in the examination and provides sufficient information for tentative diagnosis. The diagnosis with 60% accuracy can be made with only taking a good patient history. As always patient history begins noting down the demographic information such as patient's age, occupation, avocation, and hand dominance. Patient's general condition, systemic diseases such as diabetes mellitus, cardiovascular problems, etc. are also important and influence the main pathology. Any previous illness and trauma should also be noted. Especially in acute trauma, site and description of the accident (cuts, crush injuries, saw accidents, chemical or burn injuries, bite wounds, closed trauma) are important in the means of making the diagnosis and deciding the subsequent treatment strategy.

Inquiring pain symptoms are also important. The pattern of pain and whether the pain fluctuates over time should be asked. Location of the pain, characteristics, and amplitude of the pain should be noted. Asking any aggravating or relieving factors and if the pain is constant or work related are also important. How does the pain affect the patient's daily living activities? What was the patient capable of doing in the past and what is he/she is capable of doing now? Accompanying symptoms beside the pain should be inquired. For example, accompanying numbness and weakness in the index and middle finger is often characteristics of carpal tunnel syndrome.

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Pain aggravating with heat and often worse in the morning and with rest in the metacarpophalangeal and proximal interphalangeal joints are usually signs of inflammatory conditions, especially rheumatoid arthritis [4].

While obtaining the patient history, clinical suspicion usually develops and other diagnostic studies and physical examination are required only for confirmation. This is why, as mentioned before, taking a careful, detailed, and comprehensive history is very important and necessary in order to make a thorough diagnosis.

General Inspection

Evaluation of the patient always begins with general inspection in all kinds of physical examination, just as in hand examination. Once the patient enters the room, the examination begins and patient is observed as a whole, including patient's general being, posture, walking pattern, etc. After a general look, whole upper extremity is observed. Any asymmetry of shoulders, shape of posture of the hand, and difference between both upper extremities are documented. Any swelling, deformities, and congenital abnormalities are reported. While generalized swelling may be the sign of circulatory problem, localized swelling can indicate inflammation, fracture, tumors, and ganglia originating from tendons or joints. Axial deformities may indicate a fracture. Muscle atrophy may be due to prolonged inactivity or chronic peripheral nerve compression [5] (i.e., carpal tunnel syndrome). Skin color changes can give information about current state of vascular supply of hand and should always be observed. Hyperemia may be a result of bacterial infection, dry and shiny skin may occur with systemic diseases such as scleroderma, and hyperpigmentation of palmar furrows is seen in hyperaldosteronism. Hypo-/hyperpigmentation plus hypertrichosis and dry skin may be signs of loss of nerve function of the hand.

Inspection of finger nails can also provide information about systemic disorders. Hallow nails suggest iron-deficiency anemia. Clubbing is usually a sign of lung disorders but can also be seen in inflammatory bowel diseases, cirrhosis, etc. Posterolateral swelling of distal interphalangeal fingers due to arthritis in postmenopausal women is observed and called as Heberden's nodes; the same pathology at proximal interphalangeal joints is called as Bouchard's nodes [6, 7] (Figs. 2.1 and 2.2).

In addition to individual swelling of finger joints, bilateral symmetrical swellings of especially metacarpophalengeal and proximal interphalangeal joints are early signs of chronic inflammatory disorders especially rheumatoid arthritis [4]. Swelling can be accompanied by tenosinovitis, effusions, and in chronic conditions by characteristic finger deformities which are:

- Swan-neck deformity: flexion of metacarpophalangeal and distal interphalangeal joints, hyperextension of proximal interphalangeal joints
- Boutonnière deformity: flexion of proximal interphalangeal joint, extension of distal interphalangeal joint
- Ulnar deviation of fingers (Fig. 2.3)

Other deformities such as congenital ones should also be noted. Most frequently seen congenital anomaly is polydactyly and the second one is syndactyly. These congenital deformities may be hereditary or exogenous in origin.

Palpation

Palpation is a complementary component of examination after inspection.

What is seen with inspection is evaluated in more detail with palpation. Palpation includes not only soft tissue, bone, and joints of hand but also the whole upper extremity for a thorough examination. Skin surface texture evaluation is important.

The hand must be checked whether it is hot or cold, dry or moist, smooth or rough, if there is any swelling and for its properties, fluctuant or fixed, soft or hard, its dimensions and accompanying skin color changes, and for any tender points with palpation.

Distal pulses are also important as they give idea about current blood supply of hand.

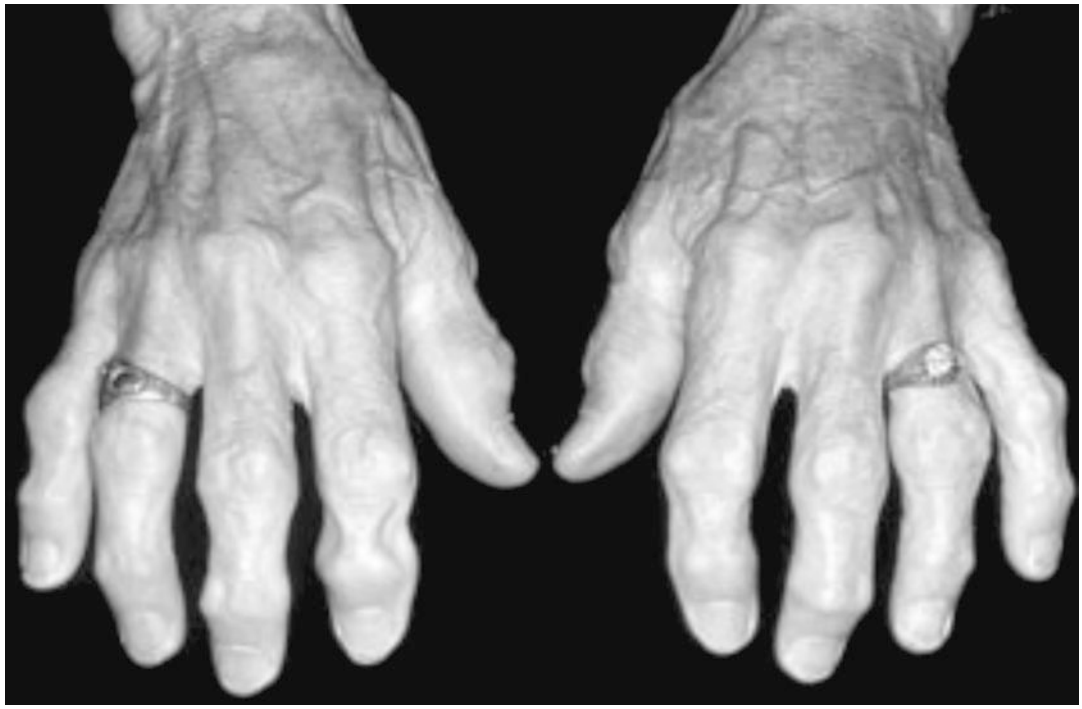

Fig. 2.1 Posterolateral swelling of distal and proximal interphalangeal joints due to osteoarthritis; Heberden and Bouchard nodes, respectively. (www.healthinplainenglish.com) (Received from the www.healthinplainenglish.com web site on 12.10.2010)

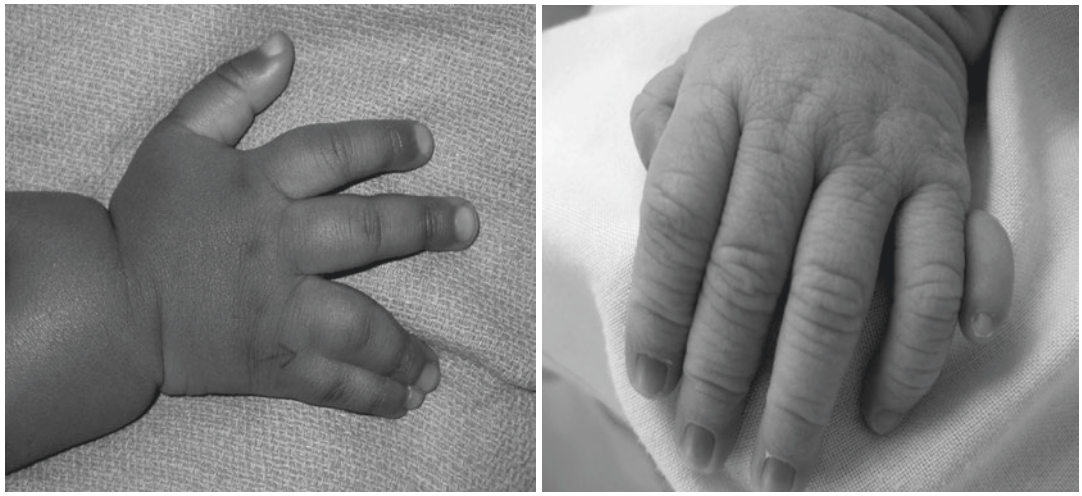

Fig. 2.2 Congenital deformities of the hand. Syndactyly on the left and polydactyly on the right. (img.medscape.com/farm3.static.flickr.com) (Received from the img.medscape.com/farm3.static.flickr.com web site on 12.10.2010)

Palpation of major landmarks of hand is important to make the differentiation between normal and pathological conditions.

Radial Styloid This is an easily palpable and important landmark for palpation of wrist. Tenderness at this point in postmenopausal

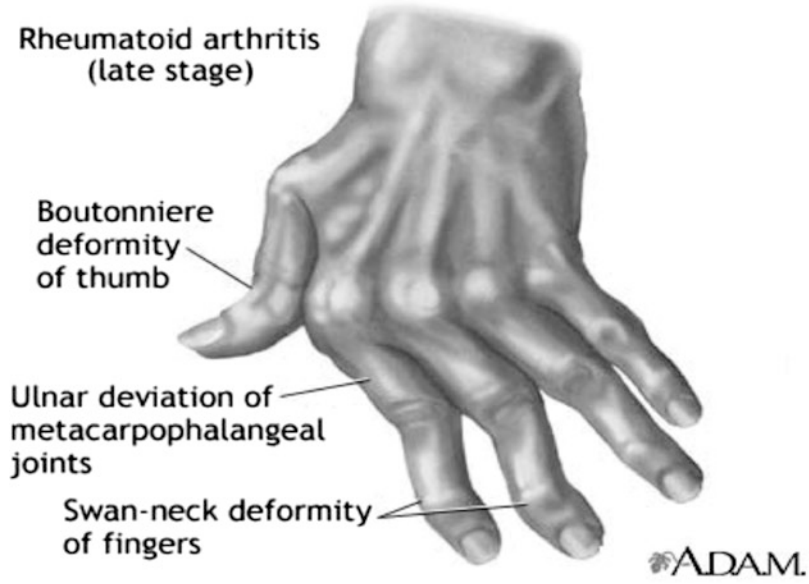

Fig. 2.3 Characteristic finger deformities of chronic inflammatory disease of the hand. (www.clarian.org) (Received from the www.clarian.org web site on 12.10.2010)

women may indicate fracture which is usually called Colles' fracture or rarely tendinitis of brachioradialis muscle which occasionally occurs in athletes performing backhand motions [3].

Anatomical Snuffbox and Scaphoid Anatomical snuffbox is located distal to radial styloid process and between abductor pollicis longus and extensor pollicis longus. It is an important landmark in two ways: first of all, radial artery passes through this hollow and can be injured in traumas to this anatomical place. Secondly, scaphoid is palpable on the floor of the hollow. Tenderness in this area usually indicates a scaphoid fracture which is the most frequently fractured carpal bone (Fig. 2.4).

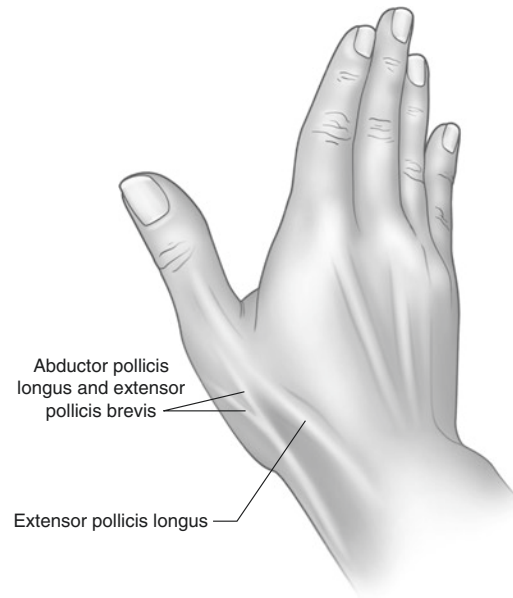

Fig. 2.4 Anatomical snuffbox of the hand. It is located distal to radial styloid between abductor pollicis longus and extensor pollicis longus tendons. (www.dartmouth.edu) (Received from the www.dartmouth.edu web site on 12.10.2010)

Trapezium and the Base of the First Metacarpal Trapezium is palpable just distal to scaphoid. Palpation of this area will be painful especially in degenerative osteoarthritis of the hand.

Capitate Capitate is palpable proximal to the largest and most prominent of all metacarpal bases, the third metacarpal.

Lunate and Lister's Tubercle Lister's tubercle lies on the dorsal aspect of the distal radius directly in line with third metacarpal. Lunate is located distally to Lister's tubercle and prone to dislocation, fracture, and avascular necrosis.

Tenderness in this area especially with the wrist motion is an important indicator of lunate damage.

Ulnar Styloid Ulnar styloid is another important and easily palpated anatomical landmark. The pain of flexor carpi ulnaris tendinitis is usually located in this area. This styloid process is also vulnerable to the traumatic injuries especially falls.

Triquetrum and Pisiform Triquetrum is distal to ulnar syloid, and pisiform is distal to triquetrum. Flexor retinaculum, extensor retinaculum, abductor digiti minimi, and fibrous complex of ulnacarpal compartment insert to pisiform.

Hamate and Guyon's Canal Hamate is located distally to pisiform, but it is difficult to palpate, because it lies deep in the hand and covered by soft tissues. Guyon's canal is between hook of hamate and pisiform, and it is an important anatomical structure because ulnar artery and nerve pass through and prone to compression with acute or chronic trauma.

Assessment of Range of Motion

Range of motion assessment is an essential component of hand function evaluation. Limitation of the motions severely impairs hand function. This is why, thorough evaluation of the range of motion of each joint carries great importance. Range of motion evaluation can be elicited with or without a goniometry. However using a goniometry improves reliability of measurements although there is not much literature supporting this statement [8]. It was found that intra-observer reliability is high [8, 9]. Intra-observer reliability is higher than interobserver reliability, but several measurements should be taken by the same examiner. Placing the goniometry dorsally or laterally has equal reliability [10], and each technique can be used in order to measure the range of motion (Fig. 2.5).

Range of motion evaluation involves active and passive motion measurements. Initially active and then passive range of motion is evaluated. Active motion refers the motion achieved by patient's own muscle power. Passive motion refers the freedom of motion of a joint when an external force is applied. If the patient is capable of doing full range of active motion, passive range of motion evaluation will not be necessary. Flexion is evaluated with the hand in "fisted" position (maximal metacarpophalangeal, proximal interphalangeal, distal interphalangeal flexion), and extension is evaluated with all these three joints in full extension [11].

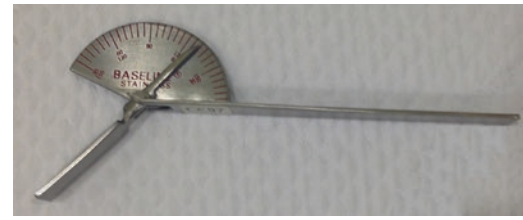

Fig. 2.5 Hand goniometry. (http://www.bpp2.com/physical_therapy_products/1310.html) (Received from the http://www.bpp2.com/physical_therapy_products/1310.html web site on 12.10.2010)

Total motion values allow one number to represent the total motion capacity of a finger. In order to estimate this number, total extension deficits, including hyperextension, are added together, and the sum is subtracted from total flexion capacity. Passive range of motion tells us if the joint is stiff or not, whereas total passive motion indicates as a functional unit finger lacks motion. Another technique that evaluates lack of overall finger flexion is measuring the distance between finger pulp and distal palmar crease while the hand is in fisted position. This is an easier way to evaluate finger flexion deficit and more comprehensible in the clinic [11] (Fig. 2.6).

Range of Motion of the Wrist

Measuring rotational movements of radioulnar joint is difficult because of long axis of the movement and lack of anatomic lever arms. In order to make the correct measurement, patient may be sitting or standing, but the elbow must be flexed 90 ° with the arm close to the side of the body. Forearm should be in mid-position defined as "0°" [11].

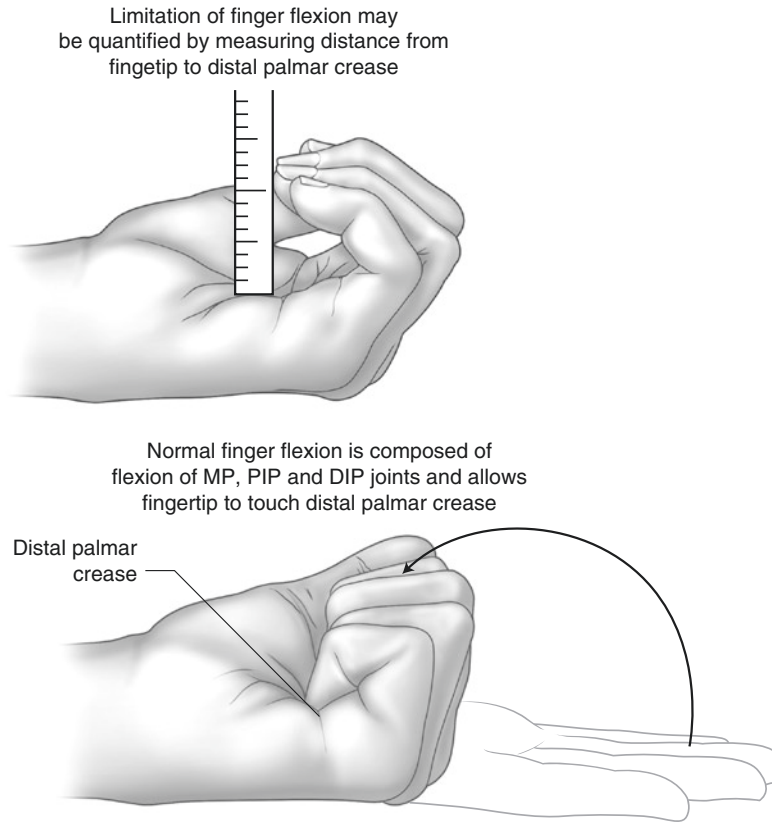

Fig. 2.6 Overall finger flexion measurement. To evaluate overall finger flexion, the distance between finger pulp and distal palmar crease is measured with the hand in fisted position. (http://www.netterimages.com/image/8323.htm) (Received from the http://www.netterimages.com/image/8323.htm web site on 12.10.2010)

Supination For supination, patient rotates the forearm to its maximum palm-up position. Stationary arm of goniometry is placed along the humeral shaft and movable arm across the volar aspect of the wrist at the level of ulnar styloid. Normal range of motion of supination is 0 °–80 °/90 ° [11].

Pronation Starting position for pronation is the same as for supination, but this time patient rotates the forearm into maximum palm-down position. Goniometry is placed similarly as for the supination measurement. The only difference is the change of position of the hand. Normal range of pronation of the wrist is 0 °–80 °/90 ° [11] (Fig. 2.7).

Flexion For assessing flexion, range of motion of the wrist goniometry can be placed laterally or dorsally. For lateral placement, goniometry is placed along the radial border of the forearm and the second metacarpal bone. Elbow must be in flexed position, and forearm and wrist must be in neutral position. When the wrist is flexed, the stationary arm of goniometry is placed along the radius and the movable arm is placed along the second metacarpal bone. Axis of goniometry is placed approximately at the level of radius. Wrist flexion with the goniometry placed dorsally requires elbow flexion, forearm pronation, and wrist in neutral position. The stationary arm is placed along the forearm and the movable arm along the third metacarpal. Normal range of flexion of wrist is 0 °–80 ° [11].

Extension Starting position for wrist extension measurement is the same as for wrist flexion. After proper positioning, wrist is extended maximally, fingers can be allowed to flex passively. The stationary arm of goniometry is placed along the long axis of forearm, and the movable arm is placed along the long axis of third metacarpal on the volar surface. Normal range of motion for extension of wrist is 0 °–70 ° [11] (Fig. 2.8).

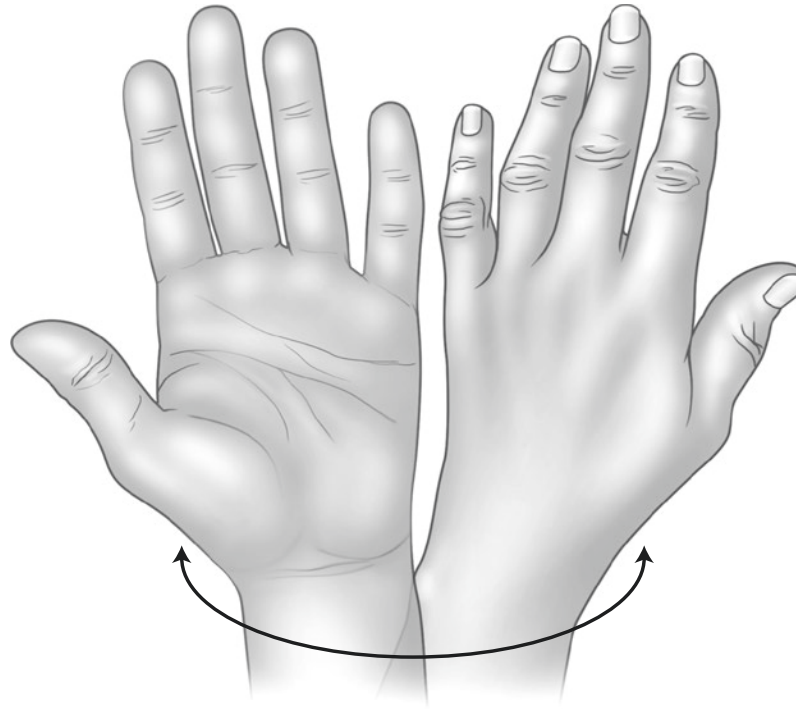

Fig. 2.7 Pronation and supination of the wrist. Normal range of pronation and supination of the wrist is 0 °–80 °/90 °. (http://www.fotosearch.com/LIF116/rwristdv/) (Received from the http://www.fotosearch.com/LIF116/rwristdv/ web site on 12.10.2010)

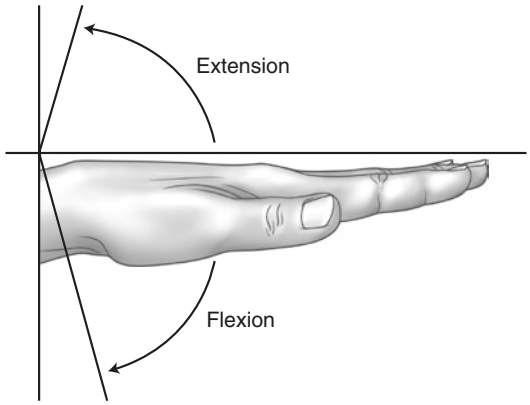

Fig. 2.8 Flexion and extension range of the wrist. Normal range of flexion wrist is 0–80. And normal range of extension of the wrist is 0–70. (http://www.netterimages.com/image/8323.htm) (Received from the http://www.netterimages.com/image/8323.htm web site on 12.10.2010)

Radial/Ulnar Deviation Assessment of radial and ulnar deviation of wrist is elicited by wrist in neutral position and forearm in pronation. Goniometry is placed in mid-position dorsally. The movable arm of goniometry is placed along the long axis of third metacarpal bone. Then, wrist is angled toward the thumb and little finger for radial and ulnar deviation, respectively. Normal range of radial deviation is 0 °–20 ° and ulnar deviation is 0 °–30 ° [11] (Fig. 2.9).

Range of Motion of Fingers

In order to assess range of motion of fingers thoroughly, wrist must be in neutral position to allow tendon excursion of long flexors and extensors of fingers. Flexion of one finger is measured by maximally flexing the other three fingers, and extension of one finger is measured by maximally extending the other three fingers actively.

Metacarpophalangeal (MCP) Joint Lateral or dorsal placement of goniometry is possible for assessing MCP joint motion. Usually dorsal placement is preferred because it is easier to apply. In dorsal placement, the stationary arm of goniometry is placed over the dorsum of metacarpal bone (MC) and the movable arm is placed along the long axis of proximal phalanx. In lateral placement, the stationary arm of goniometry is placed on the longitudinal axis of MC and the

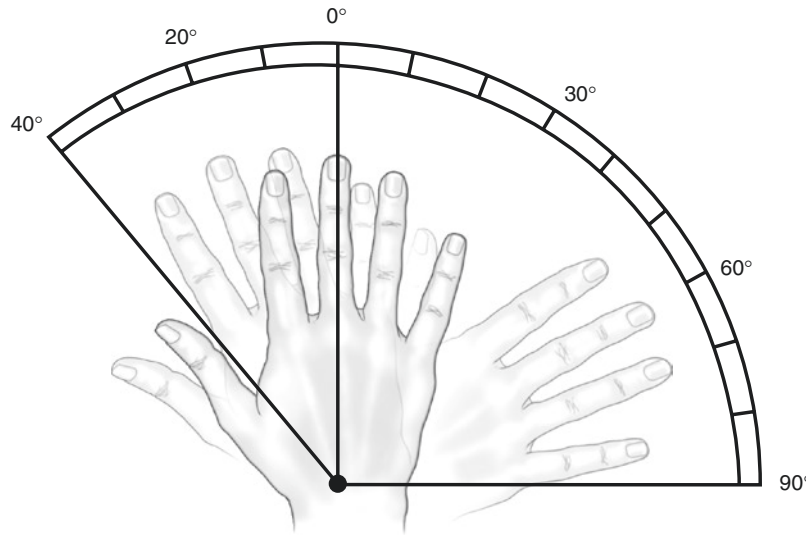

Fig. 2.9 Radial and ulnar deviation of the wrist. Normal range of radial deviation is 0 °–20 ° and ulnar deviation is 0 °–30 °. (http://www.fotosearch.com/LIF116/rom-wrist-radio-ulnar_~RWRISTDV.jpg) (Received from the http://www.fotosearch.com/LIF116/rom-wrist-radio-ulnar_~RWRISTDV.jpg web site on 12.10.2010)

movable arm is placed on the longitudinal axis of the proximal phalanx. For the second and third fingers, goniometry is placed on the radial side of fingers; for the fourth and fifth fingers, goniometry is placed on the ulnar side of fingers. Normal range of motion of MCP is 0 °–90 °, but hyperextension up to 45 ° is possible and considered to be in normal ranges [11].

Flexion and Extension of Proximal and Distal Interphalangeal (DIP) Joints Dorsal and lateral placement of goniometry is possible. Measurement technique of PIP and DIP is quite similar, so they will be discussed together. For lateral placement, the stationary arm is placed along the long axis of proximal phalanx and the movable arm is placed along the long axis of adjacent distal phalanx. The positioning of goniometry is the same for both flexion and extension. Dorsal placement of goniometry is the same as for lateral placement except that it is placed dorsally. Normal range of motion of PIP is 0 °–110 ° and DIP is 0 °–60 °/70 ° [11].

Abduction and Adduction of MCP Joint There is not a standardized technique to measure finger abduction and adduction in exact means. Finger abduction is assessed by measuring the distance between two adjacent abducted fingers. It gives only an estimated not a standard value, and it is only used to follow up the treatment [11].

Thumb Motions

Thumb has the most complex movement pattern along all other digits. This is why its movement patterns are described separately.

Flexion of thumb is the movement of thumb against the base of the fifth finger across the plane of the palm, and it involves the flexion of carpometacarpal (CMC), metacarpal (MC), and interphalangeal (IP) joints. Extension of thumb is the movement of thumb away from the second finger across the plane of the palm. Flexion and extension of thumb can be measured by placing the stationary arm of goniometry along the long axis of radius and movable arm along the long axis of first MC. Flexion of CMC joint is 15 °. Extension of CMC joint is measured by placing the stationary arm of goniometry on the second MC and the movable arm on the first MC. MCP and IP joint flexion and extension assessment technique is the same as for the other fingers [11].

Abduction of thumb is the movement of thumb perpendicular to palm and only involves CMC joint motion and so as adduction. Abduction of the thumb is measured by placing the stationary arm of goniometry on the second MC and the movable arm on the first MC. However, according to de Kraker et al. [12], pollexograph-thumb, pollexograph-metacarpal, and the intermetacarpal distance measurements are most reliable

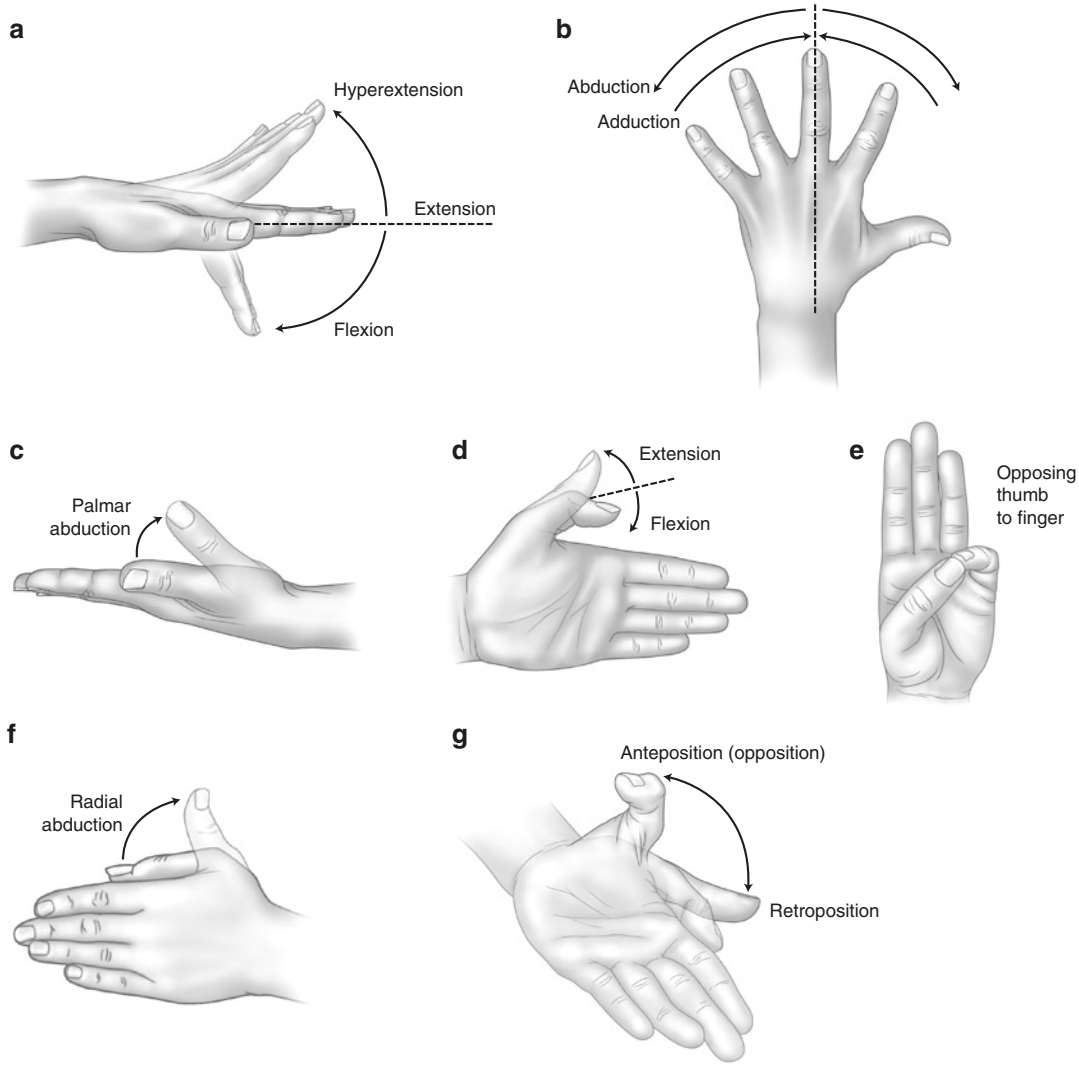

Fig. 2.10 (***a***) and (***b***) MCP joint motions are illustrated. (***c***–***g***) Thumb motions are illustrated. (http://www.ncbi.nlm.nih.gov/bookshelf/br.fcgi?book=physmedrehab&part=A4492) (Received from the http://www.ncbi.nlm.nih.gov/bookshelf/br.fcgi?book=physmedrehab&part=A4492 web site on 12.10.2010)

measurement methods for palmar abduction of the thumb in adults, and these measurements are also found to be reliable in children [13]. In adduction, thumb lies adjacent to the long axis of radius and beside the second MC.

Opposition of thumb involves multiple thumb movements which are flexion, rotation, and abduction. In order to elicit exact opposition, thumb should move to abduction first; otherwise, it would be just flexion. Measurement is done by measuring the distance between the tip of fifth finger and the tip of thumb in opposed position [11] (Fig. 2.10).

Neurological Examination

Muscle Strength Evaluation

Motor function evaluation of the hand is important and necessary especially in muscle/tendon injury and peripheral or central nerve lesions. In

Table 2.1 Medical Research Council (MRC) scale for muscle strength

The patient's effort is graded on a scale of 0–5:
Grade 5: Muscle contracts normally against full resistance
Grade 4: Muscle strength is reduced, but muscle contraction can still move joint against resistance
Grade 3: Muscle strength is further reduced such that the joint can be moved only against gravity with the examiner's resistance completely removed. As an example, the elbow can be moved from full extension to full flexion starting with the arm hanging down at the side
Grade 2: Muscle can move only if the resistance of gravity is removed. As an example, the elbow can be fully flexed only if the arm is maintained in a horizontal plane
Grade 1: Only a trace or flicker of movement is seen or felt in the muscle or fasciculations are observed in the muscle
Grade 0: No movement is observed

the order to make a thorough motor examination of muscle or muscle group, compensatory movements which can compromise the functions of the muscles being examined should be avoided. For example, failure of dorsal interossei muscle function can be masked by function of finger extensors if the test is done with MCP joints in hyperextension. Muscle strength is evaluated according to muscle strength scale of Medical Research Council [14] (Table 2.1).

Wrist Extension Wrist extensors consist of extensor carpi radialis longus (radial nerve, C6-C7), extensor carpi radialis brevis, and extensor carpi ulnaris (radial nerve, C7). These are the primary extensors of the wrist. However, extensor digitorum superficialis, extensor digiti minimi, and extensor indicis proprius also contribute to wrist extension. In order to rule out the contribution of secondary extensors of the wrist, the forearm is stabilized with the other hand and patient is instructed to make fist. Then force is applied and the patient is instructed to extend the wrist against resistance.

Wrist Flexion Primary flexors of the wrist are flexor carpi radialis (median nerve, C6-C8) and flexor carpi ulnaris (ulnar nerve, C8-T1). Flexor carpi ulnaris is the strongest wrist flexor. Flexor pollicis longus, palmaris longus, and deep and superficial finger flexors also contribute to wrist flexion as secondary flexors. In order to rule out the effect of secondary flexors, hand is clenched in fisted position again. After stabilizing the forearm, patient is instructed to flex the wrist against resistance.

Ulnar Deviation of the Wrist Ulnar deviation of the wrist is accomplished by flexor carpi ulnaris (ulnar nerve, C8-T1). In order to evaluate ulnar deviation of the wrist, again forearm is stabilized, and patient is instructed to move his wrist to ulnar deviation against resistance.

Radial Deviation of the Wrist Flexor carpi radialis (median nerve, C6-C8) is the primary muscle for radial deviation. Radial deviation examination technique is similar with that of ulnar deviation except that the wrist is moved toward the radius.

Finger Extension Extensors of fingers are extensor digitorum communis (radial nerve, C7-C8), extensor indicis proprius (radial nerve, C7-C8), and extensor digiti minimi (radial nerve, C7). In order to evaluate the function of primary finger extensors in isolation, wrist and MCP joint should be in neutral position, and proximal and distal interphalangeal joints should be in flexed position. If PIP and DIP joints are kept in extension, intrinsic muscles of hand also contribute to finger extension. Extension of PIP and DIP joints can be tested by a flicking movement of fingers.

Finger Flexion Finger flexors are flexor digitorum superficialis (median nerve, C7-C8), flexor digitorum profundus (ulnar part of ulnar nerve, C8-T1; radial part of median nerve, C7-C8), and lumbricalis. Flexor digitorum superficialis muscle primarily flexes the PIP joint, flexor digitorum profundus primarily flexes the DIP joint, and lumbricalis primarily flexes the MCP joint. Total flexor strength of fingers is tested by interlocking the fingers with the fingers of patient in flexed position. Strength of each finger flexors should be tested separately in order to make the differential diagnosis. Tendon of the flexor digitorum superficialis inserts to the base of the middle phalanx.

This is why in order to test the strength and function of this muscle in isolation, all of the fingers of the patient are held in extension except the finger to be tested. Then the patient is instructed to flex the PIP joint against resistance, while MCP is in neutral position and DIP is in extension. Tendon of the flexor digitorum profundus inserts to the base of the distal phalanx. In order to test its function, the patient is instructed to flex the DIP joint against resistance after stabilizing the PIP joint of the same finger in extension.

Finger Abduction Primary abductors of fingers are dorsal interossei muscles (ulnar nerve, C8-T1) and abductor digiti minimi muscle (ulnar nerve, C8-T1). Extensor digitorum communis also contribute to abduction when fingers are in extension. Strength of abduction of the fingers can be evaluated in two different ways. First, after patient is instructed to abduct all the fingers simultaneously, force is applied to second and fifth fingers and the patient is asked to resist the force applied. Second, the third finger can be tested in isolation by applying force against abduction (Fig. 2.11).

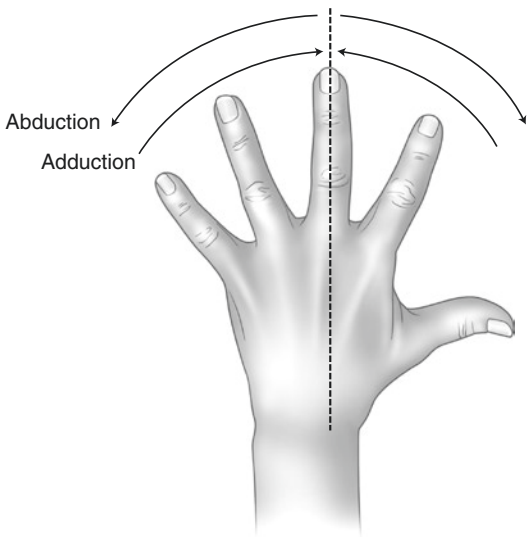

Fig. 2.11 Finger abduction strength can be tested by isolating the third finger and applying force against abduction. (http://www.ncbi.nlm.nih.gov/bookshelf/br.fcgi?book=physmedrehab&part=A4492) (Received from the http://www.ncbi.nlm.nih.gov/bookshelf/br.fcgi?book=physmedrehab&part=A4492 web site on 12.10.2010)

Finger Adduction Primary finger adductors are palmar interossei muscles (ulnar nerve C8-T1). Finger flexors contribute to adduction when fingers are flexed. In order to evaluate the function of finger adductors, you can try to separate extended and adducted fingers of patient, testing two adjacent fingers simultaneously or you can apply the "paper test." The patient is instructed to hold a paper tightly between the extended and adducted fingers and then try to pull the paper. If there is weakness of interossei muscles, patient will not be able to resist or even not be able to hold the paper between fingers. Always check the strength of the other hand for comparison.

Motor Functions of the Thumb

Thumb Extension Extensors of thumb are extensor pollicis longus (radial nerve, C7) and extensor pollicis brevis (radial nerve, C7). Extensor pollicis brevis inserts to the base of the proximal phalanx and extends the proximal phalanx; extensor pollicis longus inserts to the base of the distal phalanx and its contraction extends the distal phalanx. Thumb extension is the movement of thumb away from second MC across the plane of the palm. Extensor muscle strength of thumb is evaluated by extending the thumb of the patient against resistance.

Thumb Flexion Flexors of thumb are flexor pollicis longus (median nerve, C8-T1) and flexor pollicis brevis (deep part of ulnar nerve, C8; superficial part of median nerve, C6-C7). Flexor pollicis longus inserts to the base the distal phalanx and flexes the distal phalanx; flexor pollicis brevis inserts to the base of the proximal phalanx and flexes the proximal phalanx. Flexion of thumb is the movement of thumb toward the fifth finger in the plane of the palm. Flexion function is evaluated by applying force to the thumb in flexed position.

Thumb Abduction Abduction of thumb is achieved by abductor pollicis longus (radial nerve, C7) and abductor pollicis brevis (median nerve, C6-C7). Abduction of thumb is the movement of

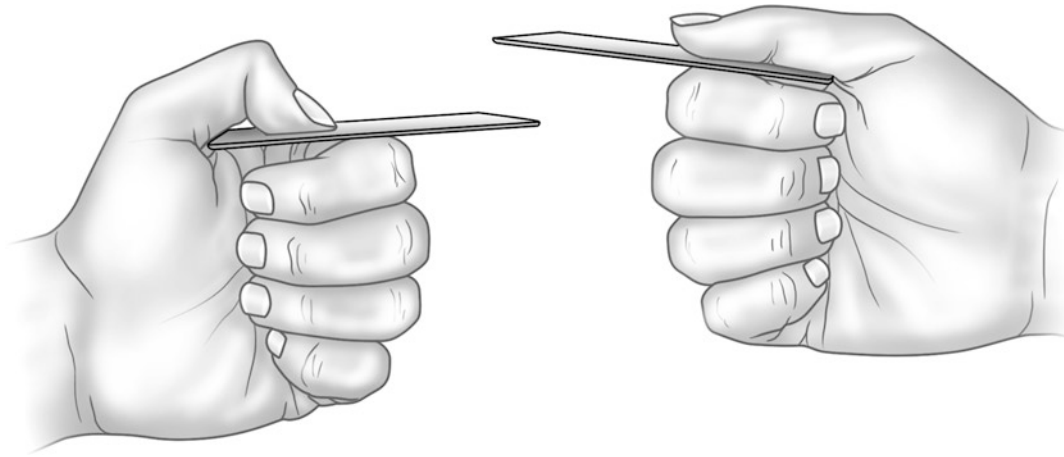

Fig. 2.12 Froment's sign. If there is weakness in adductor pollicis, flexors of the thumb will aid holding the paper, and flexion of distal phalanx will be observed. (http://www.netterimages.com/image/8323.htm) (Received from the http://www.netterimages.com/image/8323.htm web site on 12.10.2010)

thumb perpendicular to the palm and evaluated by abducting the patient's thumb against resistance. If there is a weakness of abductor muscles, especially of abductor pollicis brevis, the patient will not be able to bring the web space between the first and second fingers in contact with when holding a bottle, and there will be a gap between the web space and the bottle. This sign is called as "Lüthy bottle sign" [3].

Thumb Adduction There is a single adductor of thumb which is adductor pollicis (ulnar nerve, C8). Adductor pollicis consists of two heads which are oblique and transverse heads. In order to evaluate adduction of the thumb, patient is instructed to hold a paper between the ulnar side of the thumb and radial side of the second finger in extended position against resistance. If there is weakness in adductor pollicis, flexors of the thumb will aid holding the paper and flexion of distal phalanx will be observed. This sign is called as ***Froment's sign*** (Fig. 2.12).

Opposition of the Thumb and Little Finger Opposition is the function of both thumb (opponens pollicis: median nerve, C6-C7) and little finger (opponens digiti minimi: ulnar nerve, C8). Opposition involves abduction, flexion, and rotation of the thumb [15]. Force is applied to each of the opposing fingers using both hands in order to evaluate the function. If there is weakness of opponens pollicis, thumb will be easily separated from the pulp of the little finger.

Pinch Function of the Thumb Pulp to pulp pinch is achieved by the contraction of flexor pollicis longus and second flexor digitorum profundus. If these muscles have normal function, patient will be able to form an "O" shape with the thumb and second finger. If there is weakness of these muscles (anterior interosseous nerve syndrome), distal phalanx of the thumb and second finger will not be able to flex and remain in extension and patient will not be able form an "O" (Fig. 2.13).

Pinch and Grip Strength

There are actually three different types of pinch:

- Lateral or key pinch
- Tip-to-tip pinch
- Three-fingered pinch or three-point chuck

Lateral pinch is the strongest type of pinch followed by three-point pinch. Tip-to-tip pinch is used for more sophisticated processes requiring fine coordination. Pinch function of the hand is

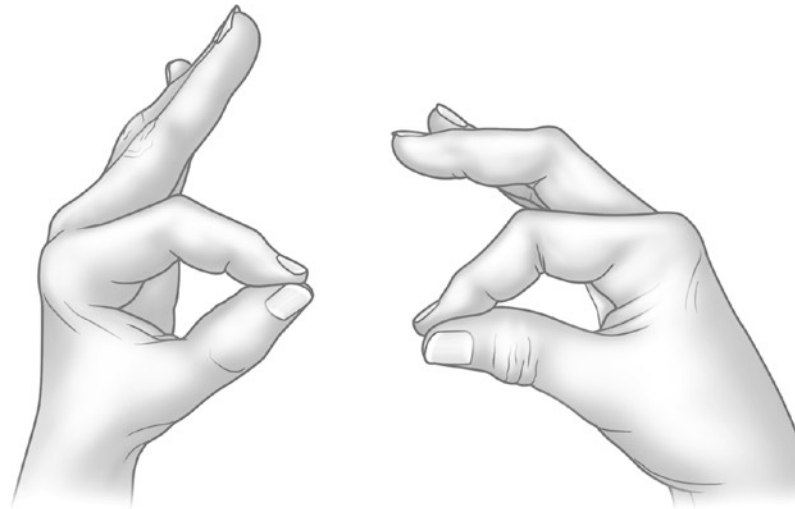

Fig. 2.13 Pinch function of the thumb. If there is weakness of flexor policis longus or second flexor digitorum profundus, patient will not be able to form an "O." (http://img.medscape.com/fullsize/migrated/408/540/mos5854.01.fig21.jpg) (Received from the http://img.medscape.com/fullsize/migrated/408/540/mos5854.01.fig21.jpg web site on 15.10.2010)

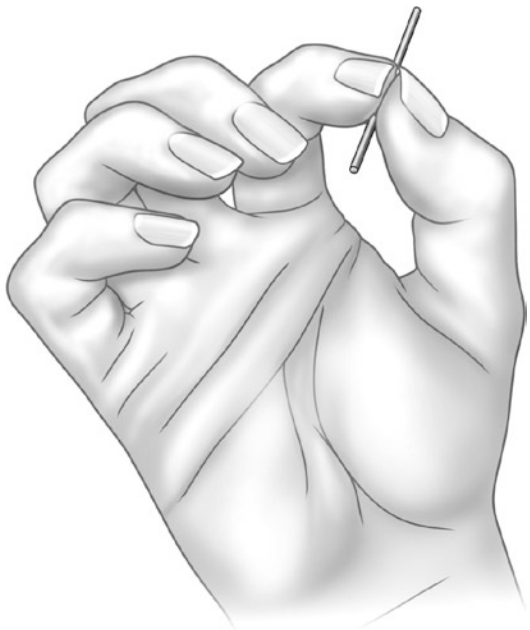

Fig. 2.14 Lateral pinch, tip-to-tip pinch, and three-point pinch, respectively. (http://www.simwork.com/products/sapphire/images/LateralPinch200x150.jpg; http://web.student.tuwien.ac.at/~e0227312/images_grasps/i_24_1; http://www.apartmenttherapy.com/uimages/kitchen/2009-07-16-ThreeFingerPinch.jpg) (Received from the http://www.simwork.com/products/sapphire/images/LateralPinch200x150.jpg, http://web.student.tuwien.ac.at/~e0227312/images_grasps/i_24_1, http://www.apartmenttherapy.com/uimages/kitchen/2009-07-16-ThreeFingerPinch.jpg web sites on 15.10.2010)

tested with a pinchmeter. Average of three trials is recorded (Figs. 2.14 and 2.15).

There are several devices to measure gross grip strength. Jamar dynamometer developed by Bechtol [16] has been showed to be a reliable test providing that the calibration is maintained [17, 18]. The dynamometer has five adjustable spacings, which are 1, $1^{1/2}$, 2, $2^{1/2}$, and 3 inches. Measurement is taken from all of these spacings after patient is instructed to grasp the dynamometer with maximum strength. Three measurements are taken, and the mean value of these three trials is recorded. Usual grip strength makes a bell-shaped curve, being the middle spacings the stronger and weakest at each ends. Both right and left hands are evaluated. There is usually 5–10% difference between dominant and non-dominant hand, usually the dominant hand being the stronger (Fig. 2.16).

Sensory Function Evaluation

Sensory innervation of upper extremity follows spinal nerve roots, plexus, and peripheral nerves. If the lesion is not central in origin, sensory deficits also follow the innervation pattern of the peripheral nerves. Evaluation of sensory function of upper extremity is usually limited to light touch and pain sensation. Evaluation of the other

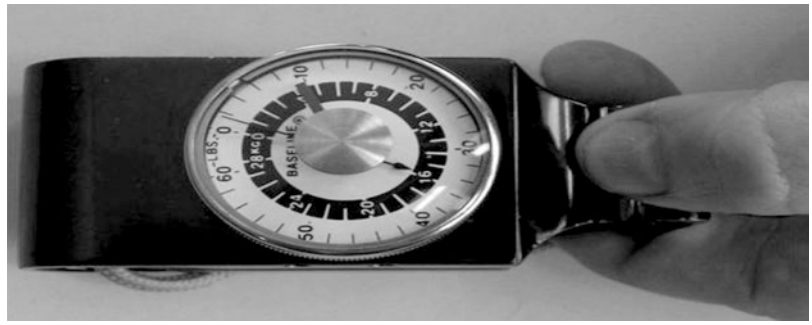

Fig. 2.15 Pinchmeter. (http://www.griprepair.com/images/baseline_pinchmeter.jpg) (Received from the http://www.griprepair.com/images/baseline_pinchmeter.jpg web site on 15.10.2010)

Fig. 2.16 Jamar dynamometer. (http://www.bpp2.com/Merchant2/graphics/00000001/2006CAT/2006CATP50/JAMAR_HAND_DYNA_L.jpg) (Received from the http://www.bpp2.com/Merchant2/graphics/00000001/2006CAT/2006CATP50/JAMAR_HAND_DYNA_L.jpg web site on 15.10.2010)

sensory functions is usually unnecessary and useless. There are several instruments available to test two-point discrimination, but sensitivity and reliability of these instruments are low when applied in the hand. Light touch sensation is examined with a cotton swab or with the tip of the finger. Variations of sensorial nerve supply on the overlapping dermatomal areas should also be taken into consideration.

Sensory innervation of the hand is mainly supplied by three peripheral nerves which are radial nerve, median nerve, and ulnar nerve (Fig. 2.17).

Radial nerve innervates only the dorsal part of the hand and fingers. Its innervation area involves two and a half finger of the dorsum of the hand (thumb, index, and radial half of the middle finger) up to distal phalanges and radial side of the dorsum of the hand.

Ulnar nerve innervates palmar side of one and a half finger (little finger and ulnar half of the ring finger) and dorsal side of two and a half finger (little finger, ring finger, and ulnar half of the middle finger) and adjacent skin area on the hand.

Median nerve innervates palmar side of three and a half finger (thumb, index finger, middle finger, and radial half of the ring finger) and adjacent skin area and dorsal side of the distal phalanges of index and middle finger.

There are several tests available to assess sensibility and dexterity of the hand:

- Semmes–Weinstein filament test
- Moberg's pick-up test [19]

The reliability of all these tests, Seddon' coin test, the moving two-point discrimination test described by Dellon, and Weber's two-point discrimination test, still remains controversial because volitional participation of the patient is required. As a result, these are rather subjective tests than being objective.

Semmes–Weinstein monofilaments are shown to produce consistently repeatable forces from set to set and from examiner to examiner, and it is

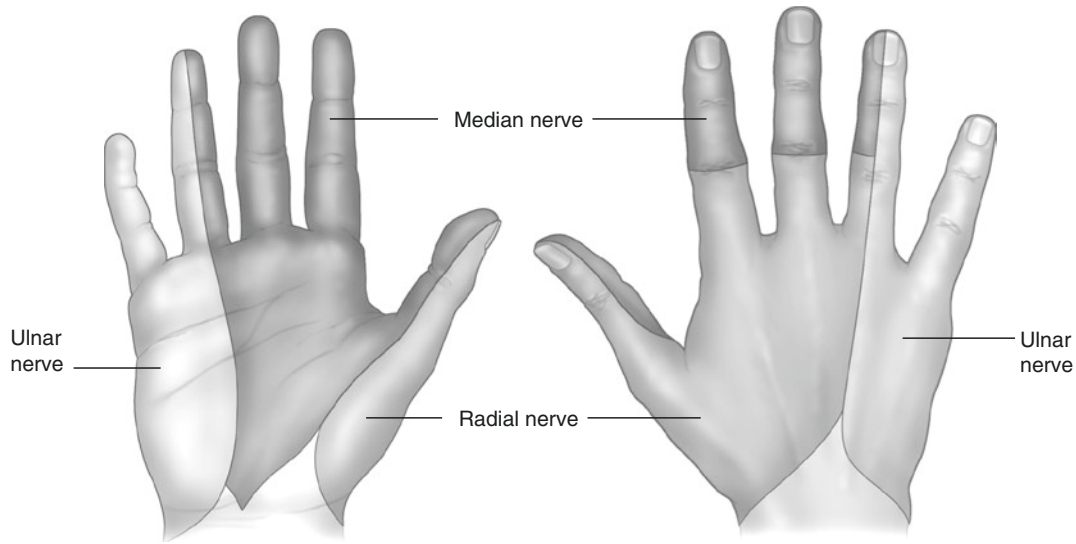

Fig. 2.17 Sensory innervation of the hand. (http://www.aafp.org/afp/2003/0715/afp20030715p265-f1.gif) (Received from the http://www.aafp.org/afp/2003/0715/afp20030715p265-f1.gif web site on 15.10.2010)

possible to control the amount of force applied [15, 20]. Thus, these monofilaments prove the most sensitive and reliable data among all other clinical sensibility assessment instruments [8, 20, 21]. Originally, there are 20 monofilaments, but now there is also a 5-filament mini set available for practical use. Using Semmes–Weinstein monofilaments, the normal touch threshold is approximately 4.86 g/mm^2.

Evaluation of Vascular Supply of the Hand

Ulnar and radial artery are vascular supply of the hand. ***Allen's test*** is a simple test to evaluate vascular supply of the hand, and it is easy to apply. Allen first described this test in 1929, but did not mention a time period that the test will be considered as positive. In time, various time periods are mentioned from 5 to 15 s. Classic Allen's test is applied by compressing the patient's ulnar and radial artery using the thumb, index, and middle finger of each hand. Then, the patient is instructed to open and close his fist in order to drain venous blood of the hand. After repeating it several times, patient is instructed to open his fist, and it will be observed that the hand becomes pale. Then the compression on one of the arteries is removed and the hand is observed if it becomes pink again. The same process is repeated for the other artery. If one of the arterial supply is occluded or somehow disrupted partially or totally, the hand will remain pale or will gain its color slower than expected after removing the compression. Allen's test should be applied to both of the hands in order to make comparison. If the hand that does not become pale, the presence of a variant artery should be considered. In 2007, a new version of Allen's test is described [22]. This test is applied by compressing radial and ulnar arteries with three digits using both hands. Then patient is instructed to clench and unclench the hand 10 times and then to open the palm. After that, ulnar or radial artery is released and flushing is observed. If flushing delays more than 6 s, the test is considered to be positive (Figs. 2.18 and 2.19).

Specific Tests

Carpal Tunnel Syndrome: Tinel's Sign This is one of the tests applied if the patient is suspected to have carpal tunnel syndrome which is

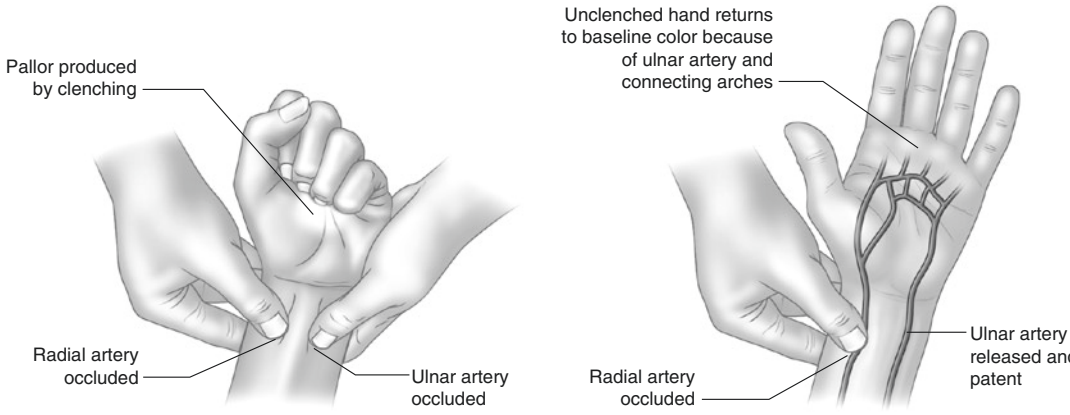

Fig. 2.18 Classical Allen's test. (http://fitsweb.uchc.edu/student/selectives/TimurGraham/Modified_Allen's_Test.html)(Received from the http://fitsweb.uchc.edu/student/selectives/TimurGraham/Modified_Allen's_Test.html web site on 15.10.2010)

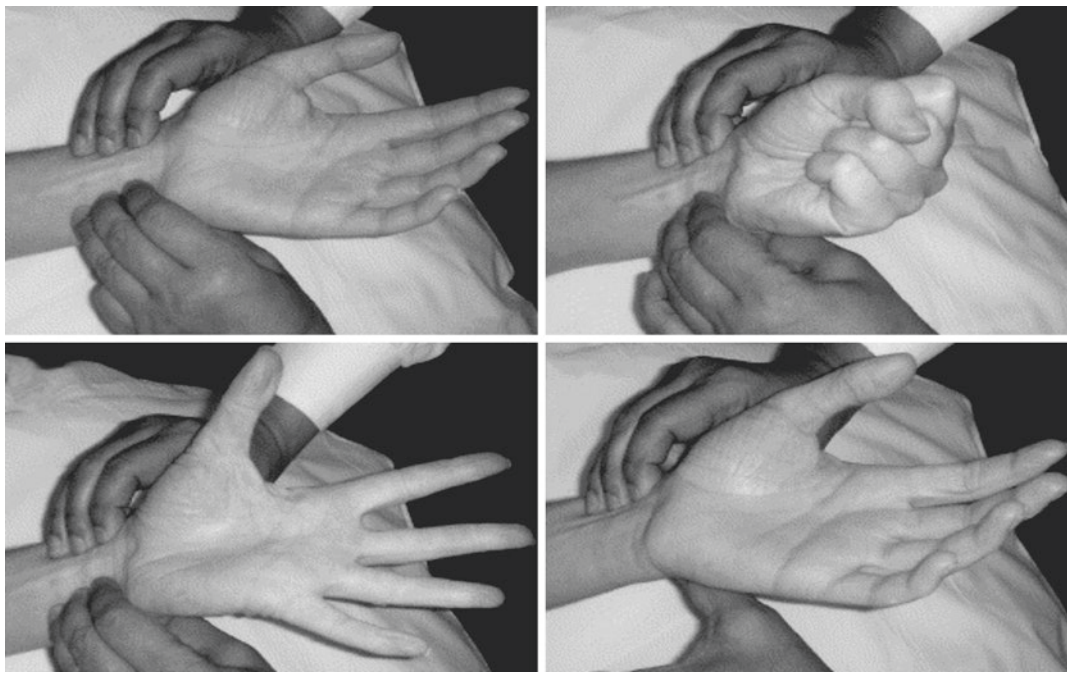

Fig. 2.19 Modified Allen's test. (Asif and Sarkar [22]) (Received from Asif and Sarkar [22] on 15.09.2010)

characterized by compression of median nerve in the carpal tunnel. The test is considered to be positive if the patient feels paresthesia with tapping on the median nerve where it is suspected to be compressed. However, this test can be false negative in the presence of chronic nerve compression or severe reduction in nerve conduction.

Carpal Tunnel Syndrome: Phalen's Test This is another test used to evaluate carpal tunnel

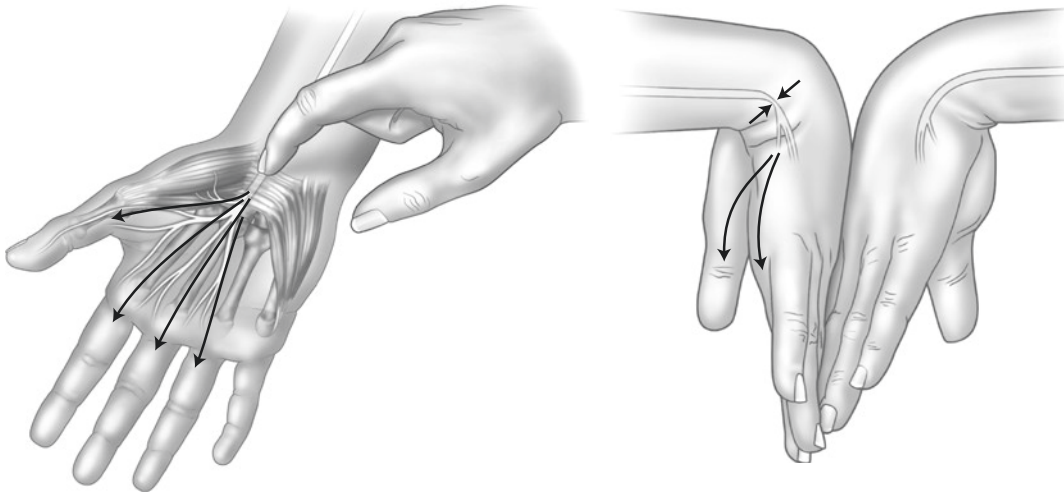

Fig. 2.20 Tests applied in carpal tunnel syndrome. Tinel's test is illustrated on the left, and phalen's test is illustrated on the right. (http://www.healthtopicsbysusan.com/?p=48) (Received from the http://www.healthtopicsbysusan.com/?p=48 web site on 15.10.2010)

syndrome. Here, patient is instructed to maximally flex or extend his wrist and wait for a few minutes in that position. The test is considered to be positive if the patient feels paresthesia after several minutes of sustained position. Both Tinel sign and Phallen's test with the history are 80% diagnostic for carpal tunnel syndrome. Electrodiagnostics are ancillary tools for confirming the diagnosis [2] (Fig. 2.20).

Wartenberg's Syndrome: Tinel Sign Wartenberg's syndrome is the compression of superficial branch of radial nerve in the distal portion of brachioradialis tendon. Test is considered to be positive if the patient feels paresthesia with tapping the nerve in the distal portion of the brachioradialis muscle (Fig. 2.21).

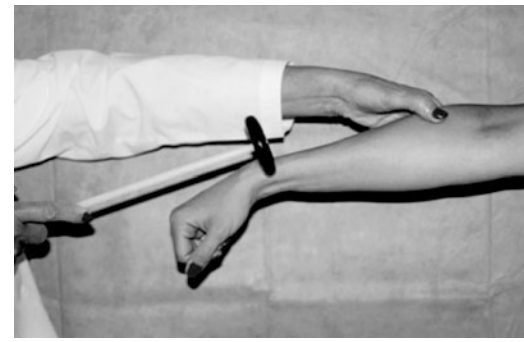

Fig. 2.21 Tinel's test in the Wartenberg's syndrome. (http://img.medscape.com/fullsize/migrated/408/540/mos5854.01.fig6.jpg) (Received from the http://img.medscape.com/fullsize/migrated/408/540/mos5854.01.fig6.jpg web site on 15.10.2010)

Proximal and Distal Ulnar Nerve Compression Syndrome: Tinel Sign Ulnar nerve can be compressed either proximally at the level of medial epicondyle or distally in the Guyon's canal. Tinel test can be applied for both of these locations. Also, scratch collapse test is a sensitive test that localizes Osborne's band in cubital tunnel syndrome [23]. Distal branch of ulnar nerve can be compressed in the Guyon's canal. Because ulnar nerve has only motor fibers in this region, clinical outcome will be only motor paresis without loss of sensation (Fig. 2.22).

Finkelstein Test This test is used to demonstrate DeQuervain's Tendinitis which is the stenosing tenosynovitis of the first dorsal compartment of the hand. Patient is instructed to adduct his thumb toward the little finger. Then, the other fingers are flexed covering the adducted thumb. Next,

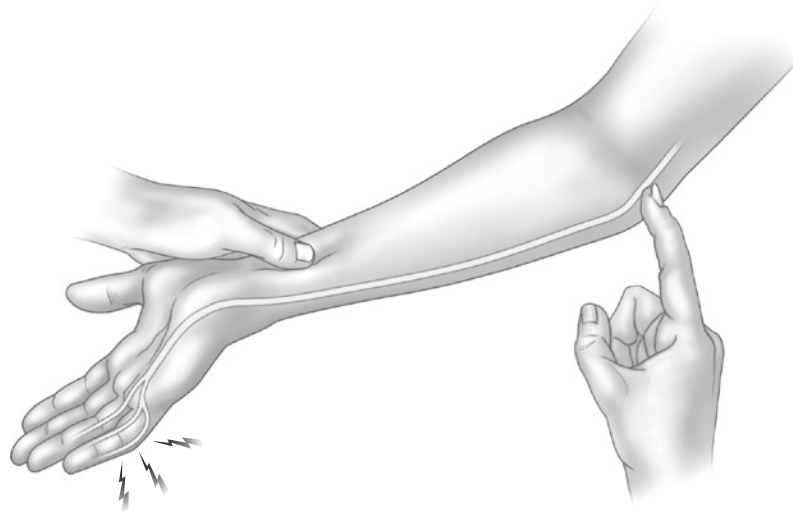

Fig. 2.22 Ulnar nerve compression test: Tinel's test. (http://www.maitrise-orthop.com/corpusmaitri/orthopaedic/mo77_dumontier/index_us.shtml) (Received from the http://www.maitrise-orthop.com/corpusmaitri/orthopaedic/mo77_dumontier/index_us.shtml web site on 15.10.2010)

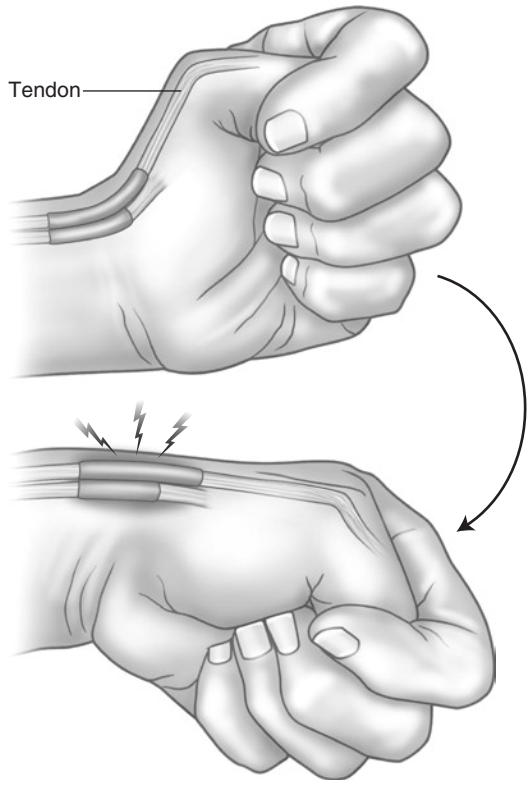

Fig. 2.23 Finkelstein's test applied in the stenosing tenosynovitis of the first dorsal compartment of the hand. (https://www.bcbsri.com/BCBSRIWeb/images/image_popup/ans7_finkelsteintest.jpg) (Received from the https://www.bcbsri.com/BCBSRIWeb/images/image_popup/ans7_finkelsteintest.jpg web site on 15.10.2010)

patient's hand is moved toward ulnar deviation. The test is considered to be positive if the patient feels pain when the wrist is moved to ulnar deviation (Fig. 2.23).

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Assessment of Hand Function

3

Mehmet Tuncay Duruöz

The hand is one of the most fascinating and sophisticated biological instruments which plays a significant role in our lives. We use our hands alone or in combination of a wide variety of ways, touching, grasping, feeling, holding, manipulating, and caressing, and sometimes we use it even for communication. Hands can perform extremely gentle, skillful, and precise activities such as painting a picture, making an embroidery, or playing the violin, and our hands also enable to perform heavy labor, such as carrying heavy objects or digging with a shovel. For centuries, outcome evaluation in medicine was limited to the evaluation of the only physiological consequences of the disease. In the last decades, the societies' growing expectations are mostly to have a life without disability and handicap. Because the hand involves our lives very deeply in daily activities, its functional status has become increasingly important to determine the quality of life [1–3].

The hand function may be defined basically as the capacity to use the hand in everyday activities depending on the anatomical integrity, sensation, coordination, strength, and dexterity. We may consider wrist as a functional part of the hand because they are the complementary structures and most of their functions affect each other. The evaluation of hand function is of critical importance in determining the extent of functional loss in patients with many rheumatic and neurologic diseases and traumatic injuries and in assessing the outcome of some surgical and rehabilitative procedures. Thus, the clinical assessment of hand function remains complex and controversial. The physicians are most interested in reducing pain (impairment), maintaining or improving the ability to perform activities of daily living (disability), and maintaining or improving independence (handicap) [2, 4].

In the last century, an important scientific debate took place on diseases and their consequences, and it generated various conceptual models. The aim of these models was the description of the relationship between pathology and functional consequences. Two models are commonly accepted worldwide which are the International Classification of Impairments, Disabilities, and Handicaps (ICIDH) and International Classification of Functioning, Disability, and Health (ICF).

The ICIDH was the first internationally shared conceptual formulation, and it was the first internationally known system to classify the consequences of diseases [5]. The intention of this model was analyzing, describing, and classifying three different consequences of diseases: impairment, disability, and handicap. The impairment is the loss or abnormality of psychological, physiological, or anatomical structure or function; the disability is the restriction, or lack of ability to

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perform an activity in the manner or within the range considered normal for a human being; and the handicap is a disadvantage for a given individual, resulting from an impairment or a disability. These three different levels in the consequences of pathology are related to different levels of experience and individual awareness.

Impairment in arthritis can be reflected by pain, swelling, and restriction in the range of movement of joints, whereas disability is expressed by difficulty or inability in the performance of daily living activities [6].

The ICF offers a useful model of functioning and disability [7], and it represents a revision of the ICIDH. The ICF model provides a multiperspective approach to the classification of functioning and disability as an interactive and evolutionary process. A person's functioning and disability are conceived as a dynamic interaction between health conditions (e.g., disease, disorders, injuries, traumas) and contextual factors (environmental and personal). The relationship between the three domains is influenced by contextual factors representing the complete background of an individual's life, including environmental and personal factors.

The ICF model of functioning and disability underscores the importance of interactions between all components of health (physiological, psychological, anatomical, activity or participation-related, personal, and environmental). Understanding the influence of health components in totality, rather than in isolation, is particularly important when evaluating function. The Duruöz Hand Index (DHI) contains 11 ICF categories as below [8].

- **d170** Writing (2 questions)
- **d4300** Lifting (1 question)
- **d4308** Lifting and carrying, other specified (2 questions)
- **d4400** Picking up (1 question)
- **d4402** Manipulating (2 questions)
- **d4453** Turning or twisting the hands or arms (4 questions)
- **d4458** Hand and arm use, other specified (1 question)
- **d50201** Caring for teeth (1 question)
- **d550** Eating (2 questions)
- **d560** Drinking (1 question)
- **d6300** Preparing simple meals (1 question)

Functional Components of the Hand

Hand has some main motor functions, and it uses the harmonization of these functions to realize daily activities. Many factors support these motor functions such as sensory processes for coordination and visual properties.The decreased visual acuity, accommodation, eye-hand coordination, and depth perception can affect hand function [9, 10]. Because the hand is the extension of the upper extremity, their disorders affect the hand function directly. Age, gender, and the motivation of the individual to complete specific tasks also influence the hand function level.

The full hand grip and pinch are the main functions of the hand. The hand has already nonprehension and bilateral prehension functions. Although they are basic functions, they could not be entirely performed if the fingers were amputated. Patients with various hand problems, such as wrist limitations, ruptured extensor tendons, and MCP subluxation, frequently report difficulty or inability in performing nonprehension tasks.

Grip (Prehension)

The grip function of the hand is of great importance in professional and daily life activities. There are four main items to classify and assess the grip. Daily activities are generally the combinations of these different types of grips.

1. *Pinch Grip.* It is the holding of objects between the thumb and fingers of a single hand. The tip pinch between thumb and fingertip is used for fine manipulation (Fig. 3.1). Tri-digit pinch (Chuck pinch) increases the stability by utilizing two fingertips instead of one (Figs. 3.2 and 3.3). Lateral (key) pinch is stronger because fingers resist the pressure of the thumb. (Fig. 3.4).

2. *Full Hand Grip (Grasp).* The holding of an object with palm forms of four fingers and the thumb. This includes all of the typical grasps: palmar, power, cylinder, and spheric (Figs. 3.5, 3.6, 3.7, 3.8, and 3.9).
3. *Nonprehenson.* Use of the hand as a base for the application of upper extremity strength such as hook grip and use of the extended hand to push objects (Fig. 3.10). Use of the fingers to apply pressure such as in patting soil around a plant (Fig. 3.11). Activities for

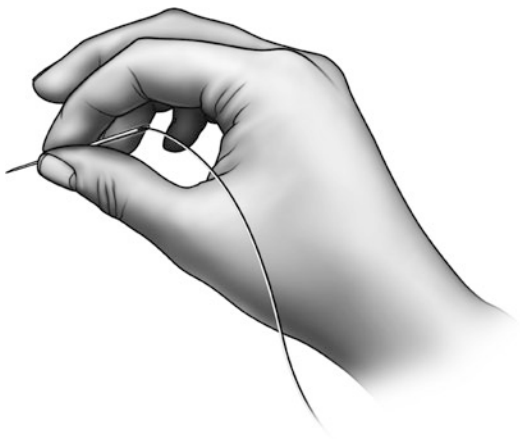

Fig. 3.1 Tip pinch. Holding object (needle) between the thumb and second finger's tips

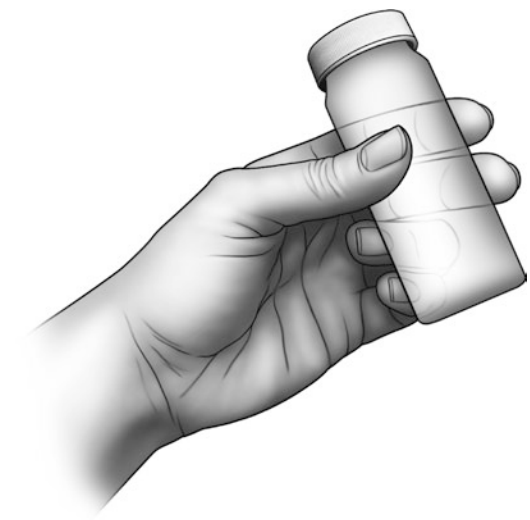

Fig. 3.2 Chuck pinch. Holding object between the thumb and second and third fingers' tips

Fig. 3.3 Chuck pinch. Holding pencil with first three fingers tips of the dominant hand. Precision and dexterity are needed

Fig. 3.4 Lateral pinch. Holding key between the lateral edge of the second finger and tip of the thumb

Fig. 3.5 Full hand grip. The cylindrical grip of thick stick needs gross grasp with power

Fig. 3.6 Full hand grip. Holding glass with thumb and the other four fingers distal part

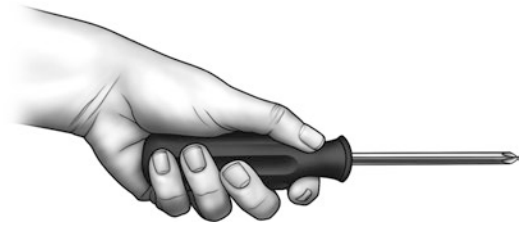

Fig. 3.7 Full hand grip. The oblique grip of a screwdriver. It is a variant of cylindrical grip and grip across the rectangular surface

precision sorting motions such as sorting coins, dialing a telephone with using fingertips (Fig. 3.12). Other nonprehension activities are using the heel of the hand or the ulnar edge of the palm to apply pressure.

4. *Bilateral Prehension.* This is the holding of objects between the palmar surfaces of both hands as in unilateral nonprehension (Fig. 3.13).

A loss in grip strength is associated with a number of different neurological and musculoskeletal conditions, and so, an assessment of hand grip strength is generally included in hand evaluations as a test of gross motor power [10–12]. Several large-scale studies have provided

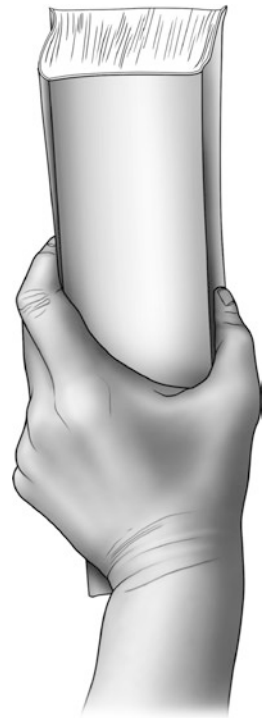

Fig. 3.8 Full hand grip. The grip of the book with all palmar surfaces of fingers and the thumb at plain finger position

Fig. 3.9 Full hand grip. A spherical grip has the thumb and all fingers abducted around an object,(small ball), and the fingers are more spread apart than in a cylindrical grip

comprehensive normative data on the grip strength of healthy children [13] and adults [14]. The peak forces generated with the three-digits and lateral pinch grips are about 40% greater than that produced with the tip pinch [14].

Many factors may affect the force of grip strength. Some studies have indicated the

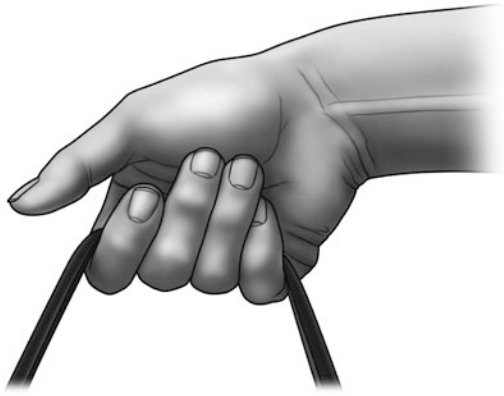

Fig. 3.10 Hook prehension is a kind of nonprehensive function of the hand. The hand is flat with curled fingers that support the load and, thumb as a stabilizer

Fig. 3.11 Nonprehensive function: patting soil around the plant with palmar surface of first four fingers at a straight position

Fig. 3.12 Nonprehensive function: dialing telephone with the tip of the finger of a single hand

importance of considering the sex, age, and hand preference of the individual when interpreting

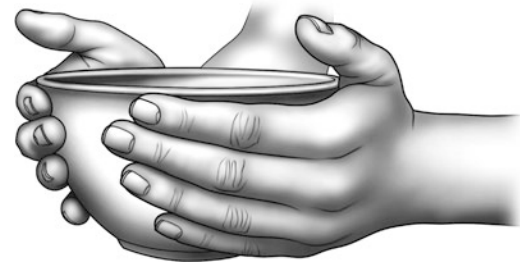

Fig. 3.13 Bimanual prehension is the holding objects between the palmar surfaces of both hands. It is mainly used to hold objects too heavy or too large to hold with a single hand

grip strength data in clinical populations. They have also shown that although height and weight are positively correlated with grip strength [15, 16], the influence of these variables is considerably smaller than that of either sex or age. The average grip strength of women is approximately 60% that of men, and for both sexes, grip strength reaches a maximum during the fourth decade of life and declined thereafter with increasing age [14, 17, 18]. Cold has been shown to reduce the force of muscle contraction and reduce the grip function of the hand [19].

The 10% rule states that the dominant hand possesses a 10% greater grip strength than the nondominant hand for right-handed persons only; for left-handed persons, grip strength should be considered equivalent in both hands [20]. Differences between the hands in strength must, therefore, be interpreted with caution if disability or loss of function is defined in terms of such a discrepancy.

Although grip strength is one aspect of hand function which can be objectively and accurately measured, it may bear little relationship to the patient's actual hand function. Clinical experience suggests that some patients with deformed hands and poor grip strength (or high levels of impairment) are able to perform a wide range of hand functions (have low levels of disability). Although the link between grip strength and subjective measures of hand function based on assessment questionnaires has been established, the relationship between objective measures of disability and impairment is not clear [2, 21].

Grip strength assessment is frequently used in clinical trials and has been shown to be a sensitive indicator of disease activity. Grip strength is a composite measure and may be influenced by dysfunction in muscles, tendons, and any of the small joints of the hand and wrist [22].

McPhee pointed out that most description of hand grip functions categorized static patterns and they have limited value because they fail to consider the dynamic aspects of hand use [4].

The daily activities of the hand may be classified into three main functional groups according to the factor analysis of a study of Duruöz et al. [2]. The first group activities are requiring force and rotation (e.g., unscrewing the jar lid). The second group activities are requiring dexterity and precision (e.g., peeling fruits). The third factor was dynamic activities, primarily based on pinching and performed with the first two or three fingers of the dominant hand (e.g., writing with a pencil).

Dexterity

Dexterity must be evaluated because of its bearing on upper limb performance and on individual functional independence [23] Dexterity has been defined by Poirier [24] as " a manual skill requiring rapid coordination of fine and gross movements based on a certain number of capacities developed through learning, training, and experience." Speed and precision are the criteria used to measure this skill, and the tests require high-level hand-eye coordination as well as fine motor control of the hand. There are two types of main dexterity: finger dexterity and manual dexterity.

Finger dexterity is defined as the ability to make rapid, skillful, controlled, manipulative movements of small objects in which the fingers are primarily involved. The Purdue Pegboard Test [25] assesses especially finger dexterity and bimanual coordination (Fig. 3.14).

Manual dexterity is defined as the ability to make skillful, controlled, arm-hand manipulations of larger objects under speed conditions. The Box and Block Test [14] measures are an example for unilateral gross manual dexterity.

Fig. 3.14 Assessment of dexterity and coordination of hands with Purdue Pegboard

There are several accepted methods for testing dexterity. The Purdue pegboard is one of the most widely used tests in which subjects must grasp and lift small pegs and insert them into small holes in a board (also called fingerprint dexterity) [25]. The Grooved pegboard is one of the practical and valid tests where the pegs are key-shaped and finer manipulation is required to match the peg with its hole [26].

The Nine-Hole Pegboard Test measures the time that is required for a subject to place and removes nine pegs in a hole on the pegboard. Each hand is tested separately [14, 27].

The Box and Block Test has the two-compartment box and 150 cubes. The subject grasped one block with a dominant hand first and transported the cube into the opposite compartment. The subject is stopped after 1 min and the expert counts the transported cubes. The test is then repeated with the nondominant hand [14].

Assessment Methods

A functional hand assessment determines functional ability, that is, how a patient uses his or her hand in spite of limitation and functional disability. Accurate assessment of hand function is essential for evaluating treatment and the progress of the disease and also for establishing strategies to maximize functional potential and promote well-being. The clinical assessment of

"function" has generally focused on the range of motion (ROM), grip or pinch strength (impairment), and subjective assessment of activities of daily living (disability). The dexterity and coordination performance of the hand may be evaluated either with some pegboards or with some daily activities which need dexterity [21]. Although we may assess handicap with a valid scale and Visual Analog Scale (VAS-handicap) [2], we do not assess it in clinical practice routinely.

The ROM and strength assessment provide some information, but they do not demonstrate how the patient can use muscular substitutions and adaptive methods to perform a functional task (Fig. 3.15). In fact, there is often very little direct correlation between hand ROM and the patient's ability to perform functional activities.

Fig. 3.15 Assessment of range of motion of finger joints with hand goniometer

Impairment, disability, and handicap are complementary aspects of function, and we have to assess all three domains separately to have complete information about hand function in patients with hand involvement. The functional disability of the patient when we assess it without using the assistive device is called "absolute functional disability" by Duruöz [2].

The assessment of the joint ROM with goniometer, placed in clinical practice at the early 20th century. The instrumentation has become very sophisticated, including computerized goniometers, three-dimensional electrogoniometers, and video-based motion analysis systems [28, 29]. There are already observational ROM evaluation tests such as SOFI [30]. It consists of four items: grip a plastic tube (larger tube for men), bend fingers around a pencil, make a round pincer grip, and oppose the tip of the thumb to the base of the fifth finger.

Grip and pinch strengths can be measured with a dynamometer (JAMAR) or sphygmomanometer [31]. To assess the grip strength, the arm should be unsupported and the elbow held at 90 ° to eliminate the extraneous influence on the recording (Figs. 3.16 and 3.17).

In the last decades, there has been a shift toward an evaluation of hand-related function in daily living activities, and several tools for the assessment of disability have been introduced. The Duruöz Hand Index (DHI), Michigan Hand Outcome Questionnaire (MHQ), Disability of the Arm, Shoulder and Hand Index (DASH), Arthritis

Fig. 3.16 Assessment of grip strength with Jamar dynamometer

Fig. 3.17 Assessment of pinch strengths (tip, tri-digit and lateral) with Jamar pinchmeter

Hand Function Test (AHFT), Australian/Canadian (AUSCAN) Osteoarthritis Hand Index, and ABILHAND manual ability measure (ABILHAND) are some of most widely using scales in clinical practices [2, 32–36].

The DHI [2] is a questionnaire that was developed to assess the functional disability and functional handicap caused by rheumatoid hand. It was validated in other arthropathies of hand such as osteoarthritis, scleroderma, stroke, diabetes mellitus, hemodialysis, psoriasis, and flexor tendon ruptures, and was translated into 16 languages. The scale is based on 18 questions concerning activities commonly performed by the hand in a person's daily environment. The DHI has three-factor groups [2]: The first factor has eight questions and represents activities requiring force and rotational motions; the second factor has six questions and represents activities requiring dexterity and precision; the third factor has four questions and represents dynamic activities requiring the flexibility of the first three fingers of the hand. The each question's scores are summed for the total score, and higher scores indicate most disability (Appendix of the Book).

The Michigan Hand Outcome Questionnaire (MHQ) has a total of 37 kinds of questions to assess right and left hands. The pain and the work performance subgroup questions are for both hands; other subgroup questions are asked for each hand separately. The subgroups are (a) overall hand functioning, (b) physical function with the activity of daily living tasks, (c) work performance, (d) pain, (e) aesthetics, and (f) patient satisfaction. The six subgroup scores are summed to obtain the total score. Higher scores indicate better status (Appendix of the Book) [32].

The QuickDASH has 11 questions which concern symptoms and physical function in persons with disorders involving the upper extremity. The maximum total score is 100 points which indicate the most disability (Appendix of the Book) [33].

These instruments for the assessment of disability usually are self-administered questionnaires that are more or less complex and focus on the evaluation of the hand function by the patients themselves. These questionnaires give us crucial information to understand better our patients' experience and difficulties in their daily life.

The primary concern of hand functional disability questionnaires is the concept that they are subjectively reflecting the subject's perception of ability rather than their actual ability [37]. Therefore, measures of functional disability are not exactly representative of physiological hand function. This is exemplified by rheumatoid patients who make coping in the way they perform ADLs despite high levels of impaired physiological joint function [38, 39].

The handicap may be explained here as the disadvantage induced by any hand involvement (e.g., arthritis, deformities, tendon ruptures) in activities of everyday life, and it may be evaluated by VAS-handicap (0–100 mm, no handicap-maximum handicap). To assess the handicap accurately, the question of the VAS-handicap should explain the purpose very clearly.

Example of VAS-handicap Question "Considering your needs for everyday life, please indicate your handicap level due to rheumatoid arthritis in your hands on the line of the scale with putting (x) mark?"

Many new techniques are ready to use the assessment of hand function such as video recording, electrogoniometers, optoelectronic and electromagnetic trackers, instrumented gloves for kinematic evaluation, dynamometers including isokinetic and isometric devices, work simulators, refined techniques of evaluation of dexterity, and finger coordination of measurement of tactile and thermal discrimination. These systems can be enhanced by way of visual feedback [40, 41]. A haptic interface methodology is developed recently which provides an objective, quantitative, and repeatable method for the assessment of the upper limb functional state, especially for movement capabilities. The tests include tracking tasks to assess the accuracy of movement, to assess the patient's control abilities, to assess both speed and accuracy, and to assess the maximal force capacity of the upper extremity [42].

Which Assessment Method Is the Best?

There is no single assessment method that can be recommended for all clinics, and there is no gold standard to assess the hand function because there are many variables which affect the hand function.

There are many types of functional hand assessment currently in use, ranging from simple to complex, quantitative to non-quantitative, and standardized to nonstandardized. The simple tests are better than complex ones, and it is better to use hand function test concerning the objective of the research and the clinical assessment. The test or questionnaire should be valid for the aim of the evaluation and should be valid for targeted patient group, disease, and population. If we want to assess the functional disability of the rheumatoid hand, the test (scale) should include items for functional disability in hand, and it should be valid to assess the rheumatoid hand in that population. The reliability and sensitivity to clinical change (or responsiveness) properties of the scales are already important.

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Section II

Hand Function in Clinical Practice

Pain and Hand Function

4

Sevtap Acer Kasman and Mehmet Tuncay Duruöz

Introduction

Pain is an unpleasant somatosensory perception that each individual feels, experiences, and interprets in a unique way. Pain is necessary to alert us so that we can protect ourselves under normal physiological conditions. However, pain would be uncomfortable and affect individuals' functions if it is excessive, repetitive, or continuous. The primary goals of pain therapy are to reduce suffering and to increase the function of the patient.

Chronic pain, which is a kind of basic impairment status, may cause significant functional difficulty. Different characteristics of the pain such as duration (acute or chronic), severity (mild to severe), location (critical areas like the thumb), or style (sharp, blunt, or neuropathic) may lead to different impairments and functional losses in different levels [1]. The severity of the functional loss due to the pain generally depends on physiological, perceptual, affective, cognitive, and behavioral components of the patient [2]. Chronic pain may affect the patients' compliance with treatment, develop persistent problems, and affect the outcomes of the treatment [3].

Obviously, hand is one of the organs for which the impairment may cause critical functional loss. Hand pain is a very strong parameter for determining hand function as well as age, history, female gender, weaker hand strength, manual occupation, and neck or shoulder pain [4]. Consequently, an accurate and comprehensive assessment of hand pain is necessary to draw an optimal road to achieve an ultimate relief and functional status.

Understanding and Classifying Chronic Pain

Pain has been classified in terms of different dimensions such as pathophysiological mechanisms, duration, etiology, anatomic location, severity, body system, and frequency [5]. Table 4.1 shows three different pain classifications that are most widely used [6].

In terms of the pathophysiological mechanisms, there are two main types of pain: nociceptive and neuropathic (Table 4.1, first classification). Concerning the nociceptive pain process, peripheral nociceptors are activated when the non-neural tissue gets injured, then electrochemical impulses occur in the peripheral nerves, and they are transmitted to the brain via neural pathways. Arthritis pain and acute posttraumatic pain are the examples of the nociceptive pain. Visceral pain which is the type seen in visceral organs is considered in the subgroup of nociceptive pain. The other subgroup of the nociceptive pain is somatic pain, which is well

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Table 4.1 The most commonly used classification systems

Classification based on the pathophysiological mechanisms [5]	Nociceptive
	Somatic pain
	Visceral pain
	Neuropathic
	Peripheral pain
	Central pain
	Mixed pain
Classification based on the pain duration and ICD codes [6]	Acute
	Chronic
	Primer pain
	Postsurgical/posttraumatic pain
	Musculoskeletal pain
	Neuropathic pain
	Cancer pain
	Headache/orofacial pain
	Visceral pain
Classification based on the medical diagnosis [5]	Arthritic pain
	Vascular pain
	Muscle pain
	Myofascial pain
	Nerve pain
	Fibromyalgia
	Phantom limb pain
	Cancer pain
	Complex regional pain syndrome
	Sympathetically maintained pain

localized and expressed as aching, stabbing, gnawing, or throbbing. Neuropathic pain is defined as the pain caused by a lesion or disease of the somatosensory nervous system, according to the International Association for the Study of Pain (IASP) [7]. This kind of pain is expressed by burning, shooting, lancinating, and electric shock-like feeling. It is often located superficially and associated with allodynia, hyperesthesia, and trophic disorders [8]. Neuropathic pain is generally investigated under two subgroups as peripheral and central. Peripheral neuropathic pain is caused by a lesion or disease of the peripheral somatosensory nervous system. For instance, brachial plexus lesions or peripheral nerve syndromes may cause a peripheral neuropathic pain in hand. On the other hand, central neuropathic pain is caused by a lesion or disease of the central somatosensory nervous system [9].

When nociceptive and neuropathic pains are seen together, it is called mixed pain. Chronic pains are generally mixed type. The most dramatic example of mixed type of pain is complex regional pain syndrome (CRPS), in which dysfunctional efferent reactions of nerves can change some chemical and physical environments of the pain sensors.

Classification of pain as acute or chronic is essential in clinical practice (Table 4.1, second classification). Acute pain is differentiated from chronic pain by the following properties: it is generally self-limited, is provoked by a specific lesion or an injury, lasts less than 3 months, and serves some useful biologic purposes like warning or protection function. Chronic pain, which is persistent or recurrent lasting longer than 3 months, is usually the expression of a complex event. In this context, understanding the chronicity and central sensitization is very important. Sustained peripheral nociceptive impulses, mainly from C nociceptive afferents, may lead to central sensitization, an abnormal pain amplification process in the central nervous system. This sensitization leads to increased spontaneous impulse activities and their enhanced responses to impulses in the afferents [10]. Central sensitization may develop over time in a painful situation, regardless of being nociceptive or neuropathic. The centralized pain can lead to functional loss compared to the acute pain. However, it is not precisely predictable, because there are considerable inter-individual differences in the central nervous system factors that influence pain perception. Recent work suggests that central pain-prone phenotype may be associated with female gender, genetic background, early life trauma, family history of chronic pain and mood disturbances, personal history of fatigue, sleep disturbances, psychological distress, cognitions such as catastrophizing, lower mechanical pain threshold, and descending analgesic activity [11]. Central sensitization generally needs improved pharmacologic and non-pharmacologic interventions (Fig. 4.1). Classification of

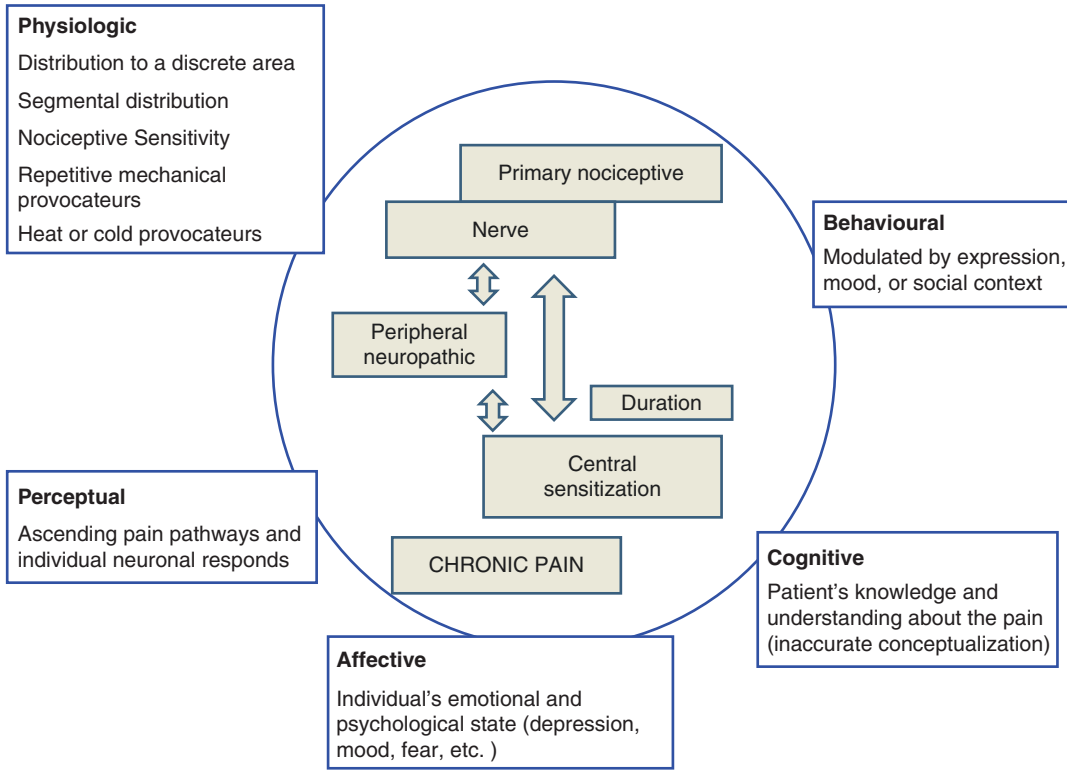


Fig. 4.1 Interactions between the basic chronic pain mechanism circle and five components of chronic pain: Physiological, perceptual, affective, cognitive, and behavioral [2]

chronic pain according to current ICD codes and medical diagnosis may provide a more practical approach (Table 4.1, second and third classifications) [6].

In addition to the characteristics mentioned above, there are some essential questions about the pain properties that can help us for a proper classification and functional evaluation:

- Quality: What does your pain feel like? Burning, dull, sharp, stabbing, crushing, lancinating, throbbing, or shooting?
- Severity: Pain may have a wide range of severity, from mild to resistance with increasing pain. Scales of assessing pain severity will be discussed in the next section.
- Region/Radiation: Where is it located? Does it radiate?
- Temporal aspects: When does the pain occur? Is it constant or intermittent?
- Provocation/Palliation: What makes your pain worse? Previous treatments, painful movements, movement restrictions, and pain modulation ways?
- Concomitant symptoms: Are there any symptoms such as nausea, vomiting, chills, or cold?
- Medical comorbidities: Are there any chronic diseases such as hypothyroidism or diabetes mellitus?
- Sleep quality and mood: Sleep is a critical target in the comprehensive assessment. The clinician should also inquire about mood, role-functioning, employment, coping, and relationships.

Finally, the effect of pain on the function and quality of life should also be investigated. A functional loss due to the pain should be described as a condition that exists after optimum physiological adjustment and maximum medical rehabilitation.

Measuring Hand Pain and Function

An accurate initial assessment and comprehensive follow up are the essential components of healthcare delivery. Identifying the goals and the scope of the treatment is fundamental. Furthermore, standardized, systematic, and formal data assessment processes are needed for scientific research. So, which assessment technic should we choose? First of all, an assessment tool or tools that have previously been validated for a particular disease and population at hand should be selected. They should be reliable and purposeful. The age group should also be taken into account. Multifactor scales may be useful to find out which domain of impairment makes the most functional loss. Additionally, multidimensional instruments may have some advantages, like saving time, because they assess many dimensions at once. However, scoring systems and evaluations of the multidimensional instruments may be more complicated than unidimensional ones. Below, we will discuss commonly used tools for hand pain, ranging from the simple pain assessment scales to the multidimensional scales.

Pain Intensity Although there are no objective tests for the exact evaluation of intensity due to the subjectivity of pain, some patient-focused outcome measures such as global pain intensity scales are commonly used by clinicans. For measuring the clinical intensity of pain, the Visual Analogue Scale (VAS) and the Numerical Rating Scale (NRS) have proved reliable [5]. In the VAS, the patient marks the intensity of his/her pain on a 10-cm-long measurement without numbers, and then the physician measures the distance of the marked point from the no-pain end and concludes a number between 0 and 10. The NRS also ranges from 0 to 10, but in this scale, the patient is aware of the number that is being selected, so the resulting number is similar to the VAS. High correlations among the VAS, NRS, and grip strength have been detected [12].

The VAS and NRS are usually included in the pain questionnaires. Patients keeping a diary can sometimes be beneficial for the assessment of the progress. The use of questionnaires and diaries can save time, provide a comparison during the time, and improve understanding the patients' pain.

Pain-Related Disability Chronic pain is characterized by physical dysfunction and disability [13]. In this case, how does the pain impair physical functioning, emotional functioning, and psychosocial role? The diagnosis relies on the subjective description and objective findings; however, the function can be assessed using a unified patient-centered approach. More elaborate tools may be needed for measuring the extent of the pain-related disability. Several scales have been developed for this purpose. For instance, the Pain Disability Index (PDI) measures the impact of the pain on the ability of a person to participate in essential life activities: self-care, family and home responsibilities, social activities, recreation, sexual behavior, life-support activities, and occupation [14]. The higher index means the greater disability due to the pain. The PDI has acceptable reliability, instrument validity, good internal consistency, and high utility for assessing pain outcomes. It can well discriminate the groups of patients with varying levels of disability due to the pain [5]. Furthermore, there are high correlations between the pain-intensity measures and the pain-related disability measures [15].

Pain-Related Fear Environmental and personal factors (such as fear, behavioral performance, motivation, and psychology) interact with body functions/structures, activities, and participation (Fig. 4.2) [16]. Fear is one of the most influential psychological factors in experiencing the pain, so pain-related fear is a major personal factor that may have detrimental effects on hand function [3]. Pain-related fear may decrease the patient's desire to initiate or continue the physical functioning. The Pain Anxiety Symptoms Scale (PASS) and the Tampa Scale are the most widely used tools to assess pain-related fear. The PASS is a 40-item questionnaire which assesses anxiety symptoms, fearful appraisals, escape, and avoidance of pain. The Tampa Scale is a 17-item questionnaire used to assess the kinesiophobia or fear of movement due to chronic musculoskeletal pain. The Tampa

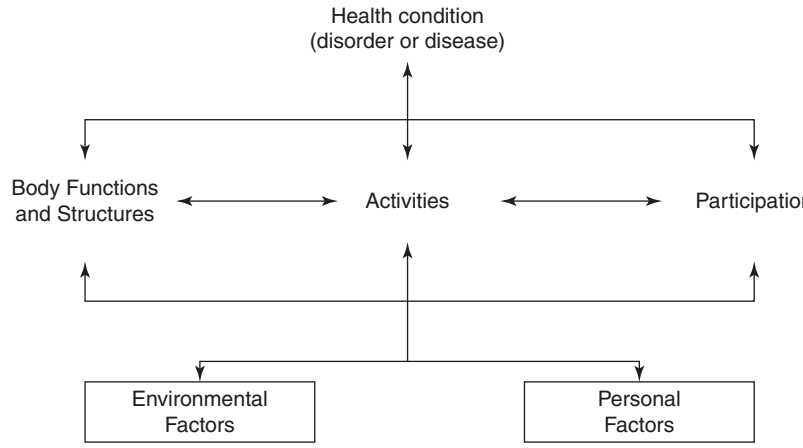


Fig. 4.2 The classification of functioning, disability, and health (ICF) model: interaction between ICF components. The functioning of an individual in a specific domain reflects an interaction between the environmental/personal factors and health condition [16]

Scale was found to be a better predictive validity than the PASS and other pain-related fear measurements [17, 18].

Multidimensional Pain Outcomes Multidimensional tools are generally practical and well integrated when assessing multiple domains of outcomes in painful situations. They integrate pain and other symptoms with function. Among them, the Brief Pain Inventory (BPI) is a 32-item instrument which assesses pain history, pain intensity, pain interference, and perceived response to treatment. Factor analysis of the BPI showed two factors: pain interference and severity in physical functioning. It is valid in the osteoarthritis and cancer pains [19]. The Multidimensional Pain Inventory (MDI) is a 52-item instrument and comprises 12 subscales: pain severity, interference, affective distress, life control, support from others, negative response, distracting responses, solicitous responses, household chores, activities away from home, outdoor work, and social activities. It has good internal consistency and reliability, and most subscales have concurrent validity [20]. The Pain Outcomes Questionnaire (POQ) is another multidimensional questionnaire which was developed to assess treatment outcomes and has 6 subscales: pain intensity, activities of daily living, mobility, vitality, negative affect, impairment, and fear [21]. Similarly, the Pain Outcomes Profile (POP) includes POQ scale items except for employment, medical utilization, and treatment satisfaction and was developed by the American Academy of Pain Management.

Functional Assessment of the Hand None of the tools mentioned above are specific to hand and they are general assessment instruments for pain and pain-related disorders. Most of them have not been validated for hand pain. Because of the complicated structure of the hand and the complex mechanisms behind the pain, some of the functions can be maintained and some may be lost after a discomfort. Furthermore, we have two hands that can compensate each other. Thus, assessing and measuring hand function is as important as evaluating the impairment, such as pain or weakness. Hand function involves some essential activities including self-care, occupational activities, perception and processing of information, defense and offense, gestural expression, and emotive touch [22]. An assessment tool which measures the ability to perform specific tasks of daily living activities can be used for evaluating hand function.

The evaluation of the grip strength may be considered as one of the functional hand parameters. Hand dynamometers and pinch meters can be used to measure the quantification of grip strength and pinch strength, respectively. Using such tools provides repeatable outcomes; however, many factors determine these outcomes, such as age, pain, handedness, amputations, and limited range of motion.

There are various useful hand and upper extremity scales to assess the functional outcomes. Although some of them do not consist

of pain domain, they have generally revealed moderate correlations with hand pain in various diseases. For instance, the Patient-Reported Outcomes Measurement Information System (PROMIS) Physical Function—Upper Extremity Questionnaire is an adaptive computer test which has recently been made available by the National Institutes of Health (NIH) to measure physical function outcomes due to the upper extremity. When you look at the other examples, the Jebsen-Taylor Hand Function Test is a hand function tool, which has seven subscales such as writing, feeding and picking up small, large, light, and heavy objects, and turning pages. It does not include pain domain as PROMIS, but is utilizable in children over 6 years of age to assess hand function [23]. The Duruöz Hand Index is a self-reported hand function questionnaire that provides a valid and reliable measure of the activities of daily living [24]. It was developed for rheumatoid arthritis hand, and then has been validated in many diseases [25]. The Moberg Pickup Test (MPUT) measures the time needed to pick up particular small objects [26]. The Arthritis Hand Function Test (AHFT) is a performance-based test and measures different aspects of hand function in the activities of daily living: grip and pinch strength, dexterity, applied dexterity, and applied strength [27]. The Health Assessment Questionnaire (HAQ) was developed to assess patients' functional capacity in daily activities [28]. The HAQ is not specific to the hand as it evaluates the person as a whole; however, it's daily activity questions are generally related to the hand. The HAQ does not include pain domain, but it has associations with swollen and tender joint counts, laboratory of inflammatory activity, and pain [29].

Functional Assessment of the Hand with Pain Domain The most commonly used scales in measuring functional outcomes that include pain domain are the Dreiser's Functional Index Score [30]; Australian/Canadian Osteoarthritis Hand Index (AUSCAN); Disabilities of the Arm, Shoulder and Hand (DASH) questionnaire [31]; Quick-DASH; and Michigan Hand Outcomes Questionnaire (MHOQ) [32]. The AUSCAN is a self-report questionnaire which assesses hand pain, stiffness, and function. The patient is asked for hand pain at resting and during activities, including gripping, turning, lifting, and squeezing objects. The DASH assesses the symptoms and function of the upper extremity concerning pain, tingling/numbness, weakness, and stiffness. It has been shown to be a valid and reliable measure of upper extremity disability. The MHOQ assesses hand function concerning pain, work performance, appearance, and satisfaction. This instrument can be used for hand/wrist injuries and arthritis. Pain is the most reliable independent predictor of hand function in the MHOQ.

Hand Pain and Function by Region

Involvement of the different hand regions has different impacts on the function. Since hand has a complicated structure, multidirectional movements, and sophisticated functions, we believe that evaluating hand pain by region may provide a more analytical and functional assessment.

Before evaluating hand pain in terms of significant functional anatomical structures, we first give brief information on the cutaneous hand sensation. Regardless of being nociceptive or neuropathic, hand pain is mediated by specific peripheral nerves. Innervation of the wrist is delivered by the posterior interosseous branch of the radial nerve, the anterior interosseous branch of the median nerve, and the deep and dorsal branches of the ulnar nerve. Sensory innervation of the lateral part of the palm is provided by the median nerve's palmar cutaneous branch. The lateral 3 fingers and 1 half finger on the palmar surface of the hand are innervated by the digital cutaneous branches of the median nerve. These digital branches also supply most of the hand joints. The point is, the palmar cutaneous branch leaves the median nerve in the distal forearm which passes superficially into the hand and does not get in the carpal tunnel. That's why neuropathic complaints of the carpal tunnel syndrome do not include the lateral part of the palm. The anterior and posterior surfaces of the 5th finger and medial half of the 4th one, and the associated palm area are innervated by the ulnar

nerve's superficial terminal branches. The skin of the medial half of the palm is innervated by the palmar cutaneous branch of the ulnar nerve. The superficial radial nerve is a cutaneous branch of the distal radial nerve and supplies the dorsolateral aspect of the lateral 3½ digits and associated hand area. This branch is separated from the radial nerve at the level of the forearm and partly superficial. The lesion of the branch causes a painful condition called clamp neuropathy.

The segmental innervation of the skin of the index finger, lateral hand, and thumb are provided by cervical spinal cord segment as C6, the middle finger is provided by C7; and the medial hand, ring, and little fingers are provided by C8. Radicular root irritation syndrome, which is a kind of neuropathic pain, causes the well-located pain, numbness, and tingling. Burning, stabbing or electric shock-like feeling may be seen together with poor reflexes and hyperalgesia. It often affects one or more dermatomes with pain shooting into the arm and/or hands [8]. Brachial plexus lesions are generally related to the disability. The primary disability may be the paralysis of the hand, but the pain itself can keep the person away from the work, hobbies, and sport.

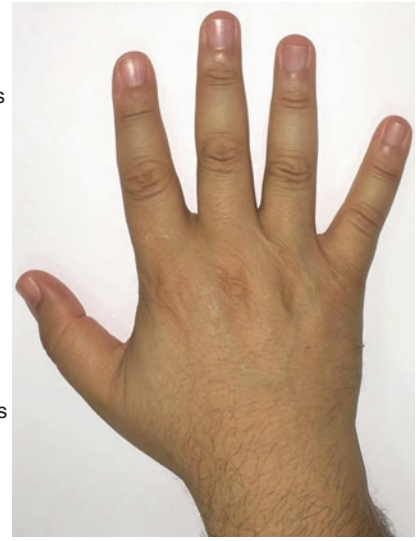
Hand parts have different functional implications: the index finger and the thumb are essential for pinching and fine dexterity, while the others are more important for grip [33]. The thumb pain can occur due to various structural reasons: on basis of the carpometacarpal (CMC) joint, such as synovial inflammation or osteoarthritis; on the basis of the tendon, such as de Quervain's tenosynovitis; on the basis of the muscle, such as trigger point; and on the basis of the bone, such as avascular necrosis or infections; or it may be neuropathic pain, such as carpal tunnel syndrome or cervical radiculopathy (Fig. 4.3). Whatever the reason is, the thumb has a critical functional meaning in terms of its position and capabilities. First of all, the joints of the thumb are both similar to and different from the other finger joints. The CMC joint contributes more function than a metacarpophalangeal (MCP) joint of a finger [34]. The simultaneous movement of the MCP and CMC joints has more than one rotational degree of freedom, so they provide a versatile movement. Secondly, the opposition is one of the fundamental movements of the thumb. When pain or weakness limits the active movement of the opposition, the thumb impedes the grasp function of the hand. In this case, only cylindrical objects of limited size can still be firmly grasped, and precision handling is painful or not possible. The pain may be aggravated by frequently used movements in everyday life such as pinching, grasping, or repetitive thumb and wrist movements. As a result, thumb is responsible for at least 50% of the overall hand function in healthy population. However, the studies on hand osteoarthritis have contradictory results in terms of the effects of thumb pain on hand function: while some studies show that CMC osteoarthritis of thumb rarely causes disability, some note that osteoarthritis of thumb joints has major effects on hand function [33, 35, 36].

The wrist joint is a synovial joint in the upper limb, which connects the forearm and the hand. Flexion, extension, adduction, and abduction can occur at this joint. Global motion of the wrist is a co-motion of the intercarpal, radiocarpal, and midcarpal joints [2]. Wrist pain may be caused by some pathologies in the tendon compartments, such as tenosynovitis or trauma; wrist capsule, such as arthritis; bony structures, such as avascular necrosis; masses, such as ganglia; and neurovascular conditions, such as radial nerve lesions or CRPS (Fig. 4.3). Lack of wrist motion does not much impact finger movement during forceful hand grip; however, wrist pain is associated with decreased function of the hand. Previous studies showed that the pain and the ability to do activities of daily living were the most critical dimensions in subjective outcome tools in posttraumatic conditions of the wrist joint [37, 38]. Regarding inflammatory processes, while wrist pain did not correlate with the sonographic inflammatory parameters, it was moderately correlated with the functional loss in rheumatoid arthritis [39]. Furthermore, wrist denervation operation can provide a significant functional improvement with the postoperative pain relief in patients with resistant pain [40]. Apparently, patients are able to value their functions better if the wrist pain is less after the denervation process.

General Reasons
Osteoarthritis
Synovitis
Tenosynovitis
Referred trigger point pain
Neoplasm
Infection
Postsurgery
Trauma
Complex regional pain syndrome
Pain due to proximal nerve lesions

Nail
Dactylitis
Subungal melonoma
Subungal haematoma
Nailfold infarcts
Digital ulcers
Perpheral gangrene

Finger
Heberdan and Bouchard's nodules
Carpal tunnel syndrome
Ulnar nerve lesion
Trigger finger
Dupuytren's Contracture
Mallet finger
Dactylitis
Raynaud's phenomenon
Acro-osteolysis
Digital ulcers
Perpheral gangrene



Thump
Heberdan and Bouchard's nodules
DeQuervain's tenosynovitis
Carpal tunnel syndrome
Radial nerve lesion
Trigger finger
Dupuytren's contracture
Dactylitis
Raynaud's phenomenon
Acro-osteolysis
Digital ulcers
Perpheral gangrene

Wrist
Bursitis
Ganglion
Nodule
DeQuervain's tenosynovitis
Radial nerve lesion
Ulnar nerve lesion
Proximal median nerve lesion
Avasculer necrosis

Palmar
Ganglion on flexor sheath
Hyperthrophy of first lumbrical
Carpal tunnel syndrome
Ulnar nerve lesions
Avasculer necrosis
Trigger finger
Dupuytren's contracture

Dorsal
Avasculer necrosis
Radial nerve lesion
Secretan's disease

Fig. 4.3 Common reasons for hand pain by regions

Achieving full hand function requires working fingers in combination with the thumb. A functional prehension and sensation are the sums of roles played by multiple digits. Painful fingers and nail disorders may cause decreased hand function, especially in fine dexterity. The reason may be a degenerative joint disease, such as Heberden's and Bouchard's nodes; an inflammatory disorder, such as dactylitis; vascular condition, such as digital ulcer or gangrene; periostitis, such as hypertrophic pulmonary osteoarthropathy; infection, such as osteomyelitis; nerve lesion; or tenosynovitis (Fig. 4.3). Common nail diseases including paronychial abscess, paronychia, felon, subungal hematomas, and nail fold infarcts do not affect any joint and hand function, if they are not severe. However, these diseases may influence the function if the nail pain is severe, which is the case for almost all other diseases as well. Some of these painful conditions will be discussed in the next section. Among the fingers, osteoarthritis of either of three radial digits (the thumb, or index, or middle finger, but not the ring or small finger) were found to be associated with more severe disability [33]. Some authors investigated the specific digits' contributions to the grip strength. They found that the index finger contributed to the grip strength by 25–30%, the middle finger by 30–35%, the ring finger by 22–25%, and the small finger by 15–18%. These relationships appeared to be mediated by pain [33, 41].

Main Causes of Chronic Hand Pain and Its Relations to Hand Function

The diagnosis of the hand pain should be made carefully and be based on current medical knowledge. Before evaluating hand function, we recommend ruling out the differential diagnosis. It will provide a function-related diagnosis for a clear treatment plan and a notion of prognosis. For convenience, the main clinical features that may cause hand pain will be simply listed here. For further details, the reader is referred to the specific sections in the other chapters of this book.

Osteoarthritis

Osteoarthritis is one of the most common joint disorders of the hand. It is presented with pain, stiffness, reduced grip strength, and decreased range of motion, leading to functional loss and difficulty with daily activities. Pain is a primary outcome of the disease, and it is aggravated by use and relieved by rest. CMC joint osteoarthritis may cause limitations in functional performance including difficulty in manipulating small objects, writing, and carrying [42]. CMC osteoarthritis contributes more to pain and disability than interphalangeal joint osteoarthritis [34]. Bouchard's and Heberden's nodes which are hard bumps of the proximal and distal interphalangeal joints may also be tender, but the pain usually decreases over time.

In hand osteoarthritis, the change in pain is related to the change in function. Pain relief by itself may improve function in these patients [43]. Clinically significant reduction in pain intensity and improvement in functional abilities may be obtained by various therapies [44]. For instance, special exercises can reduce hand pain and improve hand function [45]. Conservative intervention is recommended for people with hand osteoarthritis which are comprised of individualized or client-centered care, activities of daily living evaluation, joint protection education, provision of adaptive equipment, thermal heat, exercise, and orthotic support [46, 47]. All these interventions can reduce pain, improve range of motion and increase function.

Systemic Rheumatic Diseases

Rheumatic diseases with arthritis may result in pain, weakness, and deformities that affect the hands, especially in mornings. The pain assessment is one of the three patient-reported outcomes in the American College of Rheumatology (ACR) response indices and a part of the Outcome Measures in Rheumatology Clinical Trials core domain set [48, 49]. Hand pain is one of the significant symptoms of rheumatoid arthritis (RA). Pain is an explanatory variable in all individual subdimensions of disability in RA. Increased disability in patients with RA was found to be associated with the higher swollen joint count in the upper extremities; higher pain score of hands; limited motion of the wrist, shoulder, and knee joints; and decreased grip strength [50]. Pain and disability have strong relations, even in the early stages. Regarding psoriatic arthritis (PSA), the disability scores tend to be lower for patients with PSA than those with RA; however, pain scores are generally comparable [51]. In systemic lupus erythematosus, the degree of inflammation is not highly associated with pain, function, or fatigue; however, the presence or absence of comorbids is often the most significant predictor of pain, fatigue, and function [11].

Hand involvement (acro-osteolysis) is often the first clinical manifestation in systemic sclerosis (SSc). Skin thickening, edema, fibrosis, Raynaud's phenomenon, arthralgias, arthritis, tenosynovitis, ulcers, and calcinosis may be seen and cause pain. Hand involvement in SSc leads to functional disability based on the disease status, grip strength, wrist/finger motion, and pain. In the literature, some definite correlations between pain and functional limitation and between skin thickness of finger and measures of hand mobility are shown, which means that impaired hand mobility is mainly attributed to pain and increased skin thickness [52, 53]. Ischemic digital ulcers may be seen in systemic sclerosis, may affect multiple fingers, and are associated with pain and hand disability [54].

Tendinitis, Tenosynovitis, and Trigger Finger

Tenosynovitis is defined as the inflammation of tendon sheaths, whereas tendinitis is defined as the inflammation of one or more tendons. These conditions may cause pain, stiffness, and tenderness. Symptoms usually develop with a new and unfamiliar rapid movement of the wrist, hand, or fingers, for example, a new job or returning to work after a long layoff. Typically, the affected tendon and the associated structure are more painful in active motion. Dorsal tenosynovitis generally goes with inflammatory arthritis. De Quervain's tenosynovitis is a painful condition which affects the tendons on the thumb side of the wrist and it has similar pain localization as the CMC joint osteoarthritis. Patients typically suffer from the pain radiating from the lateral forearm to the thumb. Pain increases with the active abduction of the thumb against resistance or forced flexion of the thumb into the palm. It may cause a dramatic functional loss because the pain is more related to the basic hand movements [55].

Trigger finger is a condition in which one of the fingers gets stuck in a bent position. It is also known as stenosing tenosynovitis. A tendon nodule can be palpated and moves with the flexor tendon. It can occur spontaneously or due to rheumatoid arthritis and diabetes mellitus. Similarly, a tender spot in or near one of the forearm flexor tendons located under the thumb pad can cause the trigger thumb [56]. Trigger finger causes local pain, triggering, and loss of function, because the finger becomes fixed in flexion and opening can be painful.

Benign Masses of Wrist

A lesion that occurs in the wrist such as a ganglion cyst, bursitis, tenosynovitis, or tumor (e.g., enchondroma) may cause pain and loss of function. The most common mass in the wrist is a ganglion cyst which is filled with gelatinous fluid. Symptoms include lump/swelling and pain, but the range of motion is generally not limited. Pain may become worse when some weight is placed on the hand or wrist is bent. Pain intensity shows correlation with disability and patient satisfaction [57].

Masses in the wrist joint may also cause nerve entrapment. The most common result is carpal tunnel syndrome. In this case, neuropathic complaints in the fingers are added to the pain and limitation of the wrist, therefore the hand becomes more unusable.

Trigger Points

When a trigger point is present, a possibly unknown reason stops the muscle fibers from relaxing again. There are many theories about the mechanisms and there may be some facilitators, but the precise mechanisms are still unknown [58]. The trigger points are usually tender and may refer to pain in the local area or other areas (Fig. 4.2).

The trigger points of the forearm and hand may cause the referred pain (Fig. 4.4), which are generally the results of repetitive overuse movements such as work, hobby, or sports-related activities. Because an active muscle/tendon of the hand is affected, the functional loss would be more than expected. In addition to pain in the forearm, wrist, and hand, it can also cause grip weakness. This weakness and pain can cause dropping things while pouring or drinking. It may also cause stiff joints, twitching, and trembling [56]. The primary purpose of the treatment of chronic myofascial symptoms is pain relief, which increases patient's capacity for physical function [58].

Vascular Diseases

The insufficient blood supply results in ischemia of the hands, which presents with hand pain and often functional limitation [59]. Common vascular conditions that are seen in the hand are Raynaud syndrome (RS), intermittent claudication, gangrene, cold injury, Volkmann's ischemic contracture, thromboangiitis obliterans, digital ulcers, erythema pernio, and erythromelalgia. Most of them are associated with pain and skin lesions following exposure to the cold or wet [55].

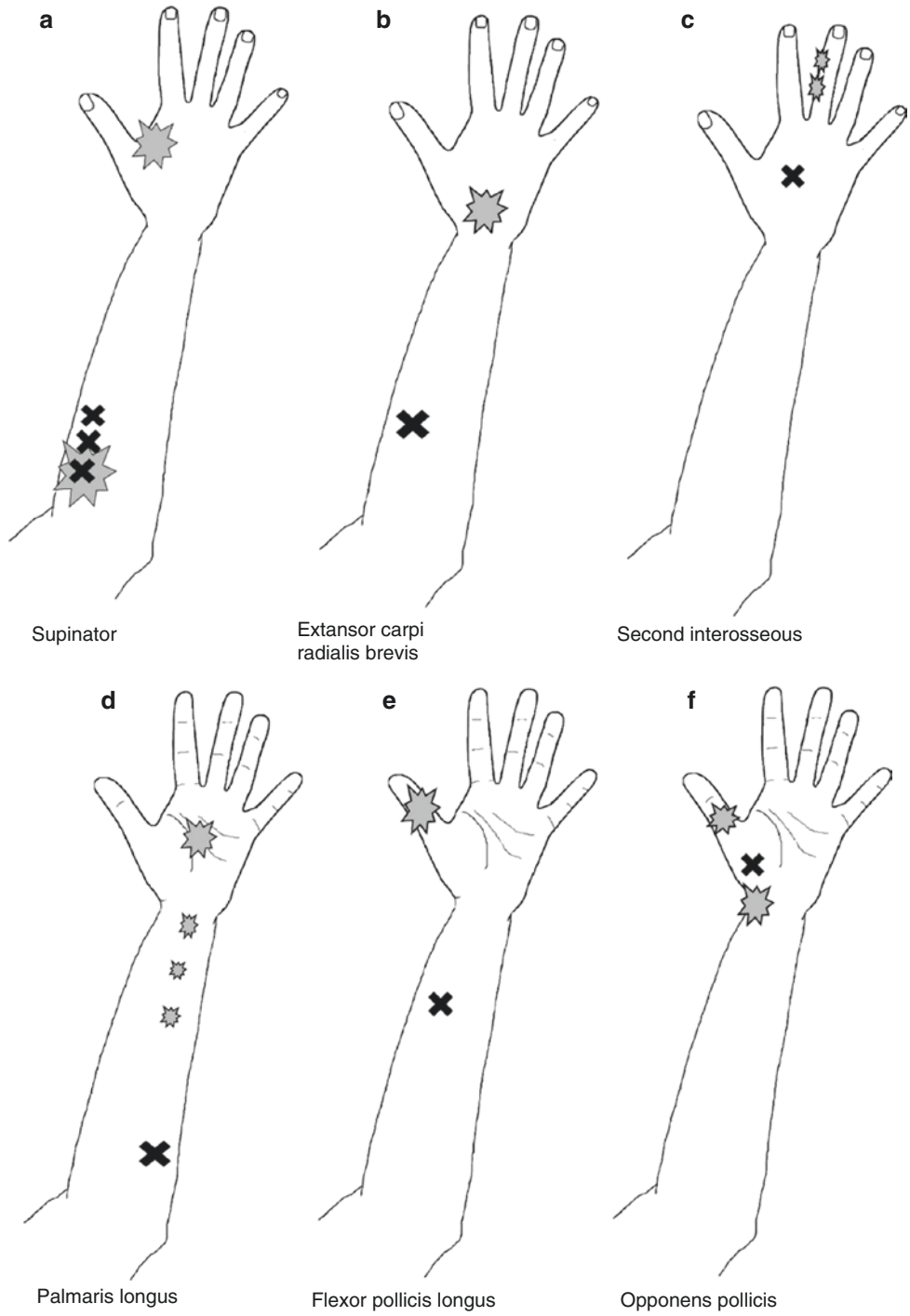


Fig. 4.4 Some referred pain examples that are caused by trigger points in the forearm or hand. (**a**) Trigger point in the supinator muscle and its referred pain at the mid-hand. (**b**) Trigger point in the extensor carpi radialis brevis muscle and its referred pain at the dorsal side of the wrist. (**c**) Trigger point in the second interosseous muscle and its referred pain at the third finger. (**d**) Trigger point in the palmaris longus muscle may cause widespread hand pain. (**e**) Trigger point in the flexor pollicis longus muscle and its referred pain at the thumb. (**f**) Trigger point in the opponens pollicis muscle may cause pain at the thumb. Of course, all of them may cause pain in their etiological region

RS is associated with the episodic attacks of vasoconstriction of the arteries of the extremities and may cause hand pain. The triphasic response develops in fingers as pallor followed by cyanosis and then by painful redness due to rebound hyperemia. It generally exacerbates in cold and emotional stress. If the condition is a response occurring in other illnesses such as collagen diseases, vascular diseases, trauma, neurovascular syndromes, cold injury, and some intoxications, it is called Raynaud's phenomenon or secondary form. Pain reduction and cure of the ulcers to prevent amputation are the primary treatment goals for these patients.

Posttraumatic Chronic Pain

Chronic pain may develop after local trauma for many reasons. Fractures of the hand and arm bones, soft tissue contusions, and vascular/neurologic injuries can occur by falling on to outstretched hand or during sports activities. The damaged portion of the nerve may develop intraneuronal fibrosis or external adhesions, or the friction on a nerve may result in inflammatory changes and further fibrosis.

Fractures of the distal radius are the most common fractures in all patients under the age of 75. Pain, grip strength, and supination are the significant predictors of the upper extremity function after operatively treated distal radius fractures. An excessive baseline pain after wrist fracture with a rating of higher pain intensity is associated with the risk of developing CRPS [60]. Over time, the pain may be reduced, but the function can show the plateau. Eventually, pain is one of the major risk factors inhibiting recovery but it is not responsible for all disability after the surgery of distal radius fractures [61].

Peripheral Nerve Syndromes

Nerve entrapments that cause hand pain may be associated with median, ulnar, or radial nerve. Careful history-taking and comprehensive examinations are generally sufficient for revealing the lesion. The most common disorder in this context is Carpal Tunnel Syndrome (CTS), which is the entrapment of the median nerve, causing pain, burning, numbness, tingling, or weakness. Some predisposing factors may play a role in the etiology such as rheumatoid arthritis, hypothyroidism, pregnancy, or menopause. The most frequent symptoms of CTS are sensory symptoms. Patients feel weakness and loss of sensation in the first three fingers, which are very important in daily activities. These patients with CTS often experience unintentional dropping of objects and clumsiness during activities of daily living. Even though the reason for decreased dexterity seems to be the weakness, there is a discrepancy between motor findings and function in CTS [62]. Experimental research works suggest that chronic pain may disturb motor control and the performance of motor tasks [63, 64]. Taken together, sensory symptoms may be a critical factor that can reconcile the discrepancy. Furthermore, neuropathic pain itself in CTS is also related to hand function [65]. Additionally, the bilaterality rate of CTS is not low, which means more loss of function.

Lesions of the ulnar nerve are generally presented with pain, numbness, and paresthesia in the hand. These complaints go with wrist pain, along with the hypothenar region, and ulnar side of the fourth and fifth fingers. With paralysis of the ulnar nerve, the grasping force is reduced to at least half the average value [55, 66]. In the condition of pain without paralysis, various degrees of neuropathic symptoms and numbness cause functional loss and affect the quality of life. The coexistence of ulnar nerve entrapment with CTS is not rare, as it can be due to a similar etiology [55].

Complex Regional Pain Syndrome

Complex regional pain syndrome (CBPS) is a kind of chronic pain with the skin or vasomotor changes in the affected extremity and it is out of proportion to the injury [67]. Pain, hyperesthesia, red skin, stiffness, puffiness, and moisture difference from the contralateral extremity may be seen in the affected region. Altered patterns of skin, hair, or nail growth; reduced strength; and

Table 4.2 International Association for the Study of Pain (IASP) diagnostic criteria for complex regional pain syndrome [67]

Continuing pain, which is disproportionate to any inciting event. There is no other diagnosis that better explains the signs and symptoms	
At least 1 symptom in 3 of the following categories:	At least 1 sign at the time of evaluation in at least 2 of the following categories:
1. Sensory: hyperalgesia and/or allodynia	1. Sensory: evidence of hyperalgesia (to pinprick), and/or allodynia (to light touch, and/or deep somatic pressure, and/or joint movement)
2. Vasomotor: temperature asymmetry, and/or skin color changes, and/or skin asymmetry	2. Vasomotor: evidence of temperature asymmetry and/or skin color changes and/or asymmetry
3. Sudomotor/edema: edema, and/or sweating changes, and/or sweating asymmetry	3. Sudomotor/edema: evidence of edema, and/or sweating changes, and/or sweating asymmetry
4. Motor/trophic: decreased range of motion, and/or motor dysfunction (weakness, tremor, dystonia), and/or trophic changes (hair, nail, skin)	4. Motor/trophic: evidence of a decreased range of motion, and/or motor dysfunction (weakness, tremor, dystonia), and/or trophic changes (hair, nail, skin)

altered body perception and proprioception may also be present. The disease has two types: in type 1, there is no known nerve injury; and in type 2, there is a recognizable peripheral nerve injury. CRPS is diagnosed by International Association for the Study of Pain (IASP) criteria (Table 4.2). Presence of noticeable autonomic changes in the region of pain can differentiate this disorder from other chronic pain conditions.

Complex regional pain syndrome is often associated with severe pain and impairments in activities of daily living [68]. Almost all patients report disability in their moods, works, and recreational activities. Pain, grip strength, limited range of motion, and higher levels of depression were found to be the strongest predictors of disability in patients with CRPS, but the pain was usually the most critical factor for disability and bad quality of life. Pain relief may provide a clinically meaningful improvement in function in these patients [69–72]. The misuse of the affected limb can be considered as a desire to avoid pain, but it often plays a role in the development of future pain exacerbations. Early treatment and mobilization help prevent the development of chronic CRPS; however, pain and disability may be seen for many years in severe cases of CRPS [69].

Phantom Limb Pain

Phantom limb pain means a painful sensation in a body part that does not exist. Eighty percent of the amputees report intensely painful sensations. The mechanism behind the phantom pain was considered to be a central pain by using functional magnetic resonance imaging and magnetoencephalography [73]. Increased activation in the primary motor cortex and the supplementary motor area has been shown in these patients by functional MRI [74]. The functional loss is related to both pain and lacking organ.

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Hand Function in Rheumatoid Arthritis

5

Janet L. Poole

Rheumatoid arthritis (RA) is a systemic, inflammatory, debilitating disease that can occur at any age. The prevalence increases with age and the peak incidence is between the fourth and sixth decade of life [1]. Although the disease does occur in men, the frequency is nearly three times more common in women. This chronic form of polyarticular joint disease has its most prominent manifestation within the diarthrodial joints of the body. Inflammation of the synovium of the joints is a precursor in the facilitation of destruction of the tissues of the joint [2]. Following the inflammatory process, the synovium becomes hypertrophic from proliferation of blood vessels and synovial fibroblasts and from multiplication and enlargement of the synovial lining layers. The destruction of the tissues progresses when the granular tissue extends into the cartilage and develops pannus. It is this tissue that is effective in the invasion and destruction of periarticular bone and cartilage at the margin between synovium and bone [2]. The supporting structures of the joint, such as the capsule and ligaments, are also damaged in the inflammatory process. The effect on the joints in the hand may lead to the frequent occurrence of boutonnière deformities, swan-neck deformities, ulnar subluxation and dislocation (radial deviation deformity), the latter contributing to ulnar drift of the metacarpophalangeal (MCP) joints [2]. Chronic metacarpal joint synovitis is also a cause of the ulnar drift deformity.

In the boutonnière deformity, French for buttonhole, chronic synovitis of the joint capsule and lengthening of the central slip leads to the displacement of the lateral bands over the proximal interphalangeal (PIP) joints [2]. This results in a flexion deformity of the PIP joint and hyperextension of the distal interphalangeal (DIP) joint. Slow progression of the disease can lead to a fixed contracture of the PIP joint that consequently affects grasp patterns. The deformity is considered to be the hardest of the deformities to treat conservatively because once the deformity has occurred, the supporting structures have become displaced and stretched [2]. Thus, the surrounding supportive tissues have lost their ability to maintain the integrity of the joint.

Swan-neck deformities occur secondary to synovitis either at the metacarpophalangeal (MCP), proximal interphalangeal (PIP), or distal interphalangeal (DIP) joints [2]. In the swan-neck deformity, chronic synovitis causes the tissue of the synovial membrane to proliferate and become thicker. Thickening of the synovial membrane in the MCP joint causes a stretch in the intrinsic muscles of the hand producing a pull of the extensor mechanism. Contractures of the lumbrical and interossei muscles and the natural hypermobility of the PIP joint can lead to MCP joint flexion and hyperextension of the PIP joints [2]. It is these deformities that give the appearance of a swan,

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leading to its name. Often times with swan-neck deformities, the individual will lose the ability to have effective pad-to-pad pinch, thus leading to the use of a lateral pinch in the manipulation of items during activities of daily living.

The ligamentous structure of the wrist is compromised in the presence of chronic synovitis that can lead to instability of the joint. Ulnar subluxation and dislocation (radial deviation deformity) occur due to the loss of the ligamentous support and fibrocartilage on the ulnar side of the wrist [2, 3]. Displacement of the carpal bones can also lead to instability of the wrist. This occurs when the proximal row of carpal bones rotates in an ulnar direction, or counterclockwise direction, and the distal row of carpal bones rotates in a radial direction, also a counterclockwise direction (Fig. 5.1). The resultant structural change is the hand radially deviating on the forearm, which often contributes to ulnar drift of the MCP joints [2, 3].

Metacarpophalangeal ulnar drift is another common occurrence seen in RA (Fig. 5.1). In the healthy hand, ulnar deviation is already present due to the anatomical structure of the hand, i.e., shape of bones and placement and length of the collateral ligaments [2, 3]. Therefore, the ulnar drift that occurs with RA is an abnormal amount of deviation caused by synovitis at the MCP joint resulting in the weakening of the annular ligaments. In the presence of the weak ligaments, the restraining power and the anatomic alignment of the flexor tendons creates a strong ulnar component for drift deformity [2, 3]. This is especially apparent during pinch and grasp when the ulnar forces increase across the MCP joint [2, 3].

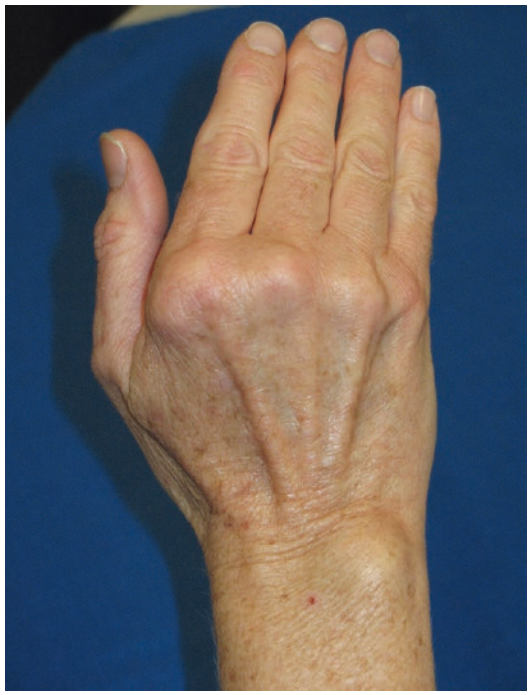

Fig. 5.1 The hand of a 50-year-old woman with a classic RA deformity pattern of radial deviation and volar subluxation of the wrist, MCP volar subluxation, and ulnar drift

Deformities of the thumb occurs in RA due to the synovial hypertrophy within any of the individual thumb joints which can destroy articular cartilage and stretch collateral ligaments and joint capsules. Thumb deformities can interfere with manipulating objects because of stability in the thumb joints. The most common thumb deformity involves MCP joint flexion and distal joint hyperextension (also known as a Type I or boutonniere deformity of the thumb) [4]. Synovitis of the MCP joint stretches the extensor mechanism which leads to flexion of the proximal phalanx and volar subluxation. To compensate, a person radially abducts the first metacarpal and hyperextends the distal joint. In the Type II and III thumb deformities, synovitis causes subluxation of the carpometacarpal (CMC) joint which leads to an adducted and flexed position with subsequent flexion of the MCP joint and hyperextension of the interphalangeal (IP) joint [4]. In the Type III deformity, a more common occurrence is that with CMC joint subluxation and metacarpal adduction, hyperextension of the MCP and flexion of the IP joint occur. In the Type IV deformity (also called gamekeeper's deformity), synovitis stretches out the ulnar collateral ligaments at the MCP joint. This causes the proximal phalanx to deviate laterally at the MCP joint and the first metacarpal to adduct. The first dorsal interrosseous and adductor muscles of the thumb may shorten and the web space contract [4]. Two other thumb deformities, the Type V and Type VI have also been described [4].

Hand Impairment, Activity Limitations, and Participation (Functional Ability)

Many of the deformities that occur with RA affect the ability to grip, pinch, grasp, and flex/extend the fingers and wrists, all which compromise functional ability. This often leads individuals to adapt their daily activities, or cease from performing different activities altogether.

Pain, soft tissue swelling (Fig. 5.2), joint subluxation and decreased articular mobility are reported to contribute to limitations in activities and participation in RA [5–8]. In particular, pain and lack of flexion in the PIP joints has been reported to be related to difficulty manipulating and holding objects or tools needed for eating, dressing, keyboarding, home management, and leisure [9]. A less studied aspect of hand involvement has been participation. Several studies have shown that the joint deformities lead to concerns about appearance and decreased participation in social activities [9, 10].

Furthermore, in early RA, the dominant hand has been shown to have more structural changes (swollen joints, joint tenderness), impairments (strength), and functional ability (decreased dexterity) compared to the non-dominant hand [11]. These findings were also observed by Horsten et al. [12] who found that after 24 years of disease duration, at least one hand or wrist impairment was observed in 70% in the dominant hand and 66% in the non-dominant hand. The most frequent impairments were limitations in passive joint motion, stenosing tenosynovitis and CMC involvement. While disease duration was not associated with functional ability, some impairments (limited passive motion in the fingers of both hands, Z-deformity of the non-dominant thumb, tendinitis of extensor tendons of the dominant hand) increased with disease duration. Johnson and Eberhardt [13] also found that

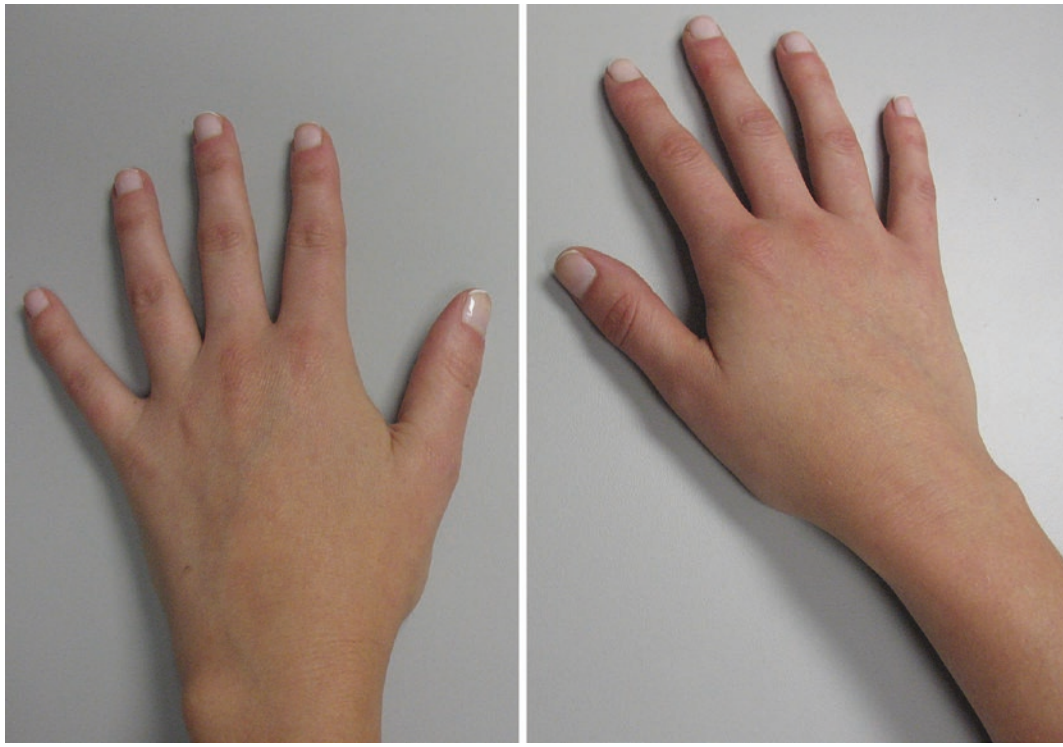

Fig. 5.2 Soft tissue swelling in a 29-year-old woman with RA

decreased joint motion or hand deformities were developed in the first year of the disease and resulted in significantly higher disease severity and functional disability.

Several studies report that grip strength correlates with measures of functional ability such as the upper limb tasks on the Arthritis Impact Measurement Scales 2 (AIMS) [8, 14], the Health Assessment Questionnaire [8, 15, 16], the Disability of the Arm, Shoulder and Hand Questionnaire (DASH) [12], and the Duruöz Hand Index (DHI) [17]. In particular, dominant hand strength appears to be an indicator of hand function and thus, might be important to evaluate and maintain in persons with RA [18].

Assessment of Hand Function

An assessment of the hand in persons with RA should consist of measurements of disease activity, joint motion, joint stability, pain, grip and pinch strength, and hand function.

Joint motion and stability. Joint motion in the hand and wrist joints can be measured with a standard manual or electric goniometer [see the American Society of Hand Therapists for procedures, 19] (Fig. 5.3). Joint instability or laxity is assessed by applying stress to individual joints in a medial/lateral and anterior/posterior direction when the joints are in a close packed position. For example, to test the laxity of the MCP joint, the MCP joint should be in flexion (closed packed position in which the collateral ligaments are tight). The examiner should stabilize the metacarpal with one hand and hold the corresponding proximal phalanges with the other hand and move the joint in the medial/lateral direction and then anterior/posterior. Laxity is noted if the joint moves more than 5–10 ° in excess of normal. To test the laxity of the proximal and distal interphalangeal joints, the joints should be in extension as extension is the position in which the collateral ligaments are tight.

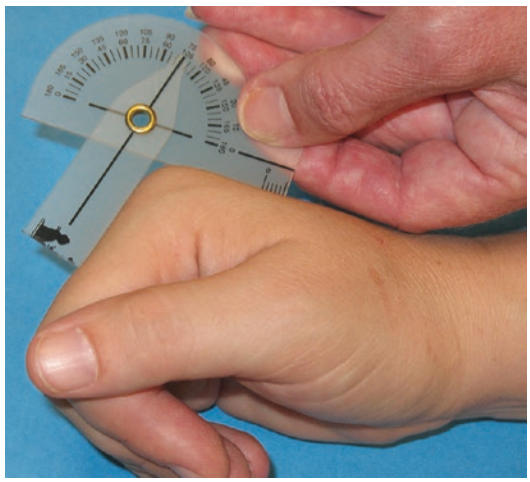

Fig. 5.3 Measuring joint range of motion of the MCP joint with a goniometer

The Hand Functional Index (HFI) consists of the 9 wrist and hand items from the Keitel Function Test (KFT) that measures patterns of joint motion: thumb and individual finger flexion, wrist flexion and extension, forearm pronation and supination [20]. Each item of the HFI is scored according to specific criteria from 0 (item performed fully without delay) to 3 (unable to perform item). Total scores range from 0 to 52 (0–26 for each upper extremity); lower scores on the HFI indicate less impairment in joint motion [20]. Each hand is assessed separately and the HFI requires about 5 min to administer.

Evaluation of joint deformities is done by observation and palpation. The more common joint deformities seen in persons with RA are described earlier in this chapter. The presence of different deformities should be noted. If a deformity can be corrected, either passively or actively, it is considered flexible; if the deformity cannot be corrected, it is considered fixed.

Pain can be assessed by a 10 cm visual analogue scale (VAS) in which patients indicate the severity of their pain with the anchors from 0 (no pain) to 10 (worst pain possible) [21]. The score is determined by measuring the distance on the 10 cm line from the "no pain" anchor to the line the patient has made to represent pain severity. A higher score indicates greater pain. The VAS can be modified to ask about pain in a specific body part such as the hand and/or thumbs or varied in regards to the recall period for pain. Joint tenderness and swelling can be quantified using the Disease Activity Score (DAS) [22, 23]. The DAS

measures joint tenderness and swelling in all four digits, plus the wrists, elbows, shoulders, and knees. Joints are scored on a 3-point scales from 0 (no pain/swelling) to 3 (severe pain/swelling).

Measures of grip and pinch strength. For both grip and pinch strength, an individual should be seated, with the shoulder joint adducted and in neutral, forearm in neutral, elbow flexed to 90 °, and wrist slightly extended [24]. Three trials are attempted, alternating the right and left hands. The score is the mean score of the three trials. Grip strength is usually measured by a dynamometer (Fig. 5.4); however, if a person has a grip strength of less than 5 pounds, an adapted sphygmomanometer or GRIPPIT may be indicated to show changes in grip strength. Pinch strength should include two-point pinch, three-point (three-jaw chuck) pinch, and lateral (key) pinch. Pinch strength is usually measured with a pinchmeter.

Fig. 5.4 Grip strength measured with a dynamometer

Measures of Hand Function

Hand function includes dexterity and the ability to perform activities of daily living that involve the hands. These measures can be self-reports or performance-based tests [25]. Table 5.1 shows the assessments used to measure hand function.

Performance tests that evaluate hand function include the *Grip Ability Test* [26] and the *Sequential Performance-Based Tests.*

The Grip Ability Test (GAT) [26] is a simple performance-based test consisting of three items: putting a sock on hand, putting a paperclip on envelope, and pouring water from a pitcher filled with 1 liter of water. The score is the sum of the timed scores for each item.

The Sequential Occupational Dexterity Assessment (*SODA*) [27] consists of 12 items: 6 unilateral and 6 bilateral. The examiner rates the performance on each item from 0 (unable to perform), 1 (able to perform task in a different way), and 2 (not difficult). The patient is also asked to rate their perceived difficulty with the item from 0 (very difficult) to 2 (not difficult). For the bilateral items, separate scores are calculated for the right and left hands. Scores are summed and higher scores indicate better function. The short version of the SODA, the SODA-S [28] consists of the 6 tasks on the SODA that were most sensitive to change.

The Arthritis Hand Function Test (AHFT) [29] is an 11-item test that measures hand strength, dexterity, applied dexterity, and applied strength. The hand strength items are grip and two-point and three-point pinch. Dexterity is the time to place and remove 9 pegs from a pegboard. The applied dexterity section is comprised of 5 tasks: lacing and tying a bow on a shoe, buttoning and unbuttoning 4 buttons, fastening and unfastening 2 safety pins from a piece of fabric, picking up and manipulating coins, and using a knife and fork to cut theraputty into 4 pieces. The applied strength items consist of pouring a measured volume of water from a pitcher and picking up a tray of cans.

The Jebsen Hand Function Test (JHFT) [30] consists of seven items that simulate everyday activities: writing a sentence, turning pages

Table 5.1 Assessments used to measure hand function

Test	What measured or subscales	Number of items	Reliability	Validity	Responsiveness
Performance-based tests					
Grip Ability Test (GAT)	Put sock on hand	3	Intraobserver	Content	Low to moderate sensitivity to change
	Put paperclip on envelope		Interobserver	Construct	
	Pour water		Internal consistency		
Sequential Occupational Dexterity Assessment (SODA)	Write a sentence	12	Interrater	Content	Low to moderate sensitivity to change
	Pick up envelope	6 unilateral	Test-test	Construct	
	Pick up coins	6 bilateral	Internal consistency		
	Hold telephone receiver				
	Unscrew tube of toothpaste				
	Squeeze toothpaste				
	Handle spoon and knife				
	Button blouse				
	Unscrew large bottle				
	Pour water into glass				
	Wash hands				
	Dry hands				
Arthritis Hand Function Test (AHFT)	Grip strength	11	Interrater	Construct	No evidence for responsiveness
	Pinch strength		Test-retest		
	Dexterity				
	Applied dexterity				
	Applied strength				
Jebsen Hand Function Test (JHFT)	Writing	7	Interrater	Construct	Moderate sensitivity to change
	Simulated page turning		Test-retest		
	Picking up small objects				
	Simulated feeding				
	Stacking checkers				
	Picking up large light				
	Picking up large heavy objects				
Self-reports					
Duruöz Hand Index (DHI)	Kitchen = 8 items	18	Interrater	Construct	Moderate sensitivity to change
	Dressing = 2 items		Test-retest		
	Hygiene = 2 items				
	Office = 2 items				
	Other = 4 items				
Michigan Hand Outcomes Questionnaire (MHQ)	Overall hand function – 5 items	37	Internal consistency	Construct	Moderate to high sensitivity
	Activities of daily living – 12 items		Test-retest		
	Pain – 5 items				
	Work performance – 5 items				
	Aesthetics – 4 items				
	Satisfaction with hand function – 6 items				

Table 5.1 (continued)

Test	What measured or subscales	Number of items	Reliability	Validity	Responsiveness
Disability of the Arm, Shoulder and Hand Questionnaire (DASH)	Symptoms	30 original	Internal consistency	Content	Moderate for shoulder conditions
	Pain – 3 items	11 quick DASH	Test-retest	Construct	
	Tingling/ numbness – 1 item			Criterion	
	Weakness – 1 item				
	Stiffness = 1 item				
	Function				
	Physical function – 21 items				
	Social/role function-3 items				
Scores for the Assessment and Quantification of Chronic Rheumatoid Affections of the Hands (SACRAH)	Hand function = 17 items	23 original	Internal consistency	Content	Moderate sensitivity to change
	Stiffness – 2 items	12 – SACRAH		Criterion	
	Pain – 4 items	5 – SF-SACRAH			
ABILHand	Hand function	27	Test-retest	Criterion Construct	Sensitive to slight changes in RA patients
The Patient-Rated Wrist Evaluation (PRWE) and Patient-Rated Wrist/ Hand Evaluation (PRWHE)	Pain – 5 items	15	Inter rater	Content	Moderate to high responsiveness to change for wrist fractures and after hand therapy
	Hand function – 10 items		Test-retest	Criterion	
				Construct	
Canadian Occupational Performance Measure (COPM)	Self-care	Semi-structured interview	Internal consistency	Criterion	Moderate for various conditions with outpatients
	Productivity		Test-retest	Construct	
	Leisure				

(turning over 3 × 5 in cards), picking up small common objects (penny, paper clip and bottle cap), simulated feeding (scooping up kidney beans with a spoon), stacking checkers, picking up large light objects, and picking five large heavy objects. Each item is first performed with the non-dominant hand and then the dominant hand. The score for each item is the time to perform the item.

Self-Reports of Hand Function

The Duruöz Hand Index (*DHI*) [31]. The DHI is a self-report and consists of 18 questions divided into 5 categories: kitchen, dressing, hygiene, office, and other. Each item is scored separately on a scale ranging from 0 (without difficulty) to 5 (impossible). Scores from the five total categories are summed to yield a total score ranging from 0 to 90. The DHI takes about 3 min to complete.

The Michigan Hand Outcomes Questionnaire (*MHQ*) [32, 33] is a self-report questionnaire that contains six distinct scales: (1) overall hand function, (2) activities of daily living, (3) pain, (4) work performance, (5) aesthetics, and (6) participant satisfaction. Questions are hand specific and can be applied to a wide range of conditions. Questions are scored on a 5-point Likert scale from 1 (very good/no difficulty) to 5 (very poor/ very difficult) [32]. Scores are normalized to a 0 to 100 scale using the MHQ Scoring Algorithm as recommended by the authors [32] with higher scores indicating poorer functional status.

The Disability of the Arm, Shoulder and Hand Questionnaire (*DASH*) [34] is an assessment of

symptoms and function of the entire upper extremity. It has 30 items regarding symptoms (pain, tingling/numbness, weakness, stiffness) and function (physical function, social/role function). Items are scored on a scale from 1 (no difficulty) to 5 (extreme difficulty/unable to do). The DASH is scored using the original formula [(sum of items −30)/1.2]. An 11-item version of the DASH, the *Quick*DASH, is also available [35]. It consists of three items for symptoms and eight for function.

The Scores for the Assessment and Quantification of Chronic Rheumatoid Affections of the Hands (*SACRAH*) is a 23-item self-report, that includes 3 domains: function, stiffness, and pain in the hands [36]. Items are scored on a 100 mm (1–10 cm) visual analogue scale. The average score from each domain is calculated and the average for the three domains summed to yield a total score between 0 (worst) and 100 (best). Recently, a modified version of the SACRAH, the m-SACRAH, has been developed. The m-SACRAH consists of 12 questions (8 function, 2 stiffness, 2 pain) but is scored using the original SACRAH method. Correlations between the two versions is 0.98 [37]. The SACRAH was shortened even more by Rintelen et al. [38] to a five-question version, the Short-Form SACRAH (SF-SACRAH), which correlated with both the SACRAH and m-SACRAH.

The ABILHand is a self-report or interview of hand ability [39, 40]. The patient rates the difficulty performing each activity on a three-point scale as impossible (0), difficult (1), or easy (2). The activities are presented in random order and there are several versions of the questionnaire. Raw scores are converted to linear measures by submitting scores to an online website (www.abilhand.org).

The Patient-Rated Wrist Evaluation (*PRWE*) and *Patient-Rated Wrist/Hand Evaluation* (*PRWHE*) are self-report questionnaires that assess pain and hand function [41, 42]. Both the PRWE and PRWHE have the same 15 items (5 pain and 10 function); however, in the PRWHE the term "wrist" is replaced with "wrist/hand." Pain is rated from 0 (no pain/never have pain) to 10 (worst ever/always have pain). Although there are no specific studies examining psychometrics with people with rheumatoid arthritis, it is widely used in rheumatology and hand therapy practices.

The Canadian Occupational Performance Measure (COPM) is a client-centered semi-structured interview to identify and prioritize clients' top concerns in self-care, productivity, and leisure activities [43, 44]. Clients are asked to rate their levels of performance and satisfaction for their top 5 areas of concern on a scale of 1 (not able to do it/not satisfied at all) to 10 (able to do it extremely well/extremely satisfied). Similar to the PRWHE, there are no specific studies on the psychometrics with people with rheumatoid arthritis; however, the COPM has been used as an outcome measure in several behavioral intervention studies for people with RA [45, 46].

Summary

Limitations in activities and participation can also be measured using standard questionnaires used in rheumatology practice such as the Health Assessment Questionnaire, the SF-36, the Arthritis Impact Measurement Scale (AIMS-2) or observation of performance during daily activities. However, these questionnaires address broader areas of function besides hand function. Both self-reports and performance-based tests can guide health professionals in assessing hand function in persons with RA. Performance-based tests require training and personnel and equipment to administer. However, they do allow the examiner to observe deficits and adaptive methods used to perform different tasks. Self-reports are quick, easy to administer and can cover a wider variety of skills than performance tests. The validity studies done with the different measures show that in general, hand strength, motion and dexterity measure different aspects of hand function, which may not correspond to what people can do or perceive they can do with their hands. Therefore, evaluation of hand impairment should be supplemented by measures of hand function. Hand strength, in particular, may be important for persons with RA as strength correlates with functional ability.

Summary

The structural changes, deformities, and pain from rheumatoid arthritis can lead to decreased hand function, which affects all aspects of daily life such as self-care, work, and leisure. A thorough assessment of the hand is imperative to preserve hand function and prevent deformities and disability. The assessments presented in this chapter should also be considered as outcome measures for intervention studies designed to improve hand function in persons with RA.

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Hand Function in Osteoarthritis

6

Roy D. Altman

Heberden [1]: "What are those hard knobs, about the size of a small pea, which are frequently seen upon the fingers, particularly a little below the top near the joint….and being hardly ever attended with pain, or disposed to become sore, are rather unsightly than inconvenient, though they must be some little hindrance to the free use of the fingers."

Epidemiology

Osteoarthritis (OA) of the hand is common, with an estimated radiographic and clinical prevalence of 43% in the adult population [2]. Although women have a higher prevalence of symptomatic and erosive changes, overall population surveys indicate a near equal overall prevalence of hand OA in men and women [3].

The initial changes of OA of the hand are most commonly noticed between 40 and 50 years of age. In women, the onset often coincides with the peri-menopausal period, but a clear relation to reduced estrogen concentrations has not been established. There is a tendency to involve the dominant hand, hence the right hand, earlier and more with more prominent changes. There is a tendency for women with hypermobility to involve the first carpometacarpal (1st CMC; trapeziometacarpal) joint. There is a strong tendency for hand OA to be present in other family members, most often of the same sex. Although a high heritability has been suggested [4], at this time, no single gene has been consistently identified.

Clinical Presentation

Patients may present only for unsightly enlargement of the hands (Fig. 6.1). Symptomatic hand OA was 8% in the United States by American College of Rheumatology (ACR) criteria [5, 6]. Some will present with pain or tenderness in or around the involved joints. OA of the hand typically involves distal interphalangeal (DIP) joints, proximal interphalangeal joints (PIP), the 1st CMC and the interphalangeal joint (IP) of the thumb (IP thumb). A predominant palmar subluxation of the DIP or IP joint may appear as a "mallet" finger. There may be some loss of dexterity. DIP involvement may induce vertical ridges on the adjacent fingernails. In a genetic study of nearly 2000 subjects, nodular changes of the DIP of the second digit were most common with the IP thumb second most common [7]. There was a strong correlation between radiographic OA of the hand and the clinical findings of OA. Controversy continues on whether those with predominant hard tissue changes (mostly of the DIPs) and those with erosive changes

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(commonly involving both DIP and PIPs) are separate diseases or the two ends of a spectrum of a single disease. The presence of purely hard tissue changes is often symptomatic only from their size (e.g., change in ring size) and mildly reduced function (e.g., inability to perform certain fine functions such as knitting). However, hand OA may be associated with a significant synovitis and synovial effusion. In the DIP joints, the effusion may rupture on the dorsal radial or ulna side of the joint into a cystic lesion. In the PIP joints, the effusion is often associated with a modest synovitis that is palpable on examination. Hand OA influences hand functions on many domains such as difficulty in writing, handling, and finger holding small objects. Symptomatic hand OA is associated with self-reported difficulty lifting 10 pounds (4.5 Kg) (Odds Ratio (OR) 2.31), dressing (OR 3.77), and eating (OR 3.77) [5]. Changes of the 1st CMC are often associated with pain, reduced grip and pinch strength, and "knobby" changes at the base of the thumb (Fig. 6.1). Isolated changes of the 1st CMC may represent a third subset of OA. Although the 1st CMC OA mostly involves the trapeziometacarpal joint, the scaphotrapezoid joint is also often involved. Pain has notable associations with hand function, reduced grasp (especially cylindrical), and pinch strength in every stage of patients with 1st CMC osteoarthritis [8–10].

Patients with hand OA show some coping styles such as decreasing activity and hand pacing [11].

A systematic review was performed of the literature on factors associated with the severity and progression, of a community-based population, where symptoms were related to the hand [12]. Progression of hand pain and loss of function over time related to limited hand function included older age, women, manual occupation, neck and shoulder pain, radiographic osteoarthritis, weak hand strength, hand pain, Parkinsonism, stroke, diabetes or rheumatoid arthritis, and illness perception.

There may be tenderness of any of the involved joints. There is often an associated deformity with subluxation and/or contracture of the involved joints, particularly when erosive changes are present. Hand OA has shown a clinical association with hypercholesterolemia (OR 2.10), autoimmune thyroiditis (OR 1.87), knee OA (OR 1.63) and hip OA (OR 1.87), without an association with systemic hypertension, ischemic heart disease and, in contrast to the study above, diabetes mellitus [13].

In a country-comparative European cohort, the association between clinical hand OA and

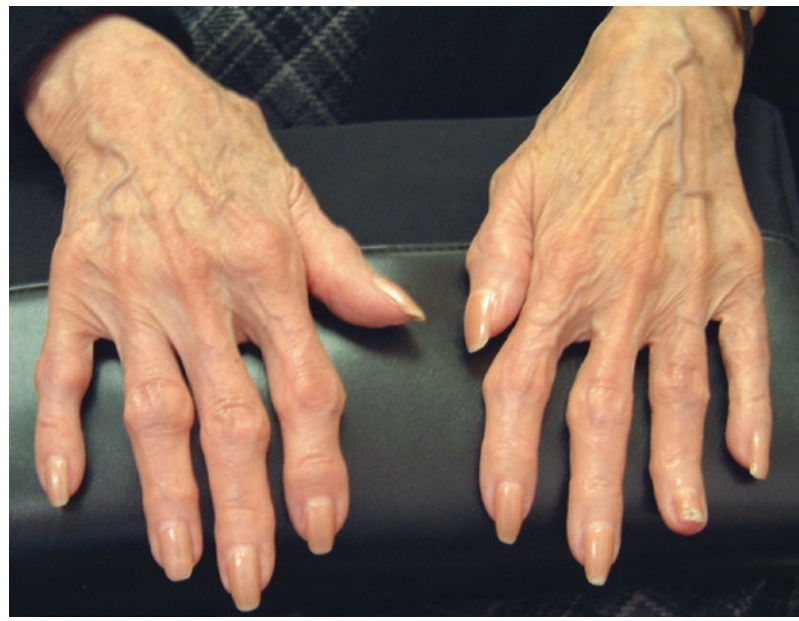

Fig. 6.1 Photograph of osteoarthritis of the hands with significant distal interphalangeal hard tissue enlargement, proximal hard and soft tissue enlargement with deformity, hard tissue enlargement of the interphalangeal joint of both thumbs, and "knobby" enlargement at the base of the thumb (trapeziometacarpal joint) on the right

poor self-rated physical function was observed. Country differences in the strength of the associations also exist [14].

Diagnostic and Classification Criteria

Diagnostic criteria were established by a EULAR working group [15], based on a literature review that emphasizes disease subsets. The diagnostic criteria have not yet been applied in other publications. Classification criteria have been defined by the ACR [6]. The latter were developed through a Delphi technique, physical examinations and radiographs. They were designed for subject selection for clinical trials and are most useful for characterizing a population for a clinical report or trial. Generally, patients should have symptoms and findings in at least two interphalangeal joint (IP), one 1st CMC joint, or a combination of one IP and the 1st CMC to be classified as having symptomatic or radiographic hand OA.

At this time, there are no uniform criteria separating erosive versus nodular hand OA. This has resulted in difficulty in combining results from different clinical trials.

There are no laboratory tests helpful in the diagnosis of hand OA. Citrullinated peptides (CCP) are not present. Low titer rheumatoid factor is common and consistent with an age-matched population.

Imaging

The radiograph may reveal osteophytes, joint space narrowing, subchondral erosions, subluxation, and subchondral sclerosis (Fig. 6.2). The 1st CMC is often subluxed radially with large osteophytes. Grading of radiographs emphasizes the osteophyte and joint space narrowing. The most often used technique for reading radiographs was developed by Kellgren and Lawrence [16]. More recent measurement techniques by Kallman et al. [17] and the Osteoarthritis Research Society International (OARSI) [18] emphasize the reading of individual radiographic features of each joint. A technique for grading degree of change in each joint that may lend itself

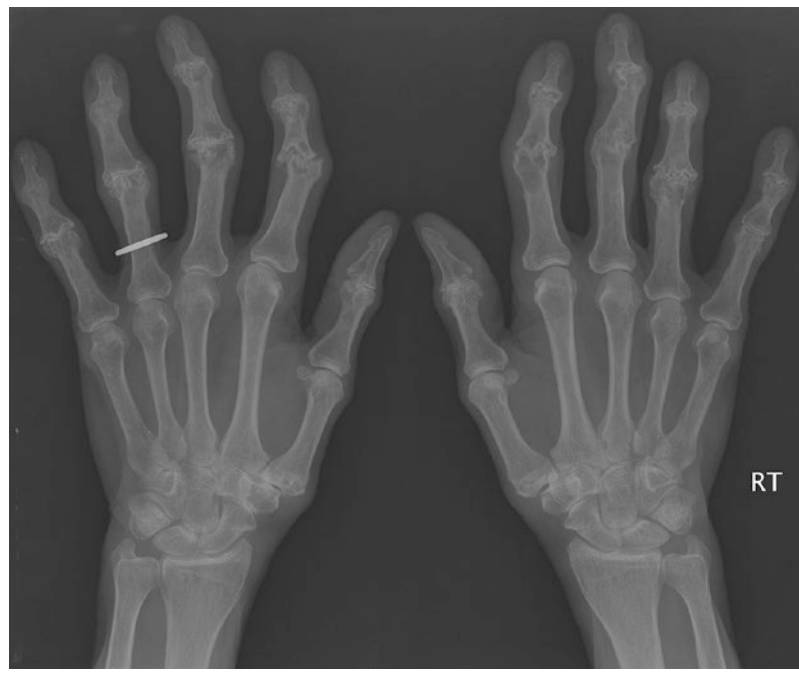

Fig. 6.2 Anteroposterior radiograph of erosive osteoarthritis of both hands demonstrates distal interphalangeal and proximal interphalangeal erosions with central erosions, osteophytes, joint space narrowing, and subluxations

to longitudinal studies was developed by Verbruggen et al. [19].

One of the limitations of the single anteroposterior radiograph is the hidden osteophyte on the dorsal or palmar surface. It is suggested that clinical trials include a photograph of the hands in order to avoid missing changes not picked up by the radiograph. High-quality photograph of the hands appear to correlate well with the radiograph and hand symptoms, particularly in women [20].

Ultrasonography is a reliable assessment tool to evaluate the articular cartilage in the PIP and metacarpophalangeal (MCP) joints [21] On the other hand, MRI is the only imaging modality that can show bone marrow lesions besides the ability to show osteophytes, cartilage, erosions/cysts, malalignment, collateral ligaments, synovitis, and tenosynovitis that may occur in patients with hand OA [22].

Instruments for Measuring Impact of Hand OA

The EULAR recommendations suggest that the primary goal of managing hand OA is to control symptoms, such as pain and stiffness, and to optimize hand function, in order to maximize activity, participation, and quality of life [23]. Pain can be measured by a 10 cm unmarked visual analog scale (VAS) or a 4–11-point Likert scale. Special pain scales have been available for impaired individuals (e.g., happy, sad face).

Specific scales have been developed or adapted for use to encompass pain and function for hand OA. These scales can be examiner-administrated or patient self-administrated. There are also generic quality-of-life instruments and general-purpose arthritis measures (Table 6.1). These scales may specify specifics of the measure, e.g., over the prior 24 h, maximum pain, etc. References are available and all are reviewed as part of the guidelines for design for conduct of clinical trial for hand OA (Table 6.1) [24].

Dresier developed hand OA-specific unidimensional investigator-administered scale which is called Functional Index for Hand Osteoarthritis (FIHOA) [25]. The FIHOA contains ten questions, each rated by a four-point Likert scale. It has been validated in multiple languages and takes only a few minutes to administer.

Table 6.1 Hand function measurements

Osteoarthritis hand-specific indices
Austrian/Canadian Hand Osteoarthritis Index (AUSCAN)
Functional Index for Hand Osteoarthritis (FIHOA)
Indices for rheumatoid arthritis often used for hand osteoarthritis
Arthritis Impact Measurement Scale (AIMS1/AIMS2)
Disability of the Arm, Shoulder and Hand (DASH) Questionnaire
Doyle Index
Duruöz Hand Index (DHI)
Health Assessment Questionnaire (HAQ)
More general measurement indices often used for hand osteoarthritis
European Quality of Life Measure (EuroQol)
Health Utilities Index (HUI)
Hospital Anxiety and Depression Scale
International Classification of Functioning, Disability and Health (ICF)
Nottingham Health Profile (NHP)
Pain indices
Score for Assessment and Quantification of Chronic Rheumatoid Affections of the Hands (SACRAH)
Short Form (SF-12, SF-36)

Duruöz Hand Index (DHI) was developed to assess the functional disability and functional handicap for rheumatoid hand [26] and it was validated for hand OA [27]. The DHI is commonly used in hand OA which has three factor groups [26]. It was validated in several hand involvement of rheumatic diseases (e.g., scleroderma, psoriatic arthritis) and in several languages, including French, Spanish, German, Arabic, Italian, and English. The DHI is composed of 18 questions on daily activities in a six-point Likert scale that takes only a few minutes to administer.

Bellamy independently developed the patient self-administered Australian/Canadian Hand Osteoarthritis Index (AUSCAN) [28], using the hip and knee Western Ontario McMaster Universities (WOMAC) osteoarthritis index as a template. In both these scales, Bellamy divided the instrument into three subsections of pain, stiffness, and function. It is available in both a 5-point Likert and 10 cm VAS format and has

been validated in multiple languages. Each of the items in the AUSCAN has been validated separately.

Several instruments developed for use in other settings, e.g., rheumatoid arthritis, are also used in the evaluation of OA of the hand. Most involve patient-reported outcomes. Examples include the Arthritis Impact Measurement Scales (AIMS1, AIMS2, AIMS-2SF), the European Quality of Life Measure (EuroQol), the Nottingham Health Profile (NHP), and the Short-Form 36 (SF-36) (Table 6.1). These and others are reviewed in the OARSI guidelines for conducting clinical trials in hand OA [24]. All of the above have undergone extensive validation.

Indeed, all of the above instruments measure pain to some extent. However, function loss in hand OA is often more problematic to the patient than pain. Hence, other instruments have been developed, most combining pain and function in the instrument. Below are several examples on how these instruments have been used in helping to understand the limitations of function in hand OA.

The most commonly used performance-based measures for hand OA are the grip strength and pinch test. Despite extensive use, performance-based measures of hand pain and function still do not have adequate validation to be used as primary outcomes in clinical trials.

All clinical trials of hand OA need to include a measure of pain, function, and a patient global question. The patient global question provides information on the patient's overall impression of improvement combined with tolerance (i.e., adverse events). Examples of the way the question may be worded are as follows: "considering all the ways your hand osteoarthritis affects you, how have you been during the last 48 hours" and "in relation to your hand osteoarthritis, how do you feel today."

Studies Comparing Instruments on Impact of Hand OA

A semi-structured patient interview was conducted on 29 mostly women. Subjects reported embarrassment due to the appearance of their hands and their inability to carry out reportedly normal tasks [29]. A few subjects indicated that work status was affected. Subjects utilized cognitive, behavioral, and avoidance forms of coping with the impairments of hand OA. These coping mechanisms are the same as those used in hip and knee OA. The groups felt therapy was inadequate and expressed a lack of understanding by themselves and their examiner of their hand OA.

In an Austrian study of 223 women and 30 men, women worked twice as many hours in housework, had a lower income than men, and were more concerned with aesthetic change [3]. However, there were no differences in gender referable to function and health status by SF-36, Moberg Picking-Up Test, grip strength measurements, the AUSCAN, and the Score for Assessment and Quantification of Chronic Rheumatoid Affections of the Hands (SACRAH) questionnaire.

In one study, using Rasch analysis, the AUSCAN, AIMS-2 hand/finger subscale, and the FIHOA were felt to be improved by minor modifications by removal of specific items [30]. It was felt the AUSCAN subscales should be used as separate constructs, and not combined into a total score. Similar conclusions were reported for the FIHOA and AIMS-2. In one specific item, removal of "pain at rest" from the AUSCAN improved the performance of the AUSCAN pain subscale.

Radiographic changes of nearly 400 men and women included grading 15 individual hand joints by Kellgren Lawrence criteria [31]. Results of the radiographs were matched to grip strength and function, using the DASH score, and grip/pinch strength of the dominant hand. The sums of the Kellgren Lawrence scores as well as the DASH scores for thumbs and middle fingers was inversely associated with grip and pinch strength. There was no association with the 4th and 5th digit.

In a Belgian group of patients, 167/270 (62%) were classified by their criteria as having erosive OA of the hand [32]. Those with erosive OA, in contrast to non-erosive OA, used more analgesics and had a worse functional outcome and higher pain score. Both the FIHOA and AUSCAN function scores showed a trend toward more

disability. Although functional impairment was correlated with women and number of destructive joints, it was not influenced by involvement of the 1st CMC. In comparing the FIHOA and AUSCAN, the AUSCAN function subscale was superior to the FIHOA in association with the number of active joints. The AUSCAN was more sensitive for pain and the FIHOA was better associated with radiographic and structural damage.

In a study of 128 patients with hand OA, the AUSCAN and FIHOA were both reliable and valid [33]. The FIHOA was shorter and had higher test-retest reliability and the AUSCAN had higher construct validity and data quality.

Several questionnaires of hand OA were evaluated referable to the International Classification of Functioning, Disability and Health (ICF) [34]. The most disease-specific, or lowest, diversity was present in the AUSCAN and the SACRAH. The FIHOA and AIMS2-SF had higher linkage to the ICF categories and demonstrated higher diversity.

The AUSCAN was evaluated in the Genetics of Generalized Osteoarthritis (GOGO) study of 531 subjects with hand OA [35]. The global assessment of change scores was significantly associated with the AUSCAN, grip strength, and right-hand pinch strength. This study supports the use of the AUSCAN for the dominant hand and also supports the use of the global assessment of symptom change over time as a longitudinal assessment tool. The same investigators found a high internal consistency in the AUSCAN in a community-based population [36]. The patient global (VAS), pain scale (VAS), and AUSCAN pain subscale were responsive in a clinical trial, whereas the tender joint count, swollen joint count, AUSCAN stiffness, and AUSCAN physical function were less responsive in a clinical trial [37]. Clinical trials for hand OA can also include the OMERACT/OARSI responder criteria [38].

The examiner-administered Doyle Index was evaluated for pain and function in a 260-patient population with OA of hand and knee/hip [39]. The authors felt the Doyle Index to be reliable and easy to perform when compared to the AUSCAN for hand OA.

Aesthetic discomfort, as measured by a VAS, was a major concern for 172 patients with hand OA in a study measuring tender joint and node count, global and pain scores, FIHOA, SF-12, Hospital Anxiety and Depression Scale, and hand radiographs [40]. Aesthetic discomfort was associated with severity of OA, erosive changes, depression, anxiety, decreased hand function, and poor health-related quality of life, more in women than men [41].

Conclusion

Hand OA is common in the general population, equal in men and women, with women more often symptomatic. Symptoms are often related to the physical aesthetics. In addition to the aesthetics, there is often pain and reduced function. We have outlined several techniques for measuring the severity and impact of hand OA that are useful for a cross-sectional evaluation of individuals or groups of patients, These instruments are also useful for longitudinal follow-up of individuals, groups, and clinical trials.

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Hand Function in Scleroderma

7

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Systemic Sclerosis

Systemic sclerosis (SSc) is a connective tissue disease characterized by immunologic abnormalities, microvascular alterations, and excessive collagen production, leading to fibrosis of skin and internal organs (lungs, heart, gastrointestinal tract) [1].

In SSc, the loss of elasticity and the tightness of the skin, followed by the cutaneous thickening and hardening (sclerosis), with concomitant changes in subcutaneous tissues, are the distinctive hallmarks of the disease [2]. It usually begins from the extremities and then, in a centripetal mode, may progressively extend to the trunk, leading to prominent disability. The classification in the 2 main clinical subsets, diffuse cutaneous SSc (dcSSc) and limited cutaneous SSc (lcSSc), is based on the extent of skin involvement [skin sclerosis extending proximal to the elbow, the knees and the neck and potentially involving truncal areas in dcSSc and distal to the above anatomical structures in lcSSc]. The two SSc subsets also differ for the strong association with presence of specific antinuclear autoantibodies [anti-topoisomerase 1 (anti-Topo1 or Scl70) antibodies in dcSSc and anticentromere antibodies in lcSSc] and for organ involvement [3].

Causes of Hand Functional Impairment in Systemic Sclerosis

In SSc, hands and fingers are notable targets of the disease [4]. SSc evolves through three consecutive phases, in which the hands are differently affected.

In the early *edematous phase*, edema of fingers (puffy fingers) and hand prevails (sometimes coexisting with edema at feet and face), often associated with or preceded by Raynaud phenomenon (RP) (Fig. 7.1a, b). In this phase, arthralgia of the fingers is often present. Edema limits the range of movement of metacarpophalangeal (MCP) and proximal interphalangeal (PIP) joints, and arthralgia and RP attacks (that may cause digital ulcers since early phases of the disease) may contribute to pain and impaired manual function [5]. Tendon friction rubs can be present since this phase, in particular in the dcSSc [6].

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In the following *sclerotic phase*, edema turns into sclerosis. The affected skin is thickened, indurated, and bound to the subcutaneous tissue. In the hands, these findings are more frequently observed over the fingers (sclerodactyly). This feature is highly disabling and leads to MCP reduced flexion and, consequently, to reduced extension of PIP and distal interphalangeal (DIP) joints, and to thumb adduction and flexion. These modifications, together with the impairment of flexion/extension of the wrist, result in the typical claw-type deformity of SSc [7, 8]. Digital ulcers at fingertips and on the extensor surface of MCP joints may be present, and can heavily contribute to pain and disability (Fig. 7.1c).

In the further *atrophic phase*, skin thickening is substituted by skin atrophy, and claw-type deformity worsens. Wrist movements are further impaired, with problems also in pronation and supination. Digital ulcers and their complications (such as infection, auto-amputation) may cause pain and contribute to affect hand function (Fig. 7.1d).

In SSc, skin and subcutaneous tissues involvement, microvascular impairment (Raynaud phenomenon and digital ulcers), and musculoskeletal and peripheral nervous system changes may therefore be among the causes of hand disability [9]. These modifications, evolving and differently overlapping during the three phases (edematous, sclerotic, and atrophic) of the disease, lead to hand dysfunction, deformities, and pain, and are responsible for the altered hand function.

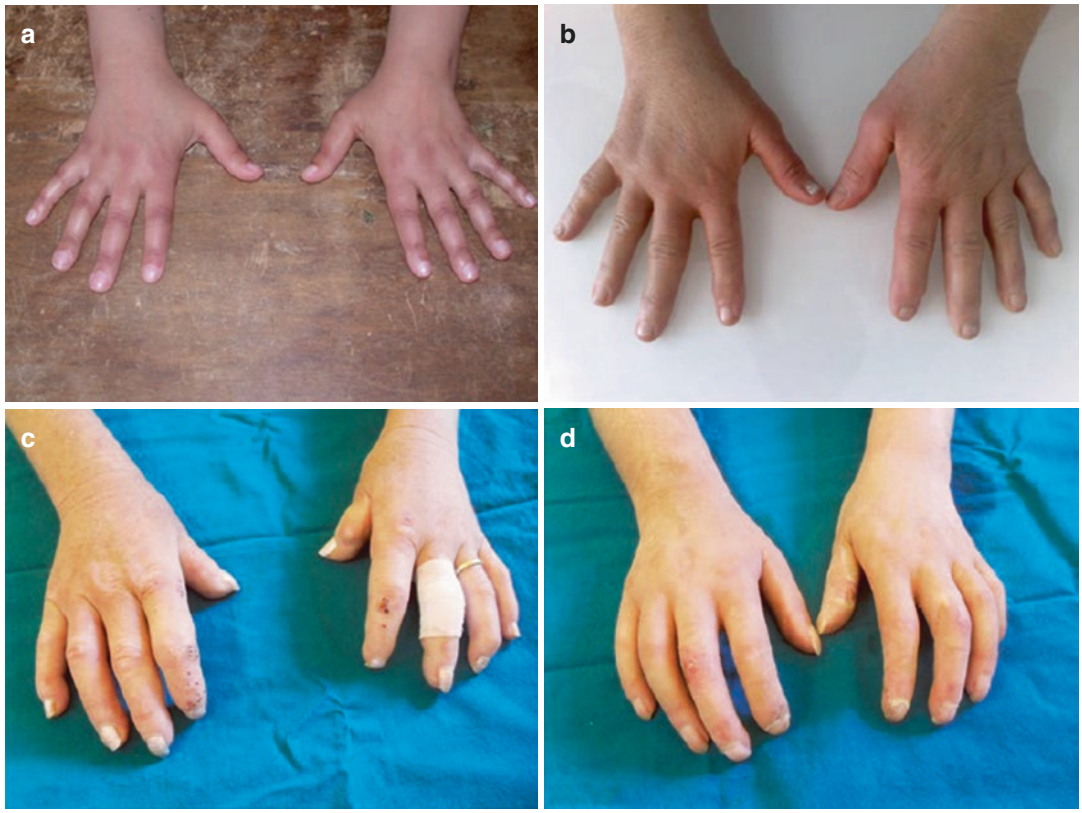


Fig. 7.1 Systemic sclerosis (SSc) hands according to the different phases of the disease (**a**) early edematous phase: puffy fingers and Raynaud phenomenon. (**b**) Edematous phase: edema of the fingers and whole hands. (**c**) Sclerotic phase: sclerosis and induration of the skin on the fingers (sclerodactyly) and on the whole hand leading to flexion contracture and "claw-type deformity" of the fingers. An extensive calcification on the dorsum of the thumb on left hand is present. (**d**) Atrophic phase: atrophy of the skin, worsening of the claw-type deformity of the hands

Skin

SSc is characterized by thickening, hardening, and tightening of the skin, changing throughout the disease course. In the early phase, skin thickness is caused by increased collagen, intercellular matrix formation in the dermis and by edema, due to microvascular injury, changes in lymphatic circulation and inflammation. Since this early phase, the skin becomes thickened and impossible to be pinched into a normal skin fold. In the following sclerotic phase, besides its thickening, the skin also becomes shiny, taut, hard, hidebound, and adherent to the subcutaneous tissues, especially at fingers (sclerodactyly). In the further atrophic phase, the skin becomes thin, atrophic, and tightly tethered to the underlying tissue [10].

The most used and validated method for measuring skin thickness is the *modified Rodnan skin score* (mRSS) [11]. Skin thickness, evaluated by palpation, is rated on a scale of 0 (normal), 1 (weak), 2 (intermediate), or 3 (severe skin thickening) and the total skin score, resulting from the sum of the skin assessments in 17 body areas, ranging from 0 to 51. mRSS areas consider 4 sites at hand level: the fingers and the hands, assessed bilaterally, with a partial score ranging from 0 to 12. Thus, a high mRSS in these sites may account for a high impairment of hand and fingers mobility in SSc patients. This has been recently confirmed by the European Scleroderma Observational Study (ESOS), which enrolled early dcSSc within 3 years from disease onset. In particular, data showed that hand functionality and disability (in particular regarding gripping) were significantly impaired in the study population, being also significantly correlated with the extent of global physical disability [12].

Subcutaneous Tissues

Subcutaneous involvement in SSc is characterized by progressive *thickening of subcutaneous tissue*, (hypoechoic on US and showing low-signal intensity on T1-weighted MRI images). *Resorption of subcutaneous tissue*, usually at fingertips, and calcifications (calcinosis), may also be found.

Subcutaneous calcifications are frequent, especially over the palmar aspect of the fingertips (10–30% of cases) [13], where extrusion of calcific material, constituted by calcium hydroxyapatite deposits, can occur through the skin. They may be minute, extensive, and more or less dense. When extensive and/or present in the upper layers of subcutaneous, calcifications may be detected by palpation of the fingers (Fig. 7.1c). They can also be shown by X-rays and US of the hands [14].

Calcinosis is present in almost one-third of SSc patients, with a higher prevalence in patients with lcSSc (formerly known as CREST syndrome; C = calcinosis, R = Raynaud phenomenon, E = esophageal involvement; S = sclerodactyly; T = telangiectasias) than in patients with dcSSc, it is associated with erosions and it is most often seen in patients with digital ulcers [15]. Calcifications can be observed at various sites, such as periarticular, subcutaneous involving sites of chronic stress, and soft tissues in pressure points (e.g., MCP joints), not only at hands [13]. Recent data support a mixed hypothesis in the pathogenesis of subcutaneous calcification, including both calcium-phosphate metabolism disorders and vasculopathy-induced hypoxia, as demonstrated by the association between advanced stages of microangiopathy at nailfold videocapillaroscopy and presence of calcinosis [16].

Articular and Periarticular Involvement

During SSc course, 46–97%, patients may develop joint and periarticular involvement representing the onset manifestation in 12–65% [17–19]. Hands (especially fingers and wrists), together with ankles, are the sites preferentially involved [20].

The most peculiar hand involvement of SSc is represented by *flexion contractures*, which may evolve painlessly to *"claw-type" deformities*, characteristic of the fibrotic and atrophic phases. In the hands, these changes may be minimal and

only involve one phalanx, or gross and involving several phalanges, including the middle or even proximal phalanges. They are caused by a reduction of vascular supply and by skin thickening with loss of elasticity and of the underlying structures. and/or by the tethering of the skin to subcutaneous tissue (Fig. 7.1c, d).

These determine a severe impairment of all the movements of the hands and of manual function, due to the reduction or impossibility in MCP flexion, in PIP and DIP extension, in thumb adduction and flexion, and in wrist flexion/extension [21]. Thus, flexion contractures may lead to a prominent disability [21], contributing to global disability, by altering quality of life (QoL) [21] and affecting Activity of Daily Living (ADL) [22, 23].

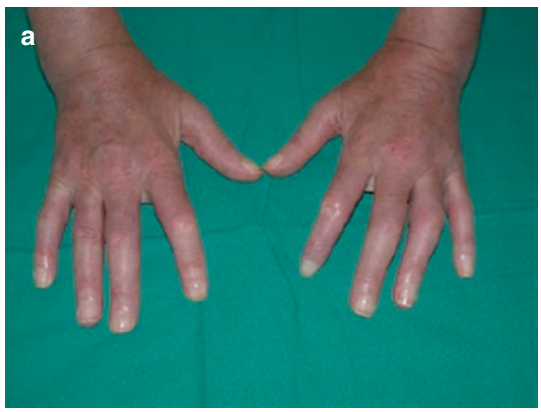
Arthralgia and arthritis can also be present and may cause both pain and disability. Arthralgia, mainly found at hands, is present in the majority of the cases and, sometimes, since the earliest, edematous, phase of the disease [24, 25]. It has been reported that 66% of SSc patients experience arthralgia and 61% have signs of arthritis [20].

Arthritis mostly involves MCP, PIP and wrist joints, and less frequently at the knees or elbows [26]. It may have an olygo-polyarticular pattern, while its course can be acute, subacute, intermittent, or chronic/remitting [20] (Fig. 7.2a). Sometimes, a symmetrical polyarthritis, usually seronegative and nonerosive, may be the presenting manifestation of SSc. In these cases, the clinical features may be similar to rheumatoid arthritis and often be confused with it.

Erosive arthropathy is found in 20–30% of these patients, especially in the wrists, and rheumatoid factor may be positive in 26–50% of the patients [20] (Fig. 7.2b). The co-existence of SSc and rheumatoid arthritis is considered as an overlap syndrome.

Bone Involvement

Bone involvement is frequently characterized by distal phalangeal re-absorption (*acro-osteolysis*), which happens more frequently in the hand than in the foot. Moreover, a general radiological bone demineralization [27] can present, associated with arthritis and systemic inflammation. *Acro-osteolysis* generally begins at the tuft, particularly on the palmar surface of the bone, and, if persisting, leads to the "pencil in cup" deformity or the sharpening of the distal phalanx and, in severe cases, to its partial or total destruction, resulting in reduction of finger length [27] (Fig. 7.2b). Acro-osteolysis is significantly associated with digital ulcers, extra-articular calcification, pulmonary arterial hypertension and microangiopathic damage represented by more advanced nailfold-



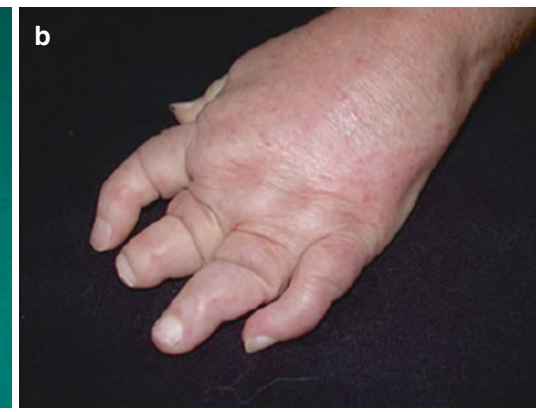


Fig. 7.2 Articular and bone involvement in SSc hands (**a**) a SSc patient with flexion contractures at fingers and inflammatory arthritis at metacarpophalangeal (MCP) joints. (**b**) A SSc patient (positive for RF) with an erosive arthropathy at MCP and proximal interphalangeal joints and acro-osteolysis that lead to destruction of distal phalanxes and reduction of finger length

videocapillaroscopic patterns, highlighting a potential role of vascular injury in its development [16], similarly to *avascular bone necrosis* [28].

Tendon Involvement

Tendon involvement is often present in SSc, in particular in dcSSc, and may affect tendons of wrist, hand, and fingers, contributing to altered range of movements of the hand and to manual disability.

Tendon friction rubs, described by patients as "leathery crepitus," can be assessed by physicians on palpation of the fingers, hands, wrists, elbows, shoulders, knees, and ankles, during active and/or passive motion [29]. They are due to edema, thickening, and fibrosis of tendon sheaths [29]. As tendon friction rubs are highly associated with dcSSc and with decreased survival in SSc, they should be assessed routinely in all the patients, especially in those with recent onset of Raynaud phenomenon and puffy fingers and early SSc [30]. Their finding should lead to a suspicion of SSc and may help to identify patients at risk for severe form of the disease.

The *fibrosis affecting tendons*, in advanced SSc (fibrotic and atrophic phases), might be responsible for a cracking noise during joint movements, and may contribute to flexion contractures of hands and, sometimes, to tendon rupture.

Muscle Involvement

Skeletal muscle involvement occurs in approximately 70–96% of SSc and results in myopathy or, much less frequently, in myositis: proximal muscle weakness is common in dcSSc [31]. An inflammatory myopathy is most prevalent, although overlap with polymyositis, piecemeal infarction due to SSc vasculopathy and fibrous myopathy are also described. Weakness might, sometimes, be an adverse effect of therapy, or due to joint/tendon involvement, disuse and/or sedentary activity.

The involvement of hand muscles has not been specifically assessed in SSc. However, the muscle weakness due to the involvement of the muscles of upper limbs may interfere both with the overall function of upper limbs and with the functionality of hands and wrists. Moreover, in the sclerotic and atrophic phases, characterized, at hands, by flexion contractures and claw-type deformity, the fibrosis and atrophy of skin and subcutaneous, periarticular and articular tissues may encase the muscles of the hand and lead to disuse myopathy, and fibrotic changes may also occur in intrinsic and extrinsic muscles of the hand.

When muscle weakness is present, muscle involvement should be suspected. Thus, serum creatinine phosphokinase, aldolase, and lactate dehydrogenase levels should be assessed, muscle strength evaluated, and electromyography and MRI of the skeletal muscles performed [20].

Vascular Involvement in SSc

The presence of vascular involvement is, together with tissue fibrosis, the more prominent pathogenic and clinical hallmark of SSc and may represent the earliest manifestation of the disease. Vascular injury, supposedly initiated by events involving endothelial cell damage [1], leads to structural changes of vessels and loss of capillaries (demonstrated with nailfold capillaroscopy), not compensated because of defective angiogenesis and vasculogenesis, remodeling of the vessel wall with intimal and median layers undergoing hyperplasia and adventitial fibrosis, causing progressive luminal narrowing and, eventually, occlusion. Perivascular inflammatory infiltrates may have a role in vessel damage. Involvement of microvasculature is widespread in SSc. Vascular changes found at hand may reflect vascular alterations in other organs, contributing to fibrotic processes. Changes in digital arteries of patients with SSc are similar to those shown in the arteries of the lung, kidney, and heart [32].

Microvascular involvement leads to Raynaud phenomenon, local ischemia, and causes frequently digital ulcers and pitting scars of fingertips [33].

Raynaud Phenomenon (RP) occurs in more than 90% of SSc patients (secondary RP). It may

be the presenting feature of SSc or it may accompany other manifestations of the disease. RP manifests in the acral parts of the body and consists in recurrent and episodic color changes of the digits (fingers and/or toes), but also of nose and ears, that turn suddenly white (ischemia), followed by blue (cyanosis) and finally red (reperfusion). Clinically, coldness and numbness of digits characterize the first two phases, while pain and tingling present during the reperfusion phase (Fig. 7.1a).

Digital Ulcers (DU) [34] are a frequent and major clinical problem in SSc, occurring in one-third of the patients/ year and affecting almost half of them [35]. Prevalence studies show DU ranging from 15% to 50% of SSc patients [35]. They may appear early in the disease course [36], the first DU occurring in 43% and in 75% of cases within 1 year and 5 years from first non-Raynaud symptom, respectively, and are present in 42.7% of dcSSc and in 33% of lcSSc patients [37].

DU may develop on the fingers (or toes) and can occur over the extensor surface of the joint, on the finger creases, under the nails, and, in the majority of cases, on the fingertips. DU may also develop from a pre-existing calcinosis and, sometimes, from digital pitting scars [38].

Fingertip DU (Fig. 7.3a, b) are due to the presence of the underlying vasculopathy, to the persistent vasospasm caused by RP and to the intraluminal thrombosis, due to platelet activation [1]. DU over the extensor surface of the joint and on the dorsum of the fingers (Fig. 7.3c, d) are, in the majority of cases, due to epidermal

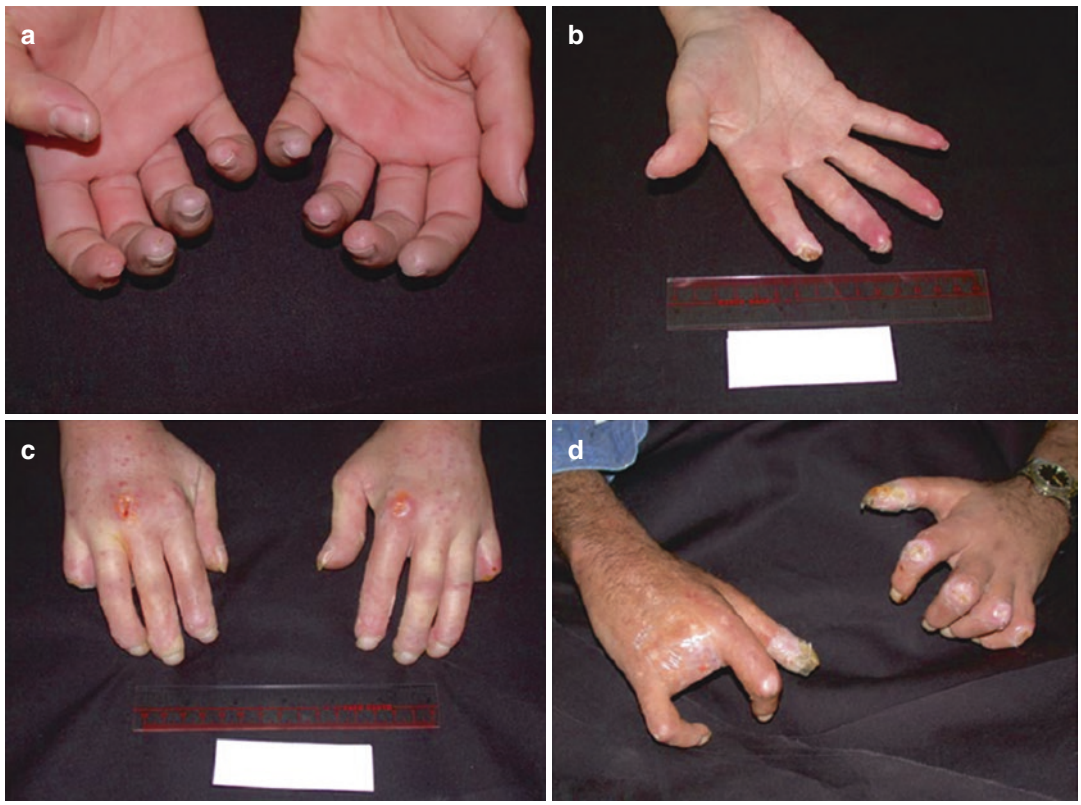


Fig. 7.3 Digital ulcers in SSc hands (**a**) digital fingertip tip ulcers in a patient with SSc; (**b**) ulceration and tissue loss at the second and third fingertips of the right hand in an SSc patient. (**c**) Ulcer on the dorsal aspect of MCP joints, pitting scars, and telangiectasias in an SSc patient with a claw-type deformity of the hands (especially at fifth fingers of both hands). (**d**) Amputation of the third and fourth fingers of right hand, ulcer on fingertips and on the dorsal aspect of MCP joints in an SSc patient

thinning and cutaneous retraction leading to cracks on the skin overlying the joints [39].

DU are persistent, difficult to heal and very painful, may be complicated by tissue loss, lead to autoamputation (Fig. 7.3a–d), and contribute to SSc morbidity. Patients with DU present higher scores in overall [35], and hand disability [40], reduced hand and wrist mobility, and impairment in QoL. In fact, it has been shown that DU had a 19/100 magnitude when represented through a visual analogic scale (VAS) and are a major predictor of disability [41].

Moreover, DU are frequently infected and, if not treated early, may lead to osteomyelitis, gangrene (eventually needing amputation of the finger) (Fig. 7.3d), and septicemia [38].

Peripheral Nervous System

SSc patients may present the involvement of peripheral nervous system. Mononeuritis and mononeuritis multiplex are described, but carpal tunnel syndrome, due to the involvement of median nerve when entering in the carpal tunnel at wrist, is one of the most frequent alterations [42], caused by compression at the wrist by edematous and fibrotic tissues and by microvascular involvement. As SSc median nerve involvement may be disabling for hands, potentially causing pain, paresthesia, and functional manual impairment, its early detection is important to prevent hand disability [43]. Electromyography often discloses significant reduction of distal median nerve sensory and motor conduction rate in SSc also in asymptomatic patients [44]. The involvement of median nerve in asymptomatic SSc patients has also been shown by US of the carpal tunnel, as an increasing of median nerve area.

Hand Functional Impairment in Different Phases of Systemic Sclerosis

The overlapping and the severe changes of the hands in skin and subcutaneous tissues, microvessels, periarticular and articular structures, and nerves, evolving throughout the course of the disease, lead to impairment of hand functionality in SSc. Disability at the hands also interferes on global disability and QoL [22]. In particular, it is one of the main factors influencing activities of daily living (ADL) [23], work ability, and employment [24].

In the *edematous phase*, hand perceived disability in SSc patients is mainly due to the difficulties and to the reduced ability in performing hand movements, due to tissue edema. The patient may experience some difficulty in completely closing and opening the fingers and in performing ADL and Instrumental Activity of Daily Living (IADL) [45].

In the *sclerotic phase* of SSc, hand disability mainly derives from the thickening of skin and periarticular tissues, reducing the range of motion of the fingers, hand, and wrist. The severe functional limitations in the flexion and in the extension of the wrist interfere on the prehension of the hand, due to the altered relation between prehension (executed by the hand) and orientation (due to wrist).

The flexion contractures at fingers 2–4 (with the extension of MCP and the flexion of PIP) alter the hand pinch abilities and prehension. In particular, the frequent involvement of the first ray severely impairs the execution of termino-terminal and latero-terminal pinches. Hand disability due to the described changes results in difficulties in making a fist, in completely extending fingers 2–5, and in a reduction of hand strength, severely impairing the execution of ADL, IADL, and work ability. Hand pain in this phase may be due, sometimes, to articular and periarticular concerns, if arthralgia or arthritis coexists, but it is mainly caused by DU, often present.

In the *atrophic phase*, the moderate flexion of the wrist (having also difficulties in pronation and supination), added to the worsening of finger flexion contractures (with MCP extension, PIP and DIP thumb adduction and flexion), leads to the more severe SSc claw-type deformity, in which the hand, due to the loss of the orientation and the prehension, loses almost completely its function.

Studies about the range of symptoms experienced by patients with SSc, and their impact on daily functioning, are limited. Patients with SSc report a number of concerns associated with disability and reduced QoL, including gastrointestinal problems, difficult breathing, pain from various sources, depression, fatigue, and pruritus [46]. An 18-item disease-related stressors questionnaire showed that functional limitations, skin deformities, and disfigurement, together with fatigue and pain, are among the most annoying symptoms [47].

Revised Illness Perception Questionnaire demonstrates that stiff joints, pain, and fatigue are the symptoms most commonly associated with SSc [48]. The five highest rated symptoms in terms of frequency and moderate-to-severe impact on daily activities are fatigue, RP, hand stiffness, joint pain, and difficulty sleeping. Moreover, items related to decreased hand function, such as difficulty making a fist and holding objects and pain intended as muscle pain and joint tenderness, are frequently reported.

These findings confirm the importance of SSc core symptoms, including hand-related issues such as RP and limitations in manual ability in affecting *QoL* and *daily functioning* [49].

In SSc women evaluated for ADL, hand function, perceived symptoms, skin thickness, and finger flexion and extension are the most impaired aspects of hand mobility, while dexterity and grip force are reduced. RP is referred as the predominant self-perceived problem, and activities based on hand and arm function are felt as harder to perform than activities depending on lower limb function. RP, stiffness, grip force, and dexterity are the factors with the strongest associations with ADL difficulties [50].

A longitudinal survey on early SSc patients shows that ADL capacity correlates significantly with grip force, self-assessed hand function, and RP at baseline, and also with hand mobility (assessed with Hand Mobility in Scleroderma -HAMIS- Scale) at follow-up [23].

Recent investigations show that hand function is related to *working ability* in SSc. In lcSSc women, 50% have a reduced working ability: the lower the working ability, the lower their perceived well-being. Greater working ability was associated with better ADL capacity, occupational performance within more occupational areas, and greater satisfaction with occupations [49].

SSc patients were assessed to identify factors influencing work ability and to evaluate the association between work ability (assessed by the Work Ability Index -WAI-) and employment status, ADL, (evaluated by the UK scleroderma functional score-UKFS-), and QoL. 13/48 patients had good or excellent WAI, 15 had less good, and 20 had poor WAI. The correlation between employment status and WAI was good and patients with good WAI perceived milder symptoms (pain, fatigue, and impaired hand function). These patients had better competence and better possibility of adaptations at work and impact at work than those with poorer WAI [24].

DU have a substantial impact on daily living and professional activities. Global disability (by Health assessment Questionnaire-HAQ-), hand disability (by Cochin hand function scale-CHFS-) and anxiety were significantly higher in patients with DU (60/189 patients) than in others. Most patients reported a limitation in daily activities related to SSc and an increased need for help at home. Patients with DU reported more need of paid household help in comparison to patients without (DU) [50].

Correlations Between Hand Functional Disturbances and Other Clinical Parameters

Hand disturbances may be due to different causes, some of which are related to or predictors of clinical parameters.

Flexion contracture of the fingers is associated to Scl70 positivity, dcSSc, arthralgias. As the prevalence of esophageal involvement, pulmonary fibrosis, or heart involvement is significantly greater in the patients with flexion contractures [14, 18], they might be regarded as markers of internal organ involvement.

Flexion contractures significantly correlate to the radiological fibrotic pattern (digital flexion, space narrowing, particularly of the DIP joints, with or without subchondral sclerosis), the severity of peripheral vascular impairment, and the skin involvement [51].

Moreover, flexion contractures are associated with dcSSc and high HAQ scores, reflecting a prominent disability. This is consistent with the tendency to fibrosis and functional impairment of the diffuse. On its part, dcSSc subset is a predictor of the progression of flexion contracture [52].

Tendon friction rubs are associated to severe skin thickening, joint contractures, and cardiac and renal involvement [30] and highly predictive for scleroderma renal crisis. They may often precede widespread skin thickening and their modifications predict changes in mRSS and HAQ over 6 and 12 months [53]. Thus, they are both associated to and predictors of a severe disease.

A strong relationship between skeletal *myopathy* and myocardial disease in SSc has been described [54, 55]. Patients with dcSSc frequently develop skeletal myopathy, those with pulmonary fibrosis being at a significantly higher risk [54].

DU predict the progression of acro-osteolysis and calcinosis, suggesting how these features, already found as associated with DU [56], may have a vascular background. DU are also regarded as predictors of internal organ involvement. In fact, patients with DU develop internal organ involvement 2–3 years earlier than patients without DU [36].

On the other hand, male sex, pulmonary hypertension and/or lower DLCO, dcSSc, early onset of SSc, presence of Scl70, smoking are regarded as risk factors for developing DU [56, 57]. The combination of male gender, early RP onset, erythrocyte sedimentation rate (ESR) >30 mm, Scl-70 positivity, and gastrointestinal and pulmonary arterial involvement showed the highest probability of developing DU (88%) [58].

Other correlations between disability of the hands, as assessed by different instruments, and clinical parameters are described in the following paragraph.

Evaluation of Hand Function

As manual function impairment has a role in determining global disability and QoL [22], ADL [23], work ability, and employment [24], it should be assessed and followed up in all SSc patients.

Throughout the years, several tools were used to evaluate disability in SSc patients. The questionnaires addressing global disability, functional district, and organ impairment due to SSc also take into account the self-perceived impairment at upper limbs. However, in SSc tools specifically assessing upper limb and manual disability were also used. These include tools not adapted for SSc, instruments adapted to SSc and tools specifically designed for SSc. Moreover, hand involvement was assessed by anthropometric measures.

Questionnaires Assessing SSc Global Disability

The disease index (DI) of HAQ (*HAQ-DI*), the most widely questionnaire used to assess and follow-up disability in patients with rheumatic diseases, is used in the assessment of disability in SSc since 1991 [59]. It consists in a self-report questionnaire, organized in 20 items divided into 8 categories: dressing and grooming, arising, eating, walking, personal hygiene, reaching, gripping, and other activities. Therefore, it includes questions assessing not only hands, but both upper and lower limbs.

Each item is rated from 0 (no difficulty) to 3 (unable to do). A score for each category is the mean score from all questions in the category. The DI is calculated by adding the scores from each category and dividing by the number of categories answered and rated from 0 (less disabled) to 3 (more disabled). HAQ-DI also contains a VAS used to report the pain experienced in the previous week.

In order to measure specific SSc symptoms, HAQ-DI was supplemented with 5 VAS by which the patient self-assesses how RP, DU, gastrointestinal symptoms, pulmonary symptoms, and

overall disease severity interfere with daily activities (*S-HAQ*) [53].

Both HAQ and S-HAQ showed sensibility, reliability, validity, and responsiveness in clinical trials [60]. S-HAQ, although not specifically addressed to score hand function, assesses also the impact of RP and DU; thus, it should be preferred to HAQ in clinical practice to evaluate the self-perceived global disability and the microvascular hand symptoms in SSc patients.

Systemic sclerosis questionnaire (SySQ) is a self-administered instrument specifically conceived to cover SSc functional limitation and symptoms. It comprises 32 items grouped into 12 scales addressing general symptoms (pain, stiffness, coldness), musculoskeletal (complex functions, strength of hands, rising, walking), cardiopulmonary (shortness of breath, upper airway symptoms), and upper gastrointestinal symptoms (eating, swallowing, heartburn/regurgitation). All the items are scored from 0 to 3 and 7/11 items assessing musculoskeletal symptoms are derived from HAQ [61]. Although SySQ appears as a valid and reliable condition-specific measure in patients with SSc, able to cover a wide spectrum of general and organ-specific SSc symptoms and functional limitation, its use in daily practice and in controlled clinical trials is limited.

Scleroderma Assessment Questionnaire (SAQ) consists of 23 questions divided into 4 groups related to symptoms of vascular, respiratory, gastrointestinal, and musculoskeletal dysfunction. Answers are assessed on a 0–3 scale, and Index of Vascular Status (IVS), Index of Respiratory Status (IRS), Index of Gastrointestinal Status (IGS), Index of Musculoskeletal Status (IMMS), and Index of Disease Status (IDS) are calculated. The scores of the single indexes are higher in patients with specific district or organ impairment. IVS score is significantly higher in patients with DU or acrosteolysis or severe capillary damage. IMSS score strongly correlates with the mRSS and is significantly higher in patients with reduced hand motility, joint contractures, muscle weakness, or arthralgia/arthritis [62]. The scores of SAQ indexes are sensitive in detecting changes of symptoms over time in a 12-month follow-up [63]. For its ability in detecting self-reported symptoms and for its sensitivity in following-up disease changes, SAQ appears as a promising tool for SSc evaluation, although, till now, it has been used only by one research group.

Symptom Burden Index (SBI), a specific tool assessing in SSc the effect of problems in eight major symptomatic areas of importance for the patients (skin, hand mobility, calcinosis, shortness of breath, eating, bowel, sleep, and pain), has been recently developed. Each problem area is measured independently by five items, each scored 0–10. The three most widely reported problem areas are pain, hand, and skin, experienced by the majority of the patients. SBI has good psychometric properties, but it should evaluated more extensively in order to understand its feasibility [64].

Questionnaires Assessing Hand Disability Not Adapted to SSc

The *Duruöz Hand Index (DHI)* is a self-report questionnaire that contains 18 items assessing hand ability in the kitchen, in dressing, in performing personal hygiene and office tasks, and in other general skills. Each question is rated from 0 (no difficulty) to 5 (impossible to do), with a total score ranging from 0 to 90. DHI, taking about 3 min to be completed, is reliable and valid in RA [65] and OA [66].

Reliability and validity of the DHI [22] has been shown in patients with SSc, and its construct validity has been demonstrated in patients concurrently administered with S-HAQ and SF36. The total score of DHI explained 75% of the variance of the HAQ [67].

The questionnaire is able in evaluating the differences between the patients presenting or not hand involvement (arthralgias, arthritis, flexion contractures, and DU) and shows a strong correlation with HAQ scores [68].

More recently, the impact of DU on SSc disability and HRQoL was assessed by SF-36, HAQ, DHI, and global hand and wrist mobility. One-third of the patients had at least one DU at the time of evaluation. Patients with DU presented

higher scores in HAQ, DHI, reduced hand and wrist mobility, and impairment in the mental component of SF36 [40].

Despite its non-SSc specificity, DHI could be useful in the clinical setting of scleroderma, as it is easy to understand for the patients and to be scored and particularly suitable at identifying patients with hand musculoskeletal and microvascular impairment.

The Arthritis Hand Function Test (AHFT) is a performance-based test, which examines hand's ability during daily life tasks through 11 items, including grip and pinch strength, dexterity, applied dexterity, and applied strength. The AHFT, although not specifically validated for SSc, was shown to be reliable and valid to be used in patients with SSc [69].

The Disabilities of the Arm, Shoulder, and Hand (DASH) questionnaire is a self-report 30-items tool, designed to assess the upper limb physical function and symptoms. It is also available in an 11-questions "Quick DASH" version. The strong correlations of the DASH and Quick DASH with the HAQ-DI and with the scale assessing physical dimensions of the SF-36 show that the disability of SSc patients is particularly dependent on the upper limb's functional impairment [70].

Questionnaires Assessing Hand Disability Adapted to SSc

The ABILHAND questionnaire, developed using the Rasch model [71], offers the advantage of selecting and hierarchizing manual activities that patients with different diseases find difficult to put into practice. Thus, SSc patients were administered with the original version of the questionnaire, including 81 manual daily activities, and asked about their perceived difficulty in performing each manual activity on a three-level scale: impossible, difficult, or easy. The 26 selected items defined a reliable, valid, reproducible, linear, and unidimensional measure to assess and follow up the manual ability of patients with SSc. The manual ability was significantly poorer in SSc patients with more severe disease, and negatively correlated with the HAQ score. Thus, the ABILHAND questionnaire could be regarded as a useful promising tool to follow up hand impairment and to assess treatment efficacy [72].

Questionnaires Assessing Hand Disability Specific for SSc

The UK scleroderma functional score (UKFS) is a self-administered 11-item functional questionnaire assessing daily activities within self-care and household chores, specifically built for SSc patients. Nine questions relate to upper limb function and two to muscle weakness and lower extremity function. It can be either self-administered or administered by an observer trained in functional assessment. Each item is scored from 0 (able to perform in a normal manner) to 3 (impossible to perform) and all items are summed, yielding a possible maximum score of 33 points [73].

In a study comparing UKFS to HAQ-DI and scleroderma-VAS of S-HAQ, 68% of dcSSc patients have moderate-to-severe disease on the UKFS, compared with 44% with lcSSc. UKFS and HAQ-DI are significantly related, and both higher in dcSSc than in lcSSc. The scleroderma-VAS correlate with the UKFS and HAQ-DI only in the scales examining overall disease severity, respiratory symptoms, and pain. Several clinical and laboratory measures are associated with higher HAQ-DI and UKFS [74].

In a longitudinal study, the UKFS is able to capture clinically significant changes in SSc-related disability over time. The concurrent validity of the UKFS is asserted through its strong correlation with the HAQ-DI [75].

Thus, the concomitant use of UFKS and HAQ-DI in the daily practice may be useful in assessing and follow-up functional and global limitation in SSc patients. As both questionnaires can be self-administered, they could be included in the routine assessment of patients with SSc attending the outpatient clinic.

The Hand Mobility in Scleroderma (HAMIS) test is a performance-based test, specifically created for SSc, found to be as a reliable and

valid to assess hand function [76, 77]. It is composed of nine items, assessing finger flexion and extension, thumb abduction, wrist dorsal extension and volar flexion, forearm pronation and supination, and ability to make a thumb pincer grip and to make finger abduction. The different performance areas of HAMIS are composed of different-sized grips and different movements, all related to tools and movements that are part of daily occupations. Each exercise is graded on a 0–3 scale (with 0: normal function and 3: inability to perform the task), with a maximum score of 27 for each hand.

HAMIS scores show significant correlation to DHI, finger to palm (FTP) distance and hand opening of homolateral hand, and HAQ. HAMIS scores are higher in dcSSc and are capable of identifying patients with hand arthritis and flexion contractures with respect to those not presenting these features (due to their respectively higher and lower scores) [78].

Recently, the association between three tools used to quantify hand impairment (hand anatomic index-HAI-, FTP and HAMIS) and organ involvement has been evaluated in SSc patients. By a cluster analysis, on the basis of organ involvement, cluster A and cluster B, with minor and major extent of organ involvement, respectively, were identified. The extent of organ involvement and the hand impairment were related, and the scores of hand indices were lower in cluster B. Thus, the severity of hand impairment is associated with the extent of organ involvement [79].

An important characteristic of a clinimetric scale is its sensitivity to change and the ability to monitor the modifications over time of the assessed items. Evidences from the literature confirm that HAMIS test is able in following up disease evolution and treatments [78]. In fact, in a longitudinal study evaluating hand involvement and ADL in early SSc patients over time, HAMIS was the most sensitive tool in assessing changes in hand mobility**.** Moreover, a work of our group showed that a 9-week rehabilitation protocol, treating hands of SSc patients with connective tissue massage, Mc Mennell joint manipulation and home exercises, was able to improve HAMIS scores, as well as FTP and DHI [80].

Anthropometric Measures of the Hands

The finger-to-palm (FTP) distance, also called fist closure, is the distance from the tip of the third finger to the distal palmar crease, measured in maximal active flexion. It assesses (by a ruler, usually in cm) the distance between the tip of the pulp on the third finger and the distal palmar crease while the patient attempts to make a full fist (maximal finger flexion at MCP, PIP, and DIP). Although recommended as a secondary outcome measure for clinical trials in SSc, the FTP has been validated in only one study [81]. To date, the FTP has been shown to be only a fair outcome measure [82].

The finger extension, defined as the distance between the third fingertip and the distal palmar crease while the patient attempts full finger extension, is seldom assessed in studies evaluating the mobility of hand in patients with SSc. In two recent works of our group evaluating the efficacy of rehabilitation programs tailored for patients with SSc, fist closure, but not finger extension was improved at the end of rehabilitation periods [22, 81].

Recently, *the delta FTP*, as a new measure of finger range of movement (ROM), was proposed to determine the range of motions of the fingers in SSc. The delta FTP combines both finger joint flexion and extension and is calculated as the difference of the distance measured between the third fingertip and the distal palmar crease with fingers in full extension minus the distance with fingers in full flexion (FTP). Although the FTP provides a summation of flexion of all three finger joints (MCP, PIP, DIP), it does not represent full finger motion because limitations in finger extension are not considered. The delta FTP may help especially in assessing SSc patients with fingertips fixed in palmar flexion without the ability to extend, having a severe hand dysfunction, but, paradoxically, showing a "falsely normal" traditional FTP measurement [83]. The delta FTP is a valid and reliable measure of finger motion in patients with SSc, which outperforms the FTP [84].

The hand anatomic index (HAI) is a quantitative measure of hand deformity, defined as the difference between the measure of open hand span and closed hand span, divided by the lateral height of hand. When evaluated in SSc patients, HAI was confirmed as a reliable measure, able to distinguish patients with increasing hand deformity and to separate patients with dcSSc and lcSSc. The HAI significantly correlated to HAQ, hand strength, and hand grip and accounted for 25% of the total HAQ global disability. Thus, it reliably and objectively measures the degree of hand deformity and functional impairment in SSc patients [84].

Conclusions

In SSc patients, the function of hands is altered since the first phases of the disease, due to the changes of skin and articular and periarticular structures and to the involvement of microvasculature and peripheral nervous system, differently overlapping. For its high prevalence and its impact on daily chores, general disability, QoL, and working abilities, hand function should be taken into account, ruled out, and scored in all SSc patients by clinical examination, imaging methods, and questionnaires.

Hand function could be partially preserved and improved by medical therapies that may act on microvessels (both systemic drugs and local medications) [58] and by drugs acting on inflammatory articular involvement and arthralgia (ranging from NSAIDs to novel biological therapies) [85].

However, rehabilitation may prevent and reduce the involvement of skin and periarticular tissues in the hand that leads to puffy fingers in the edematous phase and to finger contractures and claw-type deformities in the sclerotic and atrophic phases. SSc patients' rehabilitation should be global and tailored on disease phases and on patient's own necessities [86].

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8 Functional Assessment in Hand with Flexor and Extensor Tendon Injuries

Banu Kuran

Hand function is the ability to use the hand in daily activities. These daily activities are accomplished by various kinds of grips like cylindrical and spherical – platforms which require enough hand volume plus space and also various kinds of precision grips which require dexterity together with power. The interaction between bones, joints, nerves, muscles, and tendons of the hand is essential for prehension. Tendon lacerations adversely affect normal hand functions by disrupting the synergy between extension and flexion of the hand.

As the hand muscles contract, they shorten and exert force on the joints and bones by producing tension on the tendons. The tendons must glide proximally to transmit the tension and must glide distally to let the muscle stretch or elongate. Hand function is the result of the harmony between muscle contraction and relaxation in an otherwise normally innervated, painless hand with an integrated bony architecture.

After tendon repair, the immature scar tissue attaches to the tendon and moves with it during hand motion. The immobilized tendon loses the gliding function due to peritendinous adhesions starting from the first 10 days after repair. Several contributing factors have to be considered in the formation of adhesions around the flexor tendons that travel within the fibro-osseous digital sheath. Tendon sheath injury, tendon suture, edema, and postoperative immobilization are unavoidable consequences of the injury and the repair process.

For optimum function, the bond between the tendon and the scar tissue should be broken by applying force through various exercises. The outcome of tendon gliding is experimentally described as tendon excursion and clinically described as joint range of motion. Tendon excursion is mainly limited by adhesions within the digital fibro-osseous sheaths and extensor retinaculum.

The repaired tendon also loses tensile strength in the first 2 weeks after repair. While 50% of the repair strength decreases in the first postoperative week, 20% is lost at the end of the sixth week. The decrease in the tensile strength causes tendon gapping if an uncontrolled stress is applied during mobilization of the tendon. Tendon gapping more than 2 mm causes friction which prevents gliding and rupture [1].

Evaluation of Function in Flexor Tendon Injuries

Superficial and profundus flexor tendons originate from the muscles in the proximal one-third of the forearm. In the carpal tunnel and in the digits and thumb, they are surrounded by a synovial sheath. Flexor pollicis longus has its own sheath called the radial bursa. The synovial sheath which

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surrounds the flexor tendons in the carpal tunnel continues to the small finger and forms the ulnar bursa. The index, middle, and ring fingers have their own digital synovial sheaths.

The fibro-osseous tunnel extends from the metacarpal heads to the distal phalanx. The flexor retinaculum is thickened and oriented transversely to form five annular pulleys. Between them, there are three cruciform ligaments. Their function is to hold the tendons close to the bone. The superficial and profundus tendons enter together into the fibro-osseous tunnel with superficialis lying volar to the profundus. At the proximal phalanx level, the superficial flexor is divided into two slips, allowing the profundus to travel in between. The two slips join dorsally in a chiasm (Camper's chiasm) at the level of the proximal interphalangeal joint.

Normal tendon function requires free gliding of the tendon without hindrance from surrounding tissues. The tendon must also be strong enough to withstand the normal forces without rupture or gap formation due to unnecessary elongation. Following a flexor tendon injury, active and passive ranges of joint motion are evaluated to assess smooth gliding. If active joint flexion is less than the passive joint flexion, the tendon may not be strong enough to flex the joint or it may have been elongated. If distal joint flexion is possible when the proximal joints are held in extension and impossible when the proximal joints are in flexion, then limitation in the excursion of the tendon may be the problem.

Description and Functional Significance of Flexor Tendon Injuries (Fig. 8.1)

Zone I

Zone I extends from the terminal portion of the FDS insertion on the middle phalanx to the tip of the finger where FDP is inserted. It contains only one flexor tendon, FDP, which is the flexor of the DIP joint. A4, C3, and A5 pulleys are found in zone I. A4 pulley is the most functionally significant pulley in this zone. Its function is to provide a moment arm for the FDP and prevent bowstringing of the tendon. It may also contribute to DIP flexion contracture if resected. FDP is the dominant flexor of the digits in composite flexion of all fingers. While FDS is more important in powergrip and is essential for finger flexion when the wrist is flexed, loss of distal joint flexion of the index or long finger compromises pinch activities that necessitate precision. The loss or limitation of distal joint flexion may adversely affect people like musicians and tailors who have to work meticulously. On the ulnar side, FDS tendon of the fifth finger may congenitally be absent. In this case, the role of FDP in flexion of the little finger is much more appreciated. If lacerated FDP tendon is not repaired, it may retract proximally and block FDS function. In this case, the PIP joint may not flex beyond 90 °. The retracted FDP tendon may also pull proximally and increase the tension on the lumbrical muscle from which it originates. In this case, lumbrical muscle contraction increases, and upon finger flexion, PIP joint extends, causing "lumbrical plus" deformity [1].

The functional outcome following tendon injury is determined by active IF joint flexion and calculated by the formula [2] as follows:

$$\text{PIP} + \text{DIP flexion} - \text{extensor lag} \times 100 = \%\ \text{normal PIP} + \text{DIP flexion} \div 175^{\circ}$$

The results are expressed as excellent (>150 ° or 85–100% of normal motion), good (125–149 ° or 70–84%), fair (90–124 ° or 50–69%), and poor (<90 ° or less than 50% of normal motion).

Undesired results after FDP repair in zone I injuries are limited excursion of FDP tendon, repair site gapping, unsatisfactory distal joint flexion, PIP flexion contracture, and incomplete FDS glide. In case of limited FDP excursion, distal interphalangeal joint may actively be flexed if

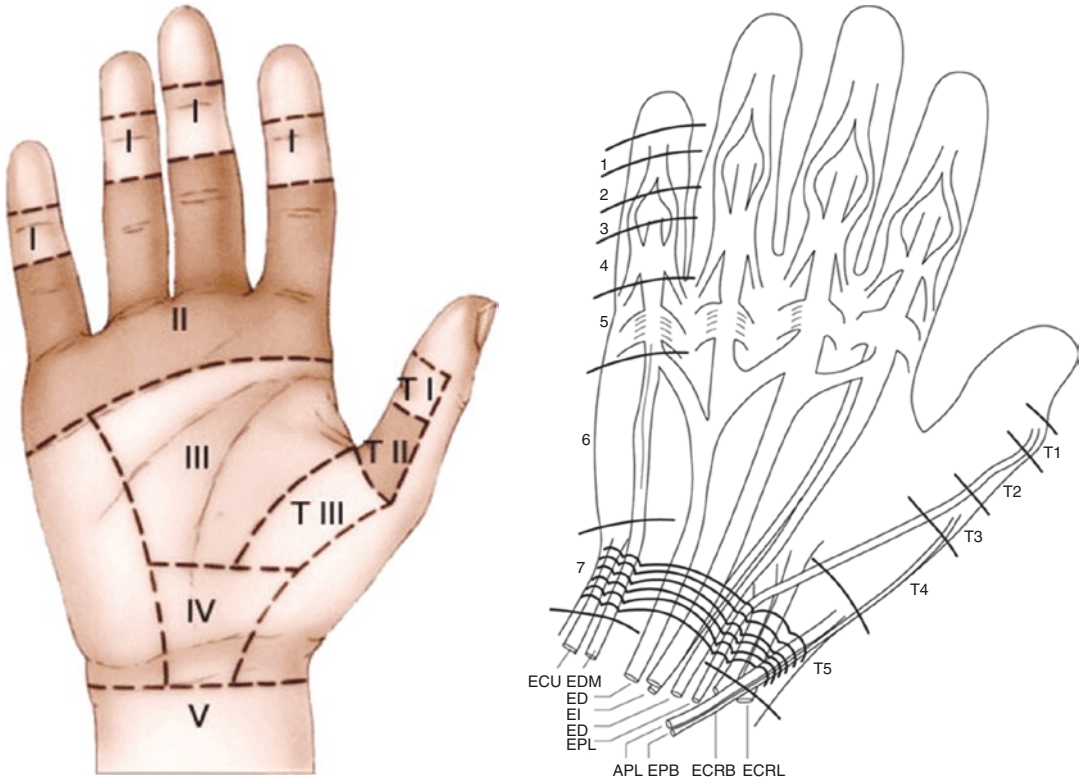

Fig. 8.1 Flexor tendons are divided into five zones according to the International Federation of Societies for Surgery of the Hand (IFSSH). Zone I is from the insertion of FDS to the insertion of FDS at the base of the distal phalanx. Zone II begins proximally from the digital synovial sheaths and extends to zone I at the middle phalanx. Zone III begins proximally from the flexor retinaculum at distal carpal row. Zone IV is known as the carpal tunnel that overlies the flexor retinaculum. Zone V is the distal third of the forearm. The thumb, which has FPL as the flexor tendon, is also evaluated by the corresponding zones.

While the major advantage of early active mobilization protocols is to provide controlled active mobilization of the repaired tendon, it necessitates maximum cooperation of the patient and the rehabilitation team. The patient must understand that the optimum result depends on both home-based and also supervised exercises repeated daily for a few times. He should also be cautioned against the risk of tendon rupture during the first weeks of the repair. Strengthening exercises and splinting to prevent contractures are implemented after the eighth week

PIP joint is held in extension. If PIP joint is left free, the excursion of FDP may not be enough to flex all IP joints, and joint motion is limited. If the DIP joint extends freely when the wrist and MP joints are flexed but begins to flex when the wrist is extended while MP joint is still in flexion, this means that FDP is tight or tethered by the surrounding tissues. In case of an adherent FDP tendon, the tendon can neither actively glide during fisting nor passively glide in passive composite hand extension.

In order to prevent tightness, the profundus tendon should not be advanced more than 1 cm during surgery.

Distal joint motion is essential to maintain differential glide between FDP and FDS. If FDS cannot glide freely and PIP joint is not allowed to move 90 ° between full extension and flexion by early mobilization, flexion contracture at the PIP joint may develop. PIP joint is also more prone to flexion contracture than DIP joint because of the presence of a volar plate which is

tightly attached to the bone. The volar plate is less distinct in DIP joint.

Without differential gliding between the flexor tendons, combined IP joint function is not satisfactory. It has been shown that at least 35 ° of DIP motion is necessary to provide 3–4 mm differential gliding of the FDP on the FDS and to prevent adhesion formation [3]. Among other fist positions, hook-fist position provides the greatest differential excursion between the two tendons. Meanwhile, one should also be aware that MP joints should be placed at 30 ° of flexion to reduce the pull of lumbrical muscles on the profundus tendon.

Following FDP repair, flexion contracture of the DIP joint may lead to swan neck deformity with hyperextension of the PIP joint. Flexion contracture of the DIP joint puts the extensor mechanism under great tension. The lateral bands of the extensors apparatus move dorsally and exert an extension effect on the PIP joint rather than on the DIP joint. Lumbrical and interosseous muscles are also extensors of the PIP joint. Normally, the volar plate and the flexor superficial tendon act to balance the extension forces. As the DIP joint contracture increases, superficial flexors, with the help of the tight lateral bands, overcome the strength of the central slip that extends the middle phalanx, especially in case of a slack volar plate [4].

Zone II

Zone II is the region between the beginning of the separate digital synovial sheath and insertion of FDS tendon. The fibro-osseous tunnel that overlies the synovial sheath of the tendons includes the annular pulleys A1, A2, and A3 and cruciate pulleys C1 and C2. These pulleys guide tendon gliding by keeping the tendon close to the phalangeal bone.

Following flexor tendon injury in zone II, the main problems are restricted PIP joint flexion due to insufficient tendon gliding, gap formation between the repaired ends of the tendon, flexion contracture of the PIP joint, or lumbrical plus position upon attempted flexion. To provide the most optimal result, both superficial and profundus tendons are advised to be repaired. This zone requires that the surgeon knows the flexor tendon anatomy, is aware of the suture techniques that provide a strong repair, and tries very hard to preserve all pulleys of the flexor retinacular sheath.

One of the methods to measure the degree of adherence is to measure the lag of the tendon. The lag is defined as a percentage (%) difference between PROM and AROM. If there is a minimum 15% difference between PROM and AROM, this difference is defined as the lag [5].

Zone III

The synovial sheath of FPL and that of the flexors of the fifth finger continue, respectively, as the radial and ulnar bursae. Injuries in this zone have favorable outcomes since this zone is out of the digital fibro-osseous sheath, but adhesions to adjacent tendons, lumbricals, and interossei are expected. One of the most common injuries that may accompany tendon injuries are digital nerve lacerations.

Zone IV

This is the carpal tunnel zone where the tendons travel in close vicinity to the flexor retinaculum. The flexor retinaculum protects the superficial and profundus flexor tendons as well as the median and ulnar nerves, the ulnar artery, and the superficial palmar arch. Since this region is protected by bony tuberances and the carpal ligament, injury is less often encountered. Yet, intertendinous adhesions between the flexor retinaculum and tendon sheath that limit differential glide are quite often and may compromise individual digit function. Bowstringing due to the insufficiency of transverse carpal ligament on attempted wrist flexion may also be a problem.

In case of tendon laceration if surgery is not undertaken primarily, muscles may retract proximally which may hinder end-to-end anastomosis of tendon ends.

Zone V

Zone V is the region proximal to the transverse carpal ligament. In this region, FPL and FDP form the deep muscle layer on the volar surface of the forearm. The profundus tendon is divided into two bundles as the radial bundle that goes to the index finger and the ulnar bundle that goes to the last three digits. Profundus tendons move as a unit. There are adhesions between the tendon and paratenon, overlying the skin and fascia.

Extensor Tendons

Since grasping an object has been considered more important than dropping it and is due to the very delicate balance between the superficial and profundus flexor muscles which causes serious problems peri- and postoperatively, flexor tendons have gained more attention than extensors. Injuries of the extensor tendon are usually underestimated although opening the hand is necessary during manipulative activities. Among impaired grip ability, various joint deformities may develop following extensor tendon injuries. When flexor tendons which are more powerful than extensors work unopposed in the absence or weakness of extensors, flexion contracture of the finger joints is inevitable.

Extensor tendons are relatively thin and have broad structures. They have a large surface area and travel very close to the skin. These factors make them easily vulnerable and prone to restricting scar formation.

If finger extension is restricted due to adhesions, active extension lag may occur. Active extensor lag is defined as a loss of full active extension of a digit when passive extension of the finger exceeds the active motion.

Extrinsic extensor tendons of the hand originate from the lateral epicondyle. At the wrist level, extensor tendons are covered by a fibrous sheath called the extensor retinaculum and travel in six separate compartments formed by septa from the superficial layer of the extensor retinaculum. By these vertical separations, the extensor tendons are positioned and maintained in accordance with the axis of wrist motion [6]. The tendons that travel in the six compartments are as follows (Fig. 8.2):

- Compartment 1: Abductor pollicis longus (APL) and extensor pollicis brevis (EPB)
- Compartment 2: Extensor carpi radialis brevis and extensor carpi radialis longus (ECRB and ECRL)
- Compartment 3: Extensor pollicis longus (EPL)
- Compartment 4: Extensor digitorum communis (EDC) and extensor indicis proprius (EIP)
- Compartment 5: Extensor digiti quinti proprius (EDQP)
- Compartment 6: Extensor carpi ulnaris (ECU)

A deep layer forms the floor of the fourth and fifth compartments. On the ulnar side, superficial and deep layers are not attached to each other to allow free rotation of ulna during pronation and supination.

The skin and fascia over the dorsum of the hand are loose in extension and tighten during finger flexion. As they tighten, they compress the underlying veins and lymphatics and serve as pump for an efficient venous and lymphatic drainage. At the metacarpal level, they are very close to the skin and hence very vulnerable to any kind of blunt or sharp trauma including human bite. Extension of the MCP joints is accomplished by extensor digitorum communis and due to the fibrous connecting bands within the common extensor muscle belly, and independent extension of the index, middle, and little

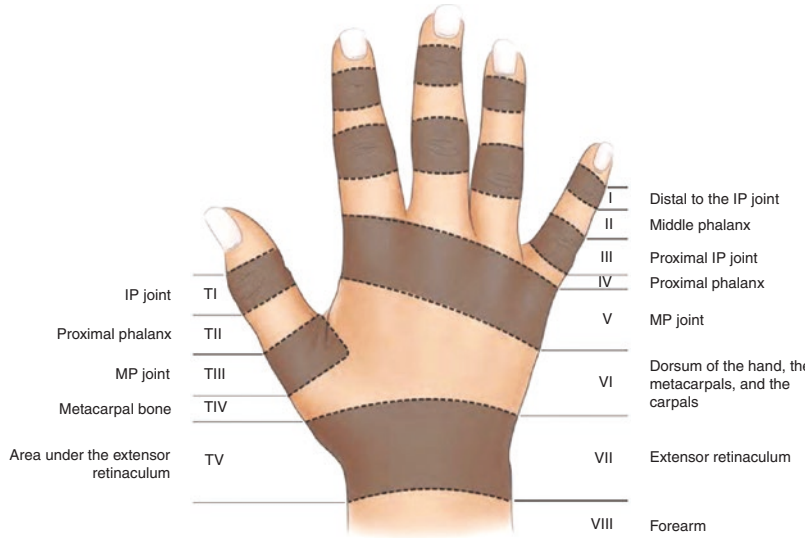

Fig. 8.2 Extensor tendons are divided into eight zones. Zones with odd numbers (1, 3, 5, 7) cover joints; zones with even numbers cover the tubular bones
Zone I: DIP joint
Zone II: Middle phalanx
Zone III: Proximal interphalangeal joint
Zone IV: Proximal phalanx
Zone V: MCP joint
Zone VI: Metacarpal bones
Zone VII: Extensor retinaculum
Zone VIII–IX: Forearm level, musculotendinous junction, and muscle bellies

fingers is lacking. On the other hand, the index and little finger are also supplied by separate muscle bellies that extend these fingers irrespective of the flexed position of the other fingers [7]. At the metacarpal head level, extensor tendons are connected with each other via juncturae tendinea which keeps the tendons together as they glide distally upon flexion of the MCP joints. Juncturae tendinum which emerges from the ring finger extensor tendon helps in extension of middle, ring, and little fingers by transmitting the extension force. At the MCP joint level, horizontal sagittal bands attach to the ulnar and radial side of the joint to stabilize and centralize the tendon. As the MCP joint flexes beyond 60 °, extensor tendons displace ulnarward. It is the sagittal band that prevents further displacement to the ulnar side of the hand.

At the base of the proximal phalanx, the intrinsic muscles (lumbricals and interosseous) join the common extensor tendon. While the medial interosseous slip assists in flexion of the MCP joint, the lateral slip unites with the lumbrical on the radial side and contributes to PIP joint extension as well as MCP joint flexion.

PIP joint extension is accomplished by the extrinsic extensor tendon as well as the contribution of lumbricals and interosseous muscles. On the proximal phalanx, the extensor tendon is divided into three bands, two lateral bands and one central band. The central band attaches to the proximal and dorsal part of the middle phalanx. The right and left lateral bands that coalesce with the lateral slips from the intrinsic muscles are inserted to the base of the distal phalanx as a single terminal tendon. The triangular ligament connects the converging lateral bands and prevents them from luxating volarly. The transverse retinacular ligaments

are located on the palmar side of the lateral bands and prevent them from luxating dorsally.

According to the anatomic and physiologic characteristics, extrinsic extensor tendons are divided into seven zones by the Committee on Tendon Injuries for the International Federation of the Society for Surgery of the Hand [8].

Description and Functional Significance of Extensor Tendon Injuries

Zone I–II

Zone I is the area over the DIP joint and zone II is the area over the distal phalanx distal to the PIP joint. When an injury at the level of DIP joint disrupts the terminal extensor tendon, extensor forces concentrate on the PIP joint, and FDP pull on the DIP joint remains unopposed. The resulting deformity is flexion in the DIP joint, called Mallet deformity and hyperextension at the PIP joint. Transposition of dorsal lateral bands and the yield of the palmar volar plate at the PIP joint further increase the deformity. The lesion may be purely related to the tendon, or an avulsion fracture of the distal interphalangeal joint may be associated. In closed injuries, if loss of active extension may be corrected passively, the lesion is purely a tendon lesion and treated conservatively within 6 weeks of uninterrupted splinting. In case of an articular fracture that involves >50% of the joint surface, reapproximation of the distal and proximal fragments may be performed by a K-wire. Open injuries that include the laceration of the terminal tendon are also treated by pinning [9].

Flexion deformity of the DIP joint is associated with some complications like extension lag, scarring of the terminal tendon, restriction of the DIP joint flexion due to tendon scarring, ischemia of the dorsal skin apparent upon passive hyperextension of the DIP joint, maceration of the dorsal skin during the immobilization period in the splint, thinning of the overlying skin, and nail bed and pulp problems.

Zone III and IV

Zone III is over the middle phalanx and zone IV is over the PIP joint. Interruption of the extensor tendon at the PIP joint may result from traumatic, mechanic, and inflammatory causes.

The primary extensor of the PIP joint is the central tendon. Lateral bands of the extrinsic extensor tendon assist in extension by displacing dorsally. Intrinsic tendons also contribute to PIP extension while flexing the MCP joint. The multiple points of connection between the intrinsic and extensor mechanism at zone IV prevent tendon shortening due to repair. During mobilization, less force is required to flex the PIP joint.

Following injury to the central tendon, the terminal extension (last 15–20 °) of the PIP joint is lost. Besides central tendon disruption, edema following injury also contributes to the flexion of the PIP joint. The PIP joint is more comfortable in the flexed position. The skin over the dorsum of the PIP joint is distended in cases of increased edema formation. While the dorsal skin requires 12 mm of lengthening for 90 ° of flexion, it requires 19 mm of lengthening for the same joint range in the presence of 5 mm edema. The collection of fluid may thus cause an increased demand on the central tendon by adding extra tension, decrease the strength of the repair, and also cause lagging of the repaired extensor tendon.

To test the integrity of the central tendon, wrist and MCP joints are kept in flexion, and the patient is asked to extend the PIP joint actively. Failure to fully extend the PIP joint is a sign of central tendon injury. If the central tendon is interrupted, the extensor tension slides proximally, leaving the flexor superficialis tendon pull unopposed. This unopposed tension in the superficial flexor tendon displaces the lateral tendons palmarly and increases the flexion in the PIP joint. The deformity where the PIP joint is in flexion and DIP joint is in hyperextension is called the boutonniere (button-hole) deformity. If the triangular ligament which keeps the lateral bands

together on the dorsal surface of the phalanx is also torn, palmar displacement of the lateral bands is inevitable, and this movement further accentuates the PIP joint flexion. The joint moves upward through the defect in the extensor apparatus as a button that passes through the hole. If the PIP joint can be extended passively and passive DIP flexion is possible when the PIP joint is in extension, this means that lateral bands may be positioned dorsally. In this case, nonsurgical treatment can proceed.

In case of a fixed deformity where volarly displaced lateral bands are tight and have coalescence with the joint capsule and collateral ligaments, the PIP joint cannot be passively extended. The DIP joint hyperextends in response to contracture of the oblique retinacular ligament. Established fixed deformities are difficult to treat.

As the flexion deformity at the PIP joint increases, the degree of functional impairment also increases. A flexion deformity of more than 30 ° is associated with significant loss of DIP joint flexion. At least 6 weeks of continuous splinting of the PIP joint in neutral position while the DIP joint is allowed to flex actively should be considered initially.

Zone V

Zone V is the area over the MCP joint. There is a direct relation between the extensor tendon excursion on the dorsal side and the motion of the MCP joint. Extensor tendons which have an excursion of 2 mm with PIP joint motion have an excursion of 12–15 mm for an average of 90 ° of MCP joint motion in this zone. The extensor strength generated by the extensor tendons over the proximal phalanx is 2.99 kg for the index finger and decreases ulnarly to 1.97 kg for the small finger. These forces depend on the position of the wrist and while increasing in wrist extension, extensor forces on the proximal phalanx decrease with wrist flexion. During mobilization of the joint after tendon surgery, 300 g of force is required to extend the MCP and PIP joints by 30 °. During the rehabilitation period, the extensor tendon should be mobilized with enough tension that will not form gapping and also should displace 10–15 mm without being limited by adhesions for a functional ROM.

Zone V is one of the most frequently injured sites on the dorsal hand where bony structures and soft tissues may extensively get injured. Injuries like “fight bite” are common and prone to contamination by mouth flora and hence infection besides tendon laceration.

Nonfight injuries due to blunt traumas or MCP joint synovitis in arthritic diseases like rheumatoid arthritis may disrupt the sagittal band and cause ulnarward luxation of the extensor tendon during flexion. Upon active extension, the MCP joint angulates to the ulnar side and is associated with finger supination. Injuries at this level are classified into three types:

Type I involves contusion without a tear, Type II involves subluxation of the extensor tendon within the borders of the bone, and Type III involves displacement of the tendon between the metacarpal heads. It becomes difficult for the patient to achieve full extension, and progressively tightness develops in the extensor tendons and surrounding structures that accentuates ulnar deviation deformity [10].

Zone VI

In this zone, extensor tendons travel over the metacarpals. They have a large surface area and are connected by the bands called juncturae tendinum which transmit extensor forces. Both of these structures and the confinement of the dorsal fascia are the reasons of severe adhesion formation at zone VI. The peritendinous scar tissue that forms after the injury is inelastic and restricts the excursion of the extensor apparatus. If the scar is fixed to the dorsal fascia, interphalangeal joints extend passively as the metacarpophalangeal joints come into flexion. Flexion of the PIP joints extends the MCP joints passively. MCP and PIP joints cannot be flexed simultaneously. This tenodesis is called the extensor plus phenomenon.

Another factor that may cause limited excursion is the suture that brings the lacerated tendon ends together. The average repair

in zone VI shortens the tendon almost 7 mm, and this acquired shortness is another factor that necessitates early mobilization during rehabilitation. While approximately 600 g of force is required for maximum finger flexion, increased tension may cause tendon elongation and gapping.

Zone VII

Injuries at zone VII are at the level of the wrist and involve the extensor retinaculum. The extensor retinaculum covers the fibro-osseous tunnels which contain the extensor tendons. Wrist motion is very important for the extensor tendon glide. Thirty-one millimeter of the extensor tendon glide which has a total displacement of 50 mm is provided by wrist flexion and extension. The same ratio is true for the thumb extensors as well. The extensor pollicis longus tendon, which has a total excursion of 58 mm, displaces 35 mm with wrist motion.

The close relationship between the extensor tendons and the retinacular system causes skin adherence and restraining scar formation that block tendon glide. If the adhesion is proximal to the extensor retinaculum, simultaneous wrist and finger flexion is limited. Wrist flexion invokes a tenodesis effect and fingers extend prematurely. If the adhesion is distal to the extensor retinaculum, simultaneous wrist and finger extension is limited. In order to extend the wrist, fingers must flex first.

Impairment of Hand Function Due to Tendon Injuries

Impairment is defined as the deviation from normal in a body part and its functioning. In the upper extremity, tendon injuries may diminish the capacity of an individual to carry out daily activities [11]. Hand flexor and extensor tendons may be injured by trauma, by inflammation as in rheumatoid arthritis, or by constricting tenosynovitis. Traumatic injuries may be crushing, sharp, or dull. Crushing or blunt injuries usually harm the surrounding tissues and also the vascular supply of the tendons which may impair the healing of the tendon. Formation of adhesions is also more common after crushing injuries. Sharp injuries may result in more isolated tendon lacerations. Additional injuries like bone fractures, pulley, sheath, and neurovascular bundle lacerations, complete cuts rather than partial lacerations, and involvement of more than one tendon (including superficial and profundus tendons) are factors that negatively affect the healing and prognosis of tendon function.

Tendon injuries may affect the anatomic, cosmetic, and functional status of the hand. Hand has a posture that is related to the transverse arches formed by carpal and metacarpal bones and to the longitudinal arches that are formed by the digital rays. Among the skeletal system, the status of the tendinous system is very important in the preservation of the normal hand posture. The hand, with the thumb ray on one end and the ring and little finger rays on the other end, must open widely on the stable index and middle finger rays to grasp large objects. The longitudinal arch that has been formed by the phalanges and metacarpal bones is especially necessary for pinch and precision activities. Muscles, tendons, and other soft tissues are supporters of this bony construction and prevent it from collapsing. They also provide flexibility of the hand. Tendon laceration, rupture, inflammation, or any other kind of disorder that prevents proper tendon functioning may distort wrist and finger joint motion and adversely affect the strength and dexterity of the hand.

Joint inflammation, the pathognomic feature of inflammatory diseases like rheumatoid arthritis, may result in extensor tendon subluxation that causes ulnar deviation and intrinsic muscle tightness. Tendon ruptures that are the consequences of bony attritions developed by synovitis are also commonly observed in rheumatoid hands. Pain which is usually associated with inflammatory or stenosing tenosynovitis is another contributing factor for diminished hand function.

Impairment may be measured by joint range of motion, grip, and pinch strengths.

Disability After Tendon Injuries

Tendon injuries may result in certain disability. Disability means that the individual's capacity to meet his personal, social, or occupational demands has decreased, and he has inability to perform some tasks. The patient may also be handicapped which means he has inability to participate in normal roles. A tendon injury impairs the physiological functioning of the affected musculotendinous unit in the hand. Injuries may be complicated and usually are not isolated only to the tendon. Preoperative evaluation which includes the nature and location of the tendon laceration and the presence of additional injuries is important with respect to both surgical reconstruction and recovery of function after the repair. The severity of the injury is assessed preoperatively and classified according to Boyes' method [12].

Preoperative Evaluation (Boyes)

Grade	Preoperative condition
I	Good, minimal scar and mobile joints
II	Notable scar tissue formation, mild contracture
III	Joint damage with decreased passive/active range of motion
IV	Nerve damage
V	Multiple system injury (combination of II, III, and IV)

According to ICF, body function and body structure that have been affected in tendon injuries are range of motion, strength, and tendon integrity. Activity and participation of the individual are measured by his capacity and performance. While outcome measures of capacity are dexterity and functional tests, activities and self-reported actual roles are the outcome measures of performance. Besides the severity of the injury, age-related changes, psychosocial factors like symptom magnification, and painful conditions like complex regional pain syndrome or arthritis may adversely affect objective evaluation. Due to these limitations, evaluation of hand function in an injured patient should frequently be repeated and filtered by the objectivity of the examiner.

Examination of Range of Motion

Motion is the primary physical impairment resulting from a tendon injury. The arc of motion of finger joints is defined by two numbers that represent the extremes of extension (the numerator) and flexion (the denominator). By using a 180-degree finger goniometer for the fingers and 360-degree universal goniometer for the wrist, 14 finger joints and the wrist joint should be measured and assigned a numerator and a denominator. Ulnar and radial deviation of the wrist and metacarpophalangeal joints may also be recorded. Range of motion measurements of the finger joints are taken by placing the goniometer laterally on the midaxis of the adjacent phalanges. If swelling and/or finger deformity is not apparent, the goniometer may also be placed on the dorsum of the finger joint. Both active motion done by the patient and also passive motion done by the examiner should be recorded to estimate tendon lag, gapping, or lack of patient compliance. While active flexion and hyperextension are positive, extension deficits are represented by a minus sign. The recordings are compared with the normal values of the uninjured hand and expressed as the percentage of the normal value [13].

A number of rating systems are available which have been mostly developed for studies on flexor tendons. Some commonly used measurement systems are listed below (Table 8.1) [14]. These systems can be applied to both flexor and extensor tendon injuries since they assess both flexion motion and extension deficits. Total active motion (TAM) is usually measured while the hand is in the composite grip position. If the involved joints form the major component of the score, for example, in zones III, IV, and V, it is logical to include active motion of all three finger joints (MCP, PIP, DIP) and then combine them

Table 8.1 Methods for assessment of flexor tendon outcome in the fingers [13]

Fingers				
The Louisville method	Grade 1	Grade 2	Grade 3	Grade 4
Pulp to distal palmar crease	0–1 cm	1.1–1.5 cm	1.5–3 cm	3 cm+
Extension deficit	0–15 °	16–30 °	31–50 °	50 °+
Excellent: both deficits grade 1		*Good: both deficits at grade 2*	*Fair: both deficits at grade 3*	*Poor: either deficit worse than grade 3*
Total active motion (TAM) method ASSH	TAM = (MCP + PIP + DIP)			
	Active flexion (MCP + PIP + DIP) − extension deficits (MCP + PIP + DIP)			
	Expressed as percentage of the normal contralateral finger (for which TAM = 260 (80 + 110 + 70)			
Excellent: 100%		*Good: >75%*	*Fair: >50%*	*Poor: <50%*
Zone II				
Strickland I and II	TAM = (PIP + DIP)			
	Active flexion (PIP + DIP) − extension deficits (PIP + DIP)			
	Expressed as percentage of the hypothetical normal finger (for which TAM = 175			
I. Original Excellent: 85–100% or > 150°		*Good: 70–84% or 125–149°*	*Fair: 50–69% or 90–124°*	*Poor: <50% or <90°*
II. Adjusted 75–100% or > 132°		*50–74% or 88–131*	*25–49% or 45–87°*	*<25% or <44°*
Buck-Gramcko	Fingernail to distal palmar crease	0.0–0.5 cm	6 points	
		0.6–1.5 cm	5 points	
		1.6–2.5 cm	4 points	
		2.6–4.0 cm	3 points	
		4.1–6 cm	2 points	
		>6.0 cm	0 points	
	Total extension lag	0–30°	3 points	
		31–50°	2 points	
		51–70°	1 point	
		>70°	0 points	
	Modified TAM	>400°	8 points	
	(MCP + 2·PIP + 3·DIP)	>320°	6 points	
		>280°	4 points	
		>240°	2 points	
		<240°	0 points	
Excellent: 16–17 points	*Very good: 14–15 points*	*Good: 11–13 points*	*Fair: 7–10 points*	*Poor: 0–6 points*
Zone II				
Moieman-Eliot	TAM = (DIP)			
	Active flexion (DIP) − extension deficits (DIP)			
	Expressed as percentage of the hypothetical normal finger for which TAM = 74			
Excellent: 85–100% or >62°		*Good: 70–84% or 52–62°*	*Fair: 50–69% or 37–51°*	*Poor: <50% or <37°*

to have the TAM. For zone II injuries, the MCP joint is not affected and the focus is on the PIP and distal interphalangeal (DIP) joints. In zone I or thumb injuries, the focus is only on the distal joint. The outcomes after surgery and rehabilitation may be reported as the percentage of normal.

Another method to measure finger motion is Boyes' linear measurement from the fingertip to the distal palmar crease. Swanson has further calculated combined angular impairment and correlated it with linear measurement of Boyes. Finger flexion degree is measured for each joint, and combined impairment is calculated by the formula A% + B% (100% − A%) where A represents the MCP joint and B represents the PIP joint. The sum is A for next calculation where B is the DIP joint. The correlation between angular impairment and linear measurement is such that 2 cm lack of flexion from fingertip to palmar crease corresponds to 30% impairment and 4 cm corresponds to 53% impairment.

Excursion of flexor pollicis longus tendon is evaluated according to different criteria (Tables 8.2, 8.3, and 8.4).

Table 8.2 Evaluation of recovery of the FPL according to the criteria of Buck-Gramcko et al. [15]

	Degrees	Points
Flexion of IP joint		
	50–90	6
	30–49	4
	10–29	2
	<10	0
Extension deficit		
	0–10	3
	11–20	2
	21–30	1
	>30	0
Total active movement >40		6
	30–39	4
	20–29	2
	<20	0
Evaluation		
Excellent	14–15	
Good	11–13	
Fair	7–10ç.	
Poor	0–6	

Table 8.3 Evaluation of the recovery of the FPL according to the criteria of Tubiana et al. [16]

Degrees assessment	
Flexion of IP joint	>60 F1
	>30 F2
	<30 F3
Extension deficit	<15 E1
	<30 E2
	>30 E3
Evaluation	
Excellent	F1E1
Good	F2E1
Fair	F3E1 or F2E2
Poor	F3E2 or E3

Table 8.4 Evaluation of FPL recovery according to Fitoussi [17]

Degrees		Points
Flexion of IP joint non-injured side – flexion of IP joint of involved side	0–20	6
	21–40	4
	41–50	2
	>50	0
Extension deficit (comparison with contralateral side)	0–10	3
	11–20	2
	21–30	1
	>30	0
Evaluation		
Excellent	8–9	
Good	6–7	
Fair	4–5	
Poor	0–3	

Evaluation of Strength

Strength is related to the cross-sectional area of the muscle fibers and distance through which it can be used. This distance is called the excursion of the muscle. The strength also depends on the number of joints it crosses and how far the tendon is from the joint axis. Grip strength reflects the global impact of the injury, including the tendon, nerve, vessel, and bone. It is assessed according to a standard method recommended by the American Society of Hand Therapists. Grip strength is usually measured by Jamar dynamometer which is a sensitive and repeatable test instrument. The

elbow should be at 90 ° flexion and the forearm in neutral, and the fingers should be placed in the second handle position. Similarly, Haldex orthotic gauge can be used to measure the strength of the individual finger. In order to eliminate subjectivity, the patient is asked to maximally contract his hand muscles three times with a few seconds of interval between each trial. The injured hand may be compared with the opposite uninjured hand, or the difference between the initial and follow-up values may be compared [18].

Assessment of Disability and Patient Satisfaction

Disability after extensor tendon injuries depends on the complexity and severity of the injury, involvement of the dominant hand, complications due to the injury or surgery, compliance with rehabilitation program, and requirements of daily living or occupation.

In hand rehabilitation, patient-centered care and patient satisfaction related with the disability are as important as other test instruments that measure the physical properties of the hand. It is an essential part of the outcome evaluation. Some of the most commonly used generic and specific evaluation tools that may be used to measure upper extremity dysfunction are *Medical Outcomes Study (MOS) 36-Item Health Survey (SF-36)*, *the Upper Extremities Disabilities of Arm*, *Shoulder and Hand (DASH)*, *Patient Evaluation Measure (PEM)*, *Michigan Hand Outcomes Questionnaire*, and *Duruöz Hand Index (DHI).*

Short-Form 36 (SF-36) which is a part of MOS measures general health status. It is composed of 36 questions related to everyday life [19]. *DASH* consists of 30 items that are rated from 1 to 5. It is designed to measure the level of disability experienced by a patient and record differences in symptoms and functional ability [20]. *QuickDASH* is the short version of the DASH and includes 11 items. It is used for most of the upper extremity pathologies including ulnar-sided wrist problems and distal radius fractures. Social and emotional health are also evaluated extensively by DASH.

PEM consists of three sections on treatment and overall assessment. Scoring is done by using a visual analogue format and expressed as a percentage of the maximum score possible [21].

Michigan Hand Questionnaire is a hand-specific outcome questionnaire that includes six categories inquiring hand function, daily living activities, pain, work, aesthetics, and patient satisfaction with his hand. The questionnaire includes 72 questions and evaluates the dominant and the non-dominant hand separately [22].

Duruöz Hand Index (DHI) has been validated for traumatic hand on patients with combined flexor tendon and nerve injuries [23].

Assessment of Performance

Jebsen-Taylor Hand Function Test is a seven-part test. By using common items such as paper clips, cans, and pencils, seven activities (writing, card turning, picking up small objects, simulated feeding, stacking, picking up large light cans and picking up large heavy objects) are tested. It is a unilateral test that measures the dominant and non-dominant hand separately. It does not take into consideration the pattern of prehension [24]. *Box and Block Test* is a manual dexterity test that requires moving 1-inch blocks from one box to another in 60 seconds. It is simple and inexpensive and assesses eye-hand coordination as well [21].

Sollerman Hand Function Test measures hand and grip function during daily activities. In 20 activities of daily living (ADL), the ability of the patient to perform 7 of the 8 most common handgrips defined by Sollerman in 1978 is evaluated. These common handgrips are volar, transverse volar, spherical volar, and pinch positions like pulp, lateral, tripod, and the five fingers. Certain ADLs are using a key, picking up coins from a flat surface, writing with a pen, using a phone, and pouring water from a jug [25].

Crawford Small Parts Dexterity Test measures the success and efficiency in jobs demanding manual dexterity and precision. Different from the other assessment methods, it introduces tools into the test protocol. Tweezers are used to insert small

pins into close-fitting holes, and screwdrivers are used to place small screws into threaded holes. The test should be reevaluated with respect to psychometric properties because reference values are changed [26].

Minnesota Rate of Manipulation Tests, *Purdue Pegboard Test*, *Functional Dexterity Test*, *Grooved Pegboard*, and *Nine-Hole Peg Test* are other hand coordination and dexterity testing instruments.

Evaluation of Flexor Tendon Rehabilitation Restrictions

During the first 6 weeks of rehabilitation after flexor tendon surgery, patients are asked to wear orthosis and protect the healing tendon. It has been reported that 59% of the patients were unable to function with one hand while protecting the injured one. One end of the challenge is to obey the restrictions and wear the orthosis both at work and at home, while the other end is to remove the orthosis and experience tendon ruptures. A standardized questionnaire including 39 questions has been constructed by Washington University, St. Louis Rehabilitation Institute [27]. Participants were also asked if they received any recommendations during hand therapy about personal factors (emotional adjustment and pain), activity performance (leisure, household, care of others, rest/sleep), and environmental interventions (technology, equipment, help from others). Participants reported that their therapists educated them not to use the involved hand, to wear the orthosis at all times, and to avoid specific bimanual activities [28]. This scope of view addresses the comfort of the patient with the orthosis and supports future modifications and use of adaptive equipment.

Evaluation of Hand Function by High Technology

Computerized hand evaluation systems are used to implement exercise program that increases range of motion, dexterity, and/or strength. Some of the common systems that are being used are STE Greenleaf EVAL_, the BTE (Baltimore Therapeutic Equipment) and E-Link (Biometrics Ltd.) and DEXTER hand evaluation tool [29]. Besides range of motion, they can also measure angular velocity, acceleration of each joint, grip and pinch strength, edema, sensation, and motor deficits due to nerve injuries.

For motion analysis, CODA CX1 3D motion analysis system (Codamotion, Charnwood Dynamics Ltd., Leicestershire, UK) and the VICON motion system (Vicon Motion Systems and Peak Performance Inc.) are used. Qualisys motion capture systems (Qualisys AB, Sweden) which have been first used for gait analysis have been expanded to evaluate upper extremity function. The CODA motion system has showed good correlation with goniometry system. The E-link is an evaluation and also an exercise system. On the other hand, Eye Toy is a virtual reality system that lacks data collection system but provides exercise facilities. The Hand Tutor is a biofeedback system. It consists of an ergonomic glove that records wrist and finger motion and also provides feedback about the speed and quality of the motion. It is useful in the follow-up of both orthopedic and neurological problems. As a new application, these advanced systems have both advantages and disadvantages. Although technology is the language of the future, its use should be balanced with traditional treatment and hand therapists' skills.

Hand Therapy Outcomes and ICF (International Classification of Functioning)

Patient-reported outcomes (PROs) allow a more comprehensive assessment of the patients who have difficulties in performing daily activities. PROs may be specific to a region or a disease. ICF, on the other hand, aims to describe a person's health by focusing on his/her ability to function and his/her relation with the environment. ICF is composed mainly of two parts. Part 1 includes physiological functions, anatomical structures, activities, and participation in a life situation.

Part 2 is composed of environmental factors in which people live. Personal factors, described as the patient's attitude, mental status, coping skills, and life style, are also important for ICF [30].

In order to describe the disability and functions of the patient, the PROs that correspond to the ICF categories are considered to better assess the complexity and burden of hand traumas. It has been found that outcomes about flexor tendon rehabilitation generally refer to the physical impairment. In order to determine which PRO is more representative of the ICF concept, the following scales have been reviewed: DHI, Duruöz Hand Index; DASH, Disabilities of Arm, Shoulder and Hand; PRW(H)E, Patient-Rated Wrist (Hand) Evaluation; MHQ, Michigan Hand Questionnaire; PRTEE, Patient-Rated Tennis Elbow Evaluation; BCTQ, Boston Carpal Tunnel Questionnaire; FIHOA, Functional Index for Hand Osteoarthritis; DFI, Dreiser Functional Index; AUSCAN, Australian Canadian Osteoarthritis Hand Index; and MAM, Manual Ability Measure. Among 11 PROs, activity and participation items have been found to be commonly included which were followed by body functions. Environmental factors were not represented in any of the listed outcome scales. Hence, in order to be in accordance with the ICF model, more than one measurement tool should be used, and also new and more comprehensive assessment tools should be developed.

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Hand Function in Stroke

9

Osman Hakan Gündüz and Canan Şanal Toprak

Introduction

Stroke is a common health problem worldwide and is the most common cause of upper extremity motor impairments among adults [1, 2]. While more than two-thirds of stroke patients have initially impaired arm function, only one-third of stroke patients regain arm function 6 months after stroke, and complete recovery occurs in only 5–10% of stroke patients [3, 4].

Upon completion of rehabilitation, 41–45% of stroke patients remain permanently disabled [5], and deficits are especially prevalent in the hand. Recently, hand function was reported to be one of the domains that showed the highest perceived impact 6 years after stroke [6]. Disabilities of the hand due to motor impairments, spasticity, and contractures cause difficulties in performing activities of daily living (ADL) [7]. Up-to-date rehabilitative approaches have only limited effectiveness in the improvement of upper extremity function, which emphasizes the need for effective treatment regimens. Also, it has been shown that the lower extremity recovers faster and more completely than the upper extremity [8]. Accordingly, new studies should focus on developing hand therapy techniques to provide greater hand functions.

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Impairments in the Upper Extremity

It is essential to understand the underlying mechanisms causing hand and arm impairments in order to develop an effective treatment protocol. In hemiparetic upper extremity, the primary impairments seen in the motor system are muscle weakness, spasticity, and reduced capacity to control the joints independently due to abnormal stereotypical movement patterns [9]. The affected upper extremity muscle tone is initially flaccid. Spasticity develops gradually in an abnormal synergy pattern, which results from damage to the descending motor pathways. The most prevalent movement pattern is flexion synergy, which is characterized by an abnormal co-activation of shoulder abduction and elbow, wrist, and finger flexion [10]. Due to this synergy pattern, many individuals find it difficult to open the hand and grasp an object when required to lift the paretic arm at the same time. This synergy also has a negative impact on forward reaching ability, which requires shoulder flexion and elbow extension [9–12]. Grasp and forward reaching have an important role in ensuring that ADL can be completed independently, and reduced capacity of these movements can lead patients to learn nonuse of the paretic upper extremity. Moreover, deficits in motor learning and planning may lead to aberrant sensory motor associations and cause impairments in motor execution [13].

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Predictors of Recovery

Estimates of the potential recovery of motor impairments are necessary for considering stroke patients' individual needs and accordingly developing effective rehabilitation plans. Although a wide range of variables have been investigated as a predictive value for upper extremity recovery, initial severity of motor impairment and neurophysiological and neuroimaging biomarkers are well-known factors that influence upper limb recovery following stroke [14]. Voluntary shoulder abduction and finger extension seen within 5 days after stroke are strongly related to recovery of some dexterity within 6 months, and the probability of recovering is the highest if both movements can be made within 72 h [15]. Similarly, the active range of motion (ROM) of the shoulder and the middle finger measured within 1 month after stroke have been reported to be two useful measures for predicting functions of proximal arm and distal segments at 3 months, respectively [16]. Studies in neurophysiology and neuroimaging with magnetic resonance imaging (MRI) and transcranial magnetic stimulation (TMS) have shown that lesion location and the structural and functional integrity of corticomotor pathways are strongly associated with the recovery of motor impairment at the subacute and chronic stages of stroke recovery [14]. The presence of motor-evoked potentials in affected upper extremity muscles induced by TMS is the predictor of greater motor recovery regardless of the initial paresis [17]. Additionally, a more severe supratentorial stroke, lower level of education, previous low level of physical activity, older age, and functional dependency at hospital discharge have been shown to be associated with the risk of persistent hand impairments [3, 18].

The seven recognized stages of stroke recovery, also known as the Brunnstrom stages, are useful for assessing the motor recovery of patients in both clinical and research settings.

Brunnstrom Stages of Stroke Recovery

1. Flaccid paralysis. No voluntary movement and reflexes.
2. Some spastic tone. No voluntary movement. A small amount of movement may be elicited through facilitation.
3. Spasticity is marked. Synergistic movements may be elicited voluntarily.
4. Spasticity decreases. Muscle control increases. Synergistic movements predominate.
5. Spasticity wanes. Complex movements begin although synergies are still present.
6. Coordination reappears. Spasticity disappears completely. Complex coordinated movements are almost fully present.
7. Normal.

Outcome Measures

Because the improvement of dexterity is a major goal of stroke rehabilitation, it is important to identify appropriate measures to determine functional recovery. There are several scales, assessments, and tests that have been described to examine qualitative properties in stroke patients.

The World Health Organization developed the International Classification of Functioning, Disability and Health (ICF) to provide efficient communication and standardization between policy-makers, health-related specialists, and the general public with the use of a common language and framework. According to ICF, the inclusion of items describing body functions or structure, activity, and participation is identified and recommended regarding outcome measures, which have the potential to establish effective treatment plans for patients in clinical researches [19].

Outcome Measures of Body Functions

Modified Ashworth Spasticity Scale

The Modified Ashworth Spasticity Scale (MAS) is a 5-point nominal scale that ranges from 0 to 4. This clinical examination should be performed on a patient who is in a relaxed and supine position. The muscle is assessed by rating the resistance to passive ROM of a single joint.

- 0: No increase in muscle tone
- 1: Slight increase in muscle tone, manifested by a catch and release or by minimal resistance at the end of the ROM
- 1+: Slight increase in muscle tone, manifested by a catch, followed by minimal resistance, less than half of the ROM
- 2: More marked increase in muscle tone through most of the ROM
- 3: Considerable increase in muscle tone, difficult passive movement
- 4: Rigid in flexion or extension

Modified Tardieu Scale (MTS)

The Modified Tardieu Scale (MTS) is a scale for measuring spasticity that considers the response of the muscles to passive movement at both slow and fast speeds [20]. Patients are positioned in a sitting position to test the upper extremities. The quality and angle of muscle reaction are measured with MTS. Patrick et al. validated MTS in stroke patients and reported that MTS is more valid than MAS because MTS differentiates spasticity from contracture [21]. MTS has also been shown to have excellent test–retest and interrater reliability to quantify spasticity in the elbow flexors of hemiplegic stroke patients [22, 23].

Fugl-Meyer Assessment

The Fugl-Meyer Assessment takes approximately 20–30 min. This assessment is one of the most widely used quantitative instruments for measuring sensory-motor stroke recovery [24]. This test requires a tennis ball, a spherical-shaped container, and an administrator to test reflexes. It is comprised of five major domains: motor function, sensory function, balance, joint ROM, and joint pain. Subscales can be administered separately. The strokeEDGE panel recommends to use this scale as primary outcome measure in intervention studies to evaluate motor function in chronic stroke populations [23].

Activity/Disability Outcome Measures

Although there are several scales for assessing upper extremity function, there are few scales for assessing hand function specifically.

Box and Block Test

The Box and Block Test takes approximately 2–5 min. This test is used to evaluate the unilateral gross manual dexterity using grasp function, transport speed, and release [25]. It is a reliable and valid questionnaire in both chronic and acute phases of stroke [26, 27].

Nine-Hole Peg Test

The Nine-Hole Peg Test takes approximately 1 min. It is a timed test that assesses motor coordination. It is administered by asking the patients to take pegs from a container and place them in nine holes as fast as possible with the affected hand and then remove the pegs with the same hand (Fig. 9.1) [28]. The test has been reported to be a valid and reliable test for stroke patients and has been recommended to be used in the subacute and chronic phases of stoke [26, 27].

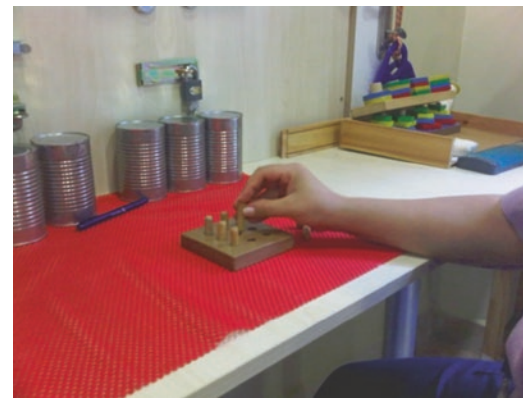

Fig. 9.1 Nine-Hole Peg Test

Fig. 9.2 Jebsen–Taylor Hand Function Test (moving heavy objects)

Jebsen–Taylor Hand Function Test

The Jebsen–Taylor Hand Function Test takes 15–20 min. This test has seven parts and evaluates unilateral hand functions required for ADLs using equipment such as paper clips, cans, and coins [29]. Although this test is not recommended for evaluating stroke patients by strokeEDGE panel, it is moderately effective at measuring upper limb function after stroke (Fig. 9.2) [30].

Action Research Arm Test (ARAT)

The Action Research Test (ARAT) is an upper extremity measurement consisting of 19 movement tasks divided into grasp, pinch, grip, and gross arm movement sub-tests. It takes approximately 10 min and only requires nonstandard equipment, such as various-sized wood blocks, stone, cricket balls, jug, and glass. It was developed to assess recovery in a hemiparetic hand after stroke and found to be reliable and valid in both the acute and chronic phases of stroke [31, 32].

Wolf Motor Function Test (WMFT)

The Wolf Motor Function Test (WMFT) consists of 17 items composed of time, functional ability, and strength parts. It takes approximately 30 min. Patients are evaluated by their performance on tasks ranging from simple movements to functional movements and ADL [33]. This test was designed to quantify the motor ability of patients who have suffered a stroke and traumatic brain injury [34]. The strokeEDGE panel recommends using WMFT or ARAT for upper extremity functioning as secondary outcome measures [23].

Duruöz Hand Index (DHI)

The Duruöz Hand Index (DHI) is a self-questionnaire with a short administration time, as it takes 3–4 min to complete the questionnaire. Consisting of 18 questions related to hand activity, the questionnaire evaluates bimanual performance in daily living activities. This scale has been validated to assess hand functional disability in stroke patients [35].

Michigan Hand Outcomes Questionnaire

The Michigan Hand Outcomes Questionnaire takes 15 min to complete. It is a self-administered, 57-item questionnaire with six domains: overall hand function, activities of daily living, pain, work performance, esthetics, and patients' satisfaction with hand function [3]. It has been validated for hand function problems in outpatients after stroke [36].

Adult Assisting Hand Assessment Stroke (Ad-AHA)

The Adult Assisting Hand Assessment Stroke (Ad-AHA) takes 10–15 min to complete. Ad-AHA has 19 items that are scored from observation of performance during the Present or the Sandwich tasks. It has been developed and found to be a valid measure of the bimanual performance in stroke patients with unilateral impairment [37].

Rehabilitation robotics may also be used to quantify upper extremity functions with sensitive and objective measurement methods in stroke rehabilitation.

Treatment

Stroke rehabilitation requires professional team members, including a physiatrist, physical therapist, occupational therapist, speech therapist, psychologist, and rehabilitation nurse. Complexities of stroke patients, such as having multiple comorbid diseases, cognitive impairment, motor and sensory impairment, pain, skin or vascular damage, dysphagia, aphasia, spasticity, hemispatial neglect, shoulder pain, depression, and bladder dysfunction, represent remarkable challenges in stroke rehabilitation [19]. Furthermore, the recovery of hand function is heterogeneous because there are different kinds of stroke (hemorrhagic/ischemic) and the size and location of lesions may vary. Therefore, rehabilitation therapies in stroke patients must be individualized to select the most effective therapy strategy for a particular patient [38].

Rehabilitation therapies are the principal interventions for regaining the best hand function in both the acute and chronic phases of stroke. Various approaches can be used to attain better functional recovery. Rehabilitation protocols should be aimed at modifying neural plasticity to improve motor performance. However, the optimal frequency and intensity of these protocols to achieve this have not yet been established.

Fig. 9.3 Exercises to improve activities of daily living

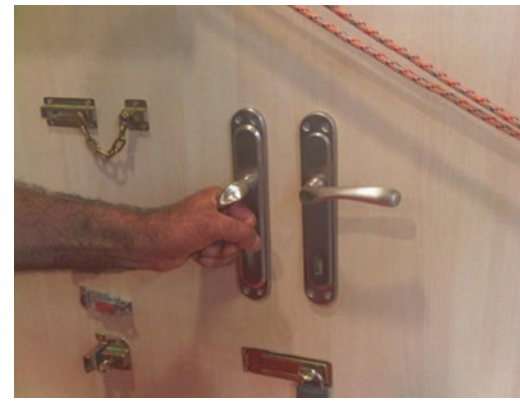

Fig. 9.4 Exercises to improve activities of daily living

Fig. 9.5 Exercises to improve activities of daily living

Exercises Therapy

Exercises therapy is the basis of stroke rehabilitation. It aims to control spasticity, avoid contractures, improve muscle strength, and enhance the functions of the upper extremity. Some of the exercises for hand dexterity in hand rehabilitation in stroke patients are shown in Figs. 9.3, 9.4, 9.5, and 9.6.

Neurophysiological Approaches/ Bobath Therapy

Bobath therapy is one of the most widely used neurophysiological approaches despite the lack of any validated evidence of its superiority when compared to other therapies. It aims to normalize tone, inhibit synergistic movements, and integrate the hemiparetic side into selective movement

Fig. 9.6 Exercises for hand dexterity

patterns and correct posture [39]. One of the key points of the Bobath approach is to utilize sensory inputs in order to facilitate the appropriate postural and task-directed motor output [40]. In a recent meta-analysis, there was a sufficient level of evidence to discourage routine use of Bobath therapy in stroke rehabilitation [38].

Task-Specific Training

Task-specific training involves activities that are meaningful to the patient's daily life. This method has been reported to produce cortical reorganization and associated functional improvements in stroke patients [41]. Studies have shown that repetitive training alone is not enough for upper extremity rehabilitation in stroke patients; rather, task-specific motor learning is also required for long-lasting cortical reorganization and representational neuronal plasticity [41, 42]. A high-quality level of evidence supported by clinical practice guidelines and systematic reviews recommends the routine use of task-specific training to improve the upper extremity functions in stroke patients [38, 43].

Constraint-Induced Movement Therapy (CIMT)

Constraint-induced movement therapy (CIMT) is accepted as a specialized, task-specific training approach. It consists of restraining the unaffected upper extremity while intensively using the affected extremity to improve the neuroplasticity and functional motor recovery [44]. Modified CIMT (mCIMT) has been developed with a lower intensity training protocol to overcome the difficulties of intensive CIMT therapy [45]. Patients with at least 20 degrees of active wrist extension and 10 degrees of active finger extension and minimal sensory or cognitive deficits are suitable for CIMT therapy. The effectiveness of CIMT in chronic stroke patients in reducing spasticity and improving the arm function has been well established [46]. CIMT has also been shown to improve upper extremity function in both the acute and chronic stages of stroke recovery, and according to one comparison study, it has been found to be more effective in early groups rather than delayed ones, where the results showed no significant difference in a 24-month follow-up [47]. According to clinical practice guidelines and systematic reviews, there is a sufficient amount of evidence that recommends the integration of CIMT therapy into stroke rehabilitation [38, 39, 43].

Bilateral Arm Training

In bilateral arm training, patients use both affected and unaffected hands simultaneously but independently of one another to complete a task; movements may be symmetrical or asymmetrical. Studies have shown that this technique improved paretic extremity functions [48] and has been found to be beneficial for improving motor functions during the subacute and chronic phases of recovery [49]. According to comparison studies, while Stoykov et al. have reported that bilateral training provides greater improvement on the proximal arm function compared to unilateral training [50], bilateral training has been found to be no more effective than unilateral training in a randomized controlled study [51].

Motor Imagery

Motor imagery, also called visualization, is an active process of the brain. In this procedure, patients experience sensations by imaging an

action without conducting any real movement [52]. According to motor simulation theory, both real action and imagination of action activate the same areas of the brain, so the technique can be applied as a therapeutic modality in rehabilitation and for strengthening [53]. As an advantage, this technique allows patients to practice independently; though patients have weakness at early stages of stroke recovery, they can still begin the rehabilitation program. It has been reported to be feasible to combine motor practice with physical practice according to clinical practice guidelines [43]. Although positive effects on stroke patients have been reported in a meta-analysis of studies, regardless of quality, no significant improvement has been shown in upper extremity functions with the use of motor imagery when low-quality studies were excluded from this analysis. Therefore, future studies with high quality are needed to properly determine the effect of using motor imagery training for stroke rehabilitation [54].

Mirror Therapy

Mirror therapy involves the use of a mirror reflecting the non-paretic extremity as if it is the paretic upper extremity. Moving the non-paretic extremity and looking at its reflection create visual feedback. This leads to cortical reorganization and restoration of function [55] (Fig. 9.7). This therapy has easy and safe administration and can possibly be used in home-based hand rehabilitation [39]. Current studies suggest that this therapy has beneficial effects on impaired hand function, pain, ADL, and visual-spatial neglect after stroke [56, 57]. However, dimmer effects on spasticity have not been well established [58].

Robot-Aided Training

Robot-assisted rehabilitation provides ideal sensorimotor support [58], which is related to activity-based therapy. This technique allows the patient to train independently with repeatable exercises and increase compliance to the treatment protocol by adding visual stimuli, such as games [59] (Fig. 9.8). It provides high-dosage and high-intensity training for patients [60]. There are various types of robotic devices and several modalities intended to recover the upper extremity functions. According to previous studies, when added to other neuro-rehabilitative treatment protocols, robotic therapy increases the benefit of rehabilitation [61]. In a recent study, it was reported that robotic therapy may enhance local upper extremity circulation and help in the acute management of spasticity, heaviness, stiffness, and pain in post-stroke patients [62].

A Cochrane review reported significant improvement in functional recovery and ADL with upper arm robotics, even without any significant improvement in arm muscle strength [63]. Due to the wide range of the robotic interventions in studies, the interpretation of the results is limited, and there is currently no available data that investigates the optimal design and

Fig. 9.7 Mirror therapy

Fig. 9.8 Robot-aided therapy

efficacy of their usage [64]. Although in a recent review robotic therapy for the paretic upper extremity was reported to be similar or inferior to conventional rehabilitation treatments with a moderate quality of evidence, robotic therapy has been supported for delivering more intensive practices for patients with moderate to severe upper extremity paresis according to clinical practice guidelines [39, 43].

Virtual Reality Training and Videogaming

Virtual reality training and videogaming allow patients to use body movements to interact with objects in a computer-generated environment [39]. These training methods allow patients to receive real-time feedback about the performance of movements. The playful aspect of these trainings is an advantage, as it may increase the patient's motivation and adherence to the treatment [39, 58]. However, it has been reported that there is an insufficient level of evidence for integrating the use of virtual reality training and videogaming into upper extremity rehabilitation in stroke patients [38].

Electrical Stimulation

There are two types of therapeutic electrical stimulation in stroke rehabilitation: sensory and motor electrical stimulation. While high-frequency transcutaneous electrical nerve stimulation (TENS) is used for sensory stimulation, low-frequency TENS and neuromuscular electrical stimulation (NMES) are used to induce the motor stimulation (Fig. 9.9). Moderate-quality evidence supports the use of high-frequency TENS to improve the upper extremity functions and diminish the spasticity when used in combination with other rehabilitation treatment methods [39]. Low-frequency TENS and NMES can be used to elicit muscle contractions for patients with minimal ability for volitional muscle activation [65]. The different methods of NMES can

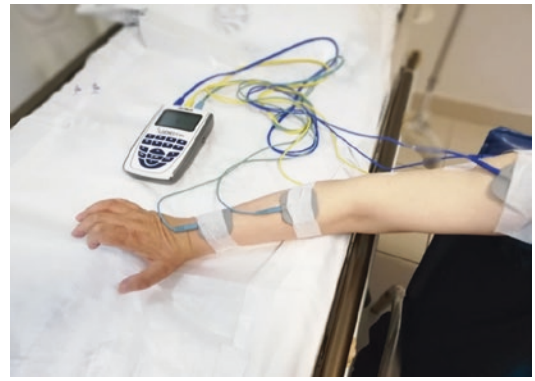

Fig. 9.9 Electrical stimulation

be used in upper extremity rehabilitation: (1) a passive technique to induce simple muscle contraction and (2) electromyographically or positionally triggered NMES to induce the active participation of patients into upper extremity rehabilitation. Electromyographically triggered NMES can be used in patients who have the ability to activate the paretic muscles voluntarily but not to produce sufficient contraction to complete the task. In a recent study, no difference based on the type of electrical stimulation was reported [66]. Although there is a sufficient level of evidence to support the use of passive NMES as an adjuvant therapy for upper extremity rehabilitation, there is an insufficient level of evidence to support the use of electromyographically triggered NMES [39].

Noninvasive Brain Stimulation

Repetitive transcranial magnetic stimulation (rTMS) and transcranial direct current stimulation (tDCS) modulate motor cortex excitability. Both methods are used as noninvasive rehabilitation approaches in stroke patients to normalize the interhemispheric imbalance and improve brain plasticity. Both methods are not found to be efficient when used alone; however, there is a moderate- to high-quality level of evidence that the use of both methods in combination with other rehabilitation treatments improves the upper extremity impairments [39].

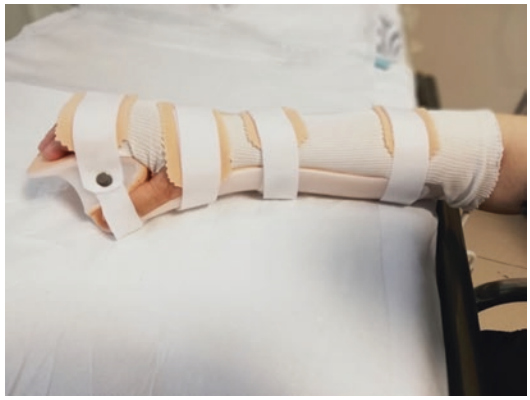

Fig. 9.10 Orthosis

Orthosis

It is known that keeping the extremity in a tonic stretch position may help to reduce tonus (Fig. 9.10). For treating hemiplegic upper extremities, static or dynamic wrist-hand splints are the most commonly used orthosis to prevent contractures, prevent edema, improve ROM, reduce spasticity, and manage pain [67] although the evidence is inadequate [68]. It is an indisputable fact that rehabilitation approaches may be effective only if the peripheral joints are kept at functional length [69].

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Hand Function in Tetraplegia

10

Tuğçe Özekli Mısırlıoğlu
and Şafak Sahir Karamehmetoğlu

Impairment or loss of motor and/or sensory function in the cervical segments of the spinal cord due to damage of neural elements within the spinal cord is referred to as *tetraplegia* and preferred to the term quadriplegia. Tetraplegia results in impairment of function in the arms, as well as the trunk, legs, and pelvic organs [1].

In tetraplegia, the entire upper extremity including the hand can be impaired to varying degrees. The extent of disability depends primarily on the level and completeness of the injury. The loss of function is greater in high-level tetraplegia (C1–C4) in comparison to low-level tetraplegia (C5–T1). Persons with high-level tetraplegia generally have no arm and hand muscle function. They usually have shoulder elevation and control for some neck muscles. Patients with some innervation to C5 myotome can flex their elbows and abduct their shoulder. They may be able to feed and partially groom themselves with the aid of adaptive devices. Wrist extension is the key function of the C6 level as it produces a weak hand grip. Patients with some innervation to C6 myotome can be independent in grooming, bathing, driving, and preparing a simple meal with the aid of adaptive devices. At the C7 level, patients can make elbow extension, wrist flexion, and possible finger extension. These movements may enable them to independently transfer themselves. They can even live alone with the aid of special hand and environmental adaptive equipment.

There are also other factors such as the degree of recovery, motivation, and occupational performance that affect the functional outcomes of individuals following cervical spinal cord injury (C-SCI) [2]. Other limb injuries, contractures, and spasticity can further complicate this picture [3].

The clinical evaluation of hand and arm function of tetraplegics is extremely important, as this is assumed to play a key role in the activities of daily living (ADL), independence, quality of life, and community participation [2]. Hanson and Franklin found that 75% of tetraplegics would prefer restoration of their upper limb function to that of any other lost function including bowel, bladder, sexual function, or walking [4]. Therefore, to evaluate the residual function after the injury, the efficacy of the treatment programs including rehabilitation or surgery, it is important to have standardized tests to assess upper limb function validly and reliably.

In this chapter, we will first discuss the expected functional outcomes according to neurologic level of injury and then review the tests that evaluate the upper limb function on several levels according to the International Classification of Functioning, Disability and Health.

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Expected Functional Outcomes by Neurologic Level of Injury

Expected functional outcomes reported below reflect a level of independence that can be expected of a person with motor complete spinal cord injury (SCI) at 1-year postinjury. These outcomes are based on consensus of clinical experts, available literature on functional outcomes, and data compiled from the Uniform Data Systems and the National Spinal Cord Injury Statistical Center [5].

C1–C4 Tetraplegia

Patients with injuries from C1 to C4 are considered to have high tetraplegia. Persons with injury level above C4 are unable to clear secretions and ventilator dependent, while C4 tetraplegic persons may be able to breathe without ventilators. For the bowel and bladder management (management of elimination, maintenance of perineal hygiene, and adjustment of clothing before and after elimination), these patients need total assistance. For the bed mobility and bed and wheelchair transfers, total assistance is needed. For the pressure reliefs and positioning, they may need total assistance, or they may be independent with equipment. Both manual and power wheelchairs are required. C1–C3 tetraplegics can only use power wheelchairs with control devices, including chin, head, and voice activation, while C4 tetraplegics can use them without the equipment independently. For the propulsion of the manual wheelchair, high tetraplegics need total assistance. Standing can be possible with total assistance on tilt table and hydraulic standing table, and ambulation is not usually needed. Total assistance is needed for eating, grooming, dressing, and bathing. They need 24-hour care to include homemaking, meal planning and preparation, and home management.

Functional goals typically focus on the use of environmental controls and other technological aids like page turners, door openers, emergency call systems, and speaker telephones. Computers are typically accessed via breath or voice control. Environmental control units can be controlled with breath, mouthsticks, or tongue switches.

C5 Tetraplegia

They have low endurance and vital capacity secondary to paralysis of intercostals, and they may require assistance to clear secretions. Total assistance is needed for the management of bowel and bladder. Some assistance is needed for the bed mobility, while total assistance is needed for the bed and wheelchair transfers. The elbow flexion present in C5 tetraplegia can be combined with orthotic management to allow performance of self-care and mobility skills. Therefore, they can do the positioning and pressure reliefs independently with equipment. They can use manual wheelchairs independently to some assistance indoors on noncarpet level surface, some to total assistance outdoors. Standing is possible with total assistance on hydraulic standing frame. Ambulation is not indicated. Static splints (long opponens splints) with utensil slots and pencil holders are used to assist with tasks such as writing, typing, and feeding. By this way, after total assistance for setup, they are independent while eating. They need some assistance while dressing. They need assistance of the caregiver 10 hours/day for their personal care and 6 hours/day for the homemaking activities.

C6 Tetraplegia

Patients with C6 level of injury have low endurance and vital capacity secondary to paralysis of intercostals, and they may require assistance to clear secretions like C5 tetraplegics. They need some to total assistance for the bowel management and some to total assistance with equipment for the bladder management. They may be independent with leg bag emptying. For the bed mobility, some assistance is needed. Bed and wheelchair transfers to level surfaces require some assistance or can be done independently; transfers to uneven surfaces require some to total assistance. C6 tetraplegics can do radial wrist

Fig. 10.1 A tetraplegic patient trying to unscrew the lid from a jar

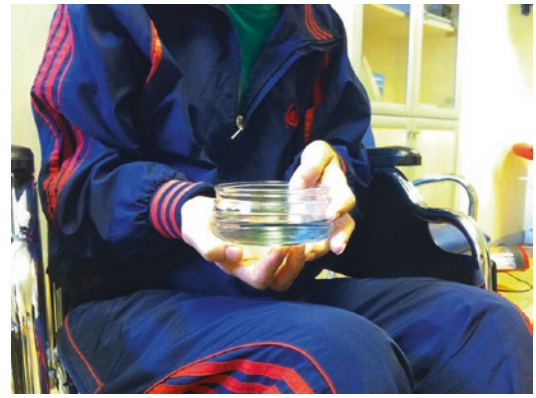

Fig. 10.2 A tetraplegic patient holding a bowl

extension. Therefore, they can do pressure reliefs and positioning independently with equipment and/or adapted techniques. The manual wheelchair is propelled independently in indoors and with some to total assistance in outdoors. Standing is possible with total assistance on hydraulic standing frame. Ambulation is not indicated. These patients eat independently with or without equipment, except cutting which needs total assistance. They dress their upper body independently and lower body with some to total assistance. They need some assistance with light meal preparation and total assistance for all other homemaking. They require assistance for 6 hours/day for their personal care and 4 hours/day for the homemaking activities (Fig. 10.1).

C7 and C8 Tetraplegics

The triceps function found at the C7 level results in significant improvements in transfer and mobility skills. Finger extension and wrist flexion strength are present and further assist ADL. The flexor digitorum profundus at the C8 level greatly improves hand function.

Patients with C7 and C8 levels of injury have low endurance and vital capacity secondary to paralysis of intercostals, and they may require assistance to clear secretions like C5 and C6 tetraplegics. They need some to total assistance for the bowel management and no to some assistance with equipment for the bladder management. They may be independent in bed mobility, or they may need some assistance. They may do bed and wheelchair transfers to level surfaces independently and to uneven surfaces independently or with some assist. They move independently on all indoor surfaces and level outdoor terrain and with some assistance on uneven terrain with manual wheelchair. They can do pressure reliefs and positioning independently. They stand independently to some assistance with hydraulic standing frame. Ambulation is not indicated. Persons at this level are independent in eating and dressing the upper body. Many of them need no to some assistance to dress lower body. They are independent during light meal preparation and homemaking. Some to total assistance is needed for complex meal preparation and heavy house cleaning. They require assistance for 6 hours/day for their personal care and 2 hours/day for the homemaking activities (Fig. 10.2).

The Use of the International Classification of Functioning, Disability and Health and Outcome Measures in Tetraplegics

To establish a good rehabilitation policy for arm and hand in patients with C-SCI, evaluation of and insight into the outcome of arm and hand and insight into training programs for arm and hand according to the different levels of the

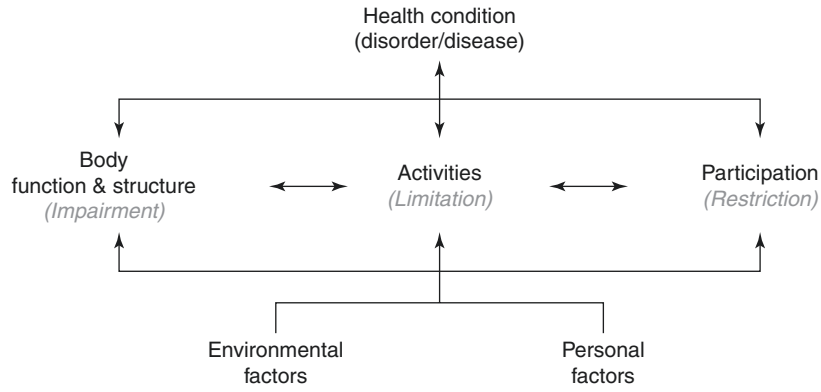

Fig. 10.3 International Classification of Functioning, Disability and Health (ICF)

International Classification of Functioning, Disability and Health (ICF) are necessary [6]. The International Classification of Impairments, Disabilities, and Handicaps (ICIDH) was first developed in 1980 by the World Health Organization (WHO) in order to provide a common language for health [7]. Later, WHO published a revision called the ICF, in 2001, to represent concepts of health and disease as interactions [8].

There is increasing recognition of the need to measure health outcomes for clinical, academic, and financial reasons. It is essential to be able to measure outcomes accurately to determine how effective our rehabilitation program and interventions. The ICF offers some practical assistance when faced with the choice of measurement tools available and the objectives of measuring [9].

According to the ICF model, "functioning" is the umbrella term for [1] body functions and structures, [2] activities, and [3] participation, and they are the results of the interaction between the person's health condition and both personal and environmental factors [8] (Fig. 10.3). While these terms indicate non-problematic aspects of health and health-related states, impairment, activity limitation, or participation restriction reflects the problematic aspects of health and health-related states under the umbrella term "disability" [8]. Definitions of the ICF components [10] are given in Table 10.1.

The term "arm hand function" (AHF) refers to the ICF "function" level. Outcome at this level was described by evaluating, among other factors, muscle strength, tonus, joint range of motion, neurological level, and motor score [6, 11, 12] (Fig. 10.4). However, clinicians and patients are more interested in the performance of arm and hand activities, termed "arm hand skilled performance" (AHSP), which refers to the "activities" level in accordance with the ICF nomenclature [11]. They want to know what patients eventually will be able to do with their arms and hands. At the activities level, we can classify the upper extremity tests as "general tests" and "specific tests." The general tests were

Table 10.1 Definitions of the ICF components

A health condition is an umbrella term for disease, disorder, injury, or trauma
Body functions are physiological functions of body systems, including psychological functions *Body structures* are anatomical parts of the body, such as organs, limbs, and their components *Impairments* are problems in body functions or structure such as a significant deviation or loss
Activity is the execution of a task or action by an individual *Activity limitations* are difficulties an individual may have in executing activities
Participation is involvement in a life situation *Participation restrictions* are problems an individual may experience in involvement in life situation
Environmental factors make up the physical, social, and attitudinal environment, in which people live and conduct their lives *Personal factors* are the particular background of an individual's life and living, and they comprise features of the individual that are not part of a health condition or health state

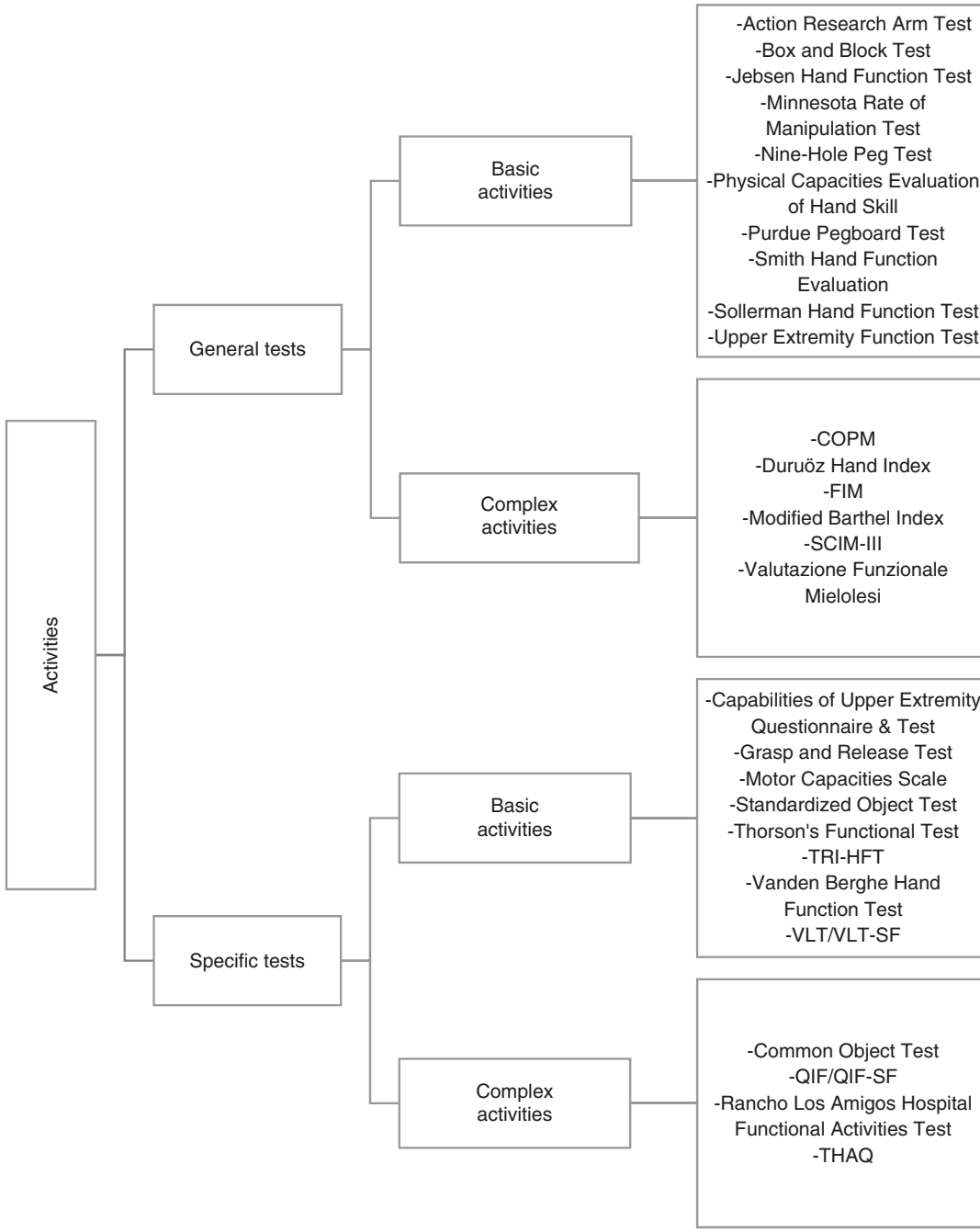

Fig. 10.4 Upper extremity outcome tools categorized according to the ICF domain "Body function and structure". *GRASSP* the Graded Redefined Assessment of Strength Sensibility and Prehension, *ICHST* The International Classification for Surgery of the Hand in Tetraplegia, *ISNCSCI* The International Standards for Neurological Classification of Spinal Cord Injury, *MMT* Manuel Muscle Test, *ROM* Range of Motion

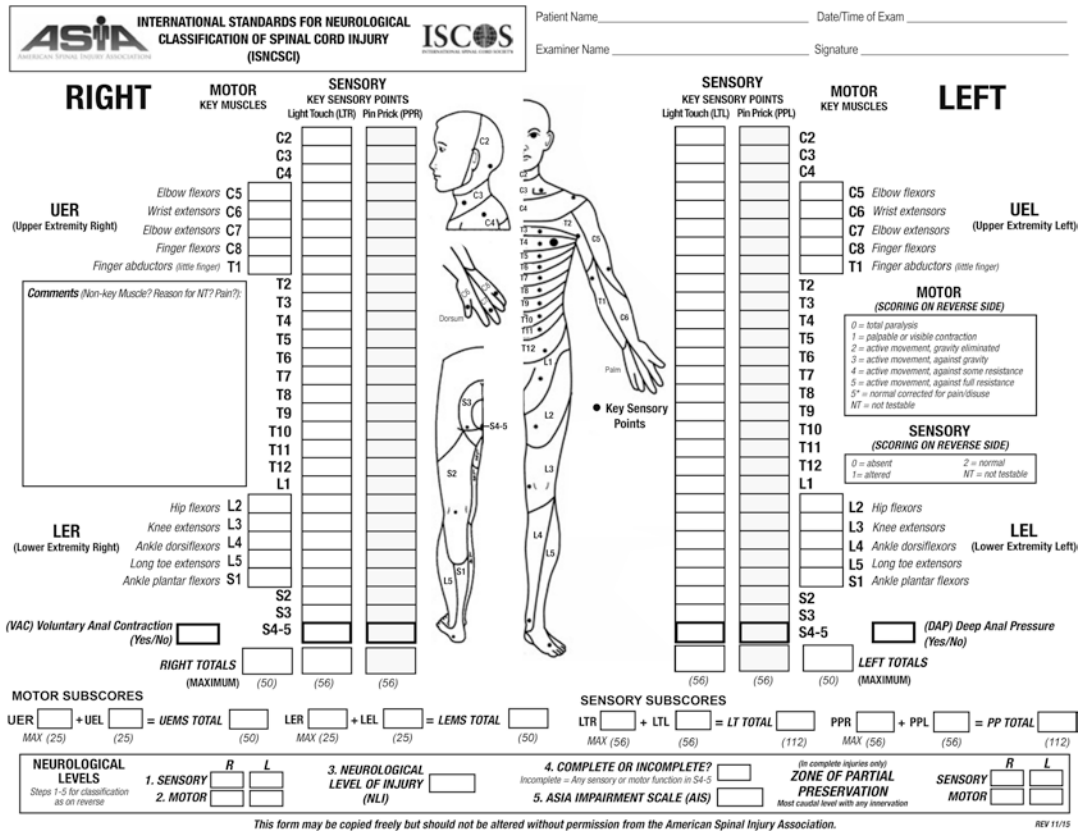

Fig. 10.5 Upper extremity outcome tools categorized according to the ICF domain "Activities". *COPM* Canadian Occupational Performance Measure, *FIM* Functional Independence Measure, *SCIM-III* Spinal Cord Independence Measure-III, *QIF* Quadriplegia Index of Function, *QIF-SF* Quadriplegia Index of Function Short Form, *THAQ* Tetraplegia Hand Activity Questionnaire, *TRI-HFT* Toronto Rehabilitation Institute–Hand Function Test, *VLT* Van Lieshout Test, *VLT-SF* Van Lieshout Test Short Form

either developed to measure hand performance in a broad patient group or initially designed to measure hand performance in a specific population but were later used in other populations including tetraplegics. The specific tests mentioned in this chapter were all specifically designed to measure hand performance of tetraplegic persons [13]. We can then divide each test category as "basic activities" (arm/hand tasks) such as grasping and reaching and "complex activities" (ADL) such as dressing oneself and eating [6]. For a tetraplegic person, an improvement in ADL is often more meaningful than an improvement in performing arm/hand tasks [13]. Upper extremity outcome tools categorized according to the ICF domains "Activities" level are given in Fig. 10.5.

Upper Extremity Outcome Tools Categorized According to the ICF Domain "Body Function and Structure"

The International Standards of Neurological Classification of Spinal Cord Injury (ISNCSCI)

The most accurate way to assess a patient who has sustained a SCI is by performing a standardized physical examination. The International Standards for Neurological Classification of Spinal Cord Injury (ISNCSCI) is considered as the gold standard to determine the levels of SCI and to classify its severity [2, 14]. It was initially

developed as the American Spinal Injury Association (ASIA) Standards for the Classification of Spinal Cord Injuries in 1982 and approved by the International Spinal Cord Society (ISCoS) [15, 16]. The most recent revision of the ISNCSCI was published in 2011 [17].

The standard examination of the patient with SCI has two main components, sensory and motor, with certain required and optional elements. The required elements are composed of the determination of the sensory, motor, and neurologic levels and determination of the completeness of the injury and classification of the impairment in the ASIA Impairment Scale (AIS). The information obtained from this examination can be recorded on a standardized flow sheet that can easily be obtained from the official internet site of ASIA [18]. This worksheet was updated with edition of non-key muscles in 2013 and later in 2015 [18] (Fig. 10.6).

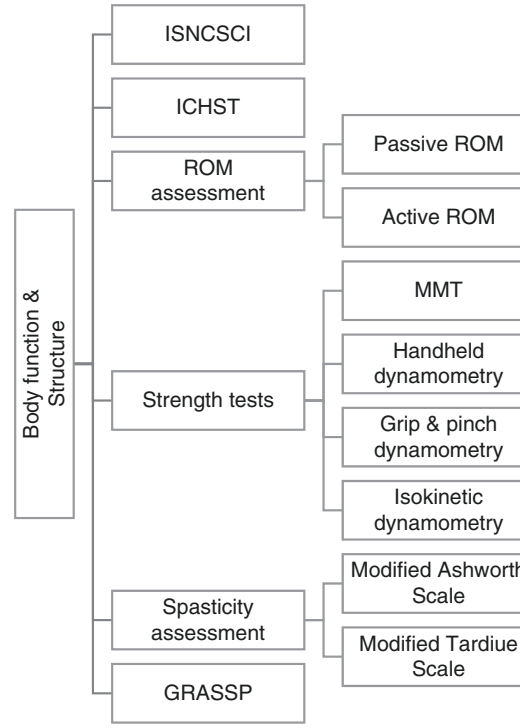

Fig. 10.6 The flowchart of the International Standards of Neurological Classification of Spinal Cord Injury

The Sensory Examination

Twenty-eight-specific skin locations, referred to as key sensory points, are tested for sharp–dull (with a safety pin) and light touch (with a cotton-tip applicator) sensations on both sides of the body. A three-point scale (0–2) is used and face is accepted as the normal control point.

For the light touch sensation, if the patient does not correctly or reliably report being touched, a score of zero (absent) is given. If the patient correctly reports being touched, but describes the feeling as different than on the face, a score of "1" (impaired) is given. The score of "2" (normal or intact) is only given if the patient correctly reports being touched and describes the feeling as the same as on the face.

For the sharp–dull discrimination, if the patients has no feeling of being touched or does not reliably distinguish between the sharp and the dull ends of the pin, a score of zero (absent) is given. If the patient reliably distinguishes between the sharp and dull ends, but states that the intensity of the sharpness is different in comparison with the face, a score of "1" (impaired) is given. The score of "2" (normal or intact) is only given if the patient reliably distinguishes between the sharp and dull ends and states that the intensity is the same as the face.

The sensory level is the most caudal dermatome to have intact sensation for both pinprick and light touch on both sides of the body.

It is also important to test the S4–S5 dermatome, which represents the most caudal segment of the spinal cord, for pinprick, light touch, and deep anal sensation.

The Motor Examination

The required part of the motor examination consists of testing ten key muscles: five in the upper limb and five in the lower limb on each side of the body. The testing of all key muscles must be done when the patient is in the supine position and graded on a traditional six-point manual muscle testing (MMT) scale from 0 to 5. Every key muscle should be tested in the grade 3 testing position first, then if the muscle is shown to have greater than antigravity strength, the muscle should be tested in the grades 4 and 5 testing positions. If the muscle is shown to have lesser than grade 3 strength, grades 2 and 1 should be tested.

Table 10.2 The key muscles and their corresponding spinal cord roots or segments

C5 Elbow flexors	L2 Hip flexors
C6 Wrist extensors	L3 Knee extensors
C7 Elbow extensors	L4 Ankle dorsiflexors
C8 Finger flexors (distal phalanx of the middle finger)	L5 Long toe extensors
T1 Finger abductors (little finger)	S1 Ankle plantar flexors

Table 10.3 The traditional six-point manual muscle scale

Grade 0	No visible or palpable muscle contraction is noted in the muscle being examined
Grade 1	A visible or palpable muscle contraction is noted in the muscle being examined
Grade 2	The muscle is able to move, at least once, the part of the extremity to which it is inserted through a full range of motion (or the maximum available range of motion), in the position in which gravity is eliminated
Grade 3	The muscle is able to move, at least once, the part of the extremity to which it is inserted through a full range of motion (or the maximum available range of motion), in the position in which gravity must be overcome
Grade 4	The muscle is able to move, at least once, the part of the extremity to which it is inserted through a full range of motion (or the maximum available range of motion) and, in addition, provides some resistance against the efforts of the examiner to oppose it
Grade 5	The muscle is able to move, at least once, the part of the extremity to which it is inserted through a full range of motion (or the maximum available range of motion), and to the examiner's judgment, exerts a normal amount of resistance against the efforts of the examiner to oppose it

The key muscles and their corresponding spinal cord roots or segments are shown in Table 10.2.

The traditional six-point manual muscle scale is shown in Table 10.3.

Voluntary anal contraction should also be tested as a part of the motor examination by sensing contraction of the external anal sphincter around the examiner's finger.

The motor level is the lowest key muscle that has a grade of at least 3, providing the key muscles represented by segments above that level are judged to be normal (grade 5).

The neurologic level of injury (*NLI*) is the most caudal segment of the cord with intact sensation and antigravity (3 or more) muscle function strength, provided that there is normal (intact) sensory and motor function rostrally, respectively.

Incomplete injury is defined as preservation of motor and/or sensory function below the neurologic level that includes the lowest sacral segments, while *complete injury* is the absence of sensory or motor function in these segments.

The ASIA Impairment Scale (AIS) classifies an SCI into five categories of severity, labeled A through E, based on the degree of motor and sensory loss. An SCI is categorized as AIS A (complete) when there is lack of any sensory or motor function, including pressure sensation, light touch or pinprick sensation, or voluntary anal contraction in the sacral segments S4–S5. When sensory but not motor function is preserved below the NLI and includes the sacral segments S4–S5, and no motor function is preserved more than three levels below the motor level on either side of the body, the AIS is B (sensory incomplete). When motor function is preserved at the most caudal sacral segments for voluntary anal contraction or the patient meets the criteria for sensory incomplete status, and has some sparing of motor function (including key or non-key muscle functions) more than three levels below the ipsilateral motor level on either side of the body, the AIS is C (motor incomplete). For AIS C, less than half of key muscle functions below the single NLI have a muscle grade ≥3. AIS D describes motor incomplete status with at least half of key muscle functions below the single NLI have a muscle grade ≥3. When sensation and motor function as tested with the ISNCSCI are graded as normal in all segments, and the patient had prior deficits, then the AIS grade is E (normal) [18].

In addition to standardizing practice and aiding research, the ISNCSCI and AIS have strong prognostic features [19, 20]. The ISNCSCI motor and sensory examinations are important since they have been the primary indicators of recovery of neurological function [21–25]. Waters et al. reported that in 1-year follow-up while the muscles of patients with C-SCI with initial motor scores of grade 1 or 2

increased to at least grade 3, the muscles with initial motor scores of grade 0 (complete paralysis) never exceeded grade 3 [21]. The extent of recovery in the tetraplegia is based mainly on ISNCSCI upper extremity motor scores, lower extremity motor scores, and AIS grade [26–28].

International Classification for Surgery of the Hand in Tetraplegia

While the ISNCSCI remains the most commonly used motor and sensory assessment in tetraplegia, the International Classification for Surgery of the Hand in Tetraplegia (ICSHT), an alternative classification scheme, has been introduced specifically for surgical planning in the upper limb in tetraplegia [29, 30]. Like the ISNCSCI, the ICSHT involves both examination of motor and sensory function and classification of neurological status. As opposed to five key muscles tested in ISNCSCI, the motor examination of ICSHT consists of the evaluation of all upper limb muscles. Unlike the motor examination of ISNCSCI which accepts muscle strength of grade 3 as functional, ICSHT accepts grade 4 as the donor muscle is expected to lose a grade of strength due to its new action after transfer.

The ICSHT sensory examination involves testing two-point discrimination on the thumb and index finger; sensation is considered intact if two-point discrimination is ≤10 mm and these patients are classified as "O-Cu" (ocular–cutaneous). When two-point discrimination is >10 mm, these patients are considered to only have ocular input for hand function and classified as "O" (ocular). This classification takes into account the motor groups that are functioning and available for transfer, as well as sensibility.

Modified International Classification for Surgery of the Hand in Tetraplegia is shown in Table 10.4.

Table 10.4 Modified International Classification for Surgery of the Hand in Tetraplegia

Motor	
Group	Functional muscles[a]
0	Weak or absent BR (grade 3 or less)
1	BR
2	BR, ECRL
3	BR, ECRL, ERCB
4	BR, ECRL, ERCB, PT
5	BR, ECRL, ERCB, PT, FCR
6	BR, ECRL, ERCB, PT, FCR, finger extensors
7	BR, ECRL, ERCB, PT, FCR, finger extensors, thumb extensors
8	BR, ECRL, ERCB, PT, FCR, finger extensors, thumb extensors, finger flexors
9	Lacks intrinsics only
Sensory	
0	Two-point discrimination in thumb >10 mm
Cu	Two-point discrimination in thumb ≤10 mm

BR brachioradialis, *ECRL* extensor carpi radialis longus, *ECRB* extensor carpi radialis brevis, *PT* pronator teres, *FCR* flexor carpi radialis

[a]Functional muscle: grade 4 or 5

The Strength Tests

These tests include MMT, handheld dynamometry, pinch and grip strength measurement, and isokinetic dynamometry.

Manual Muscle Testing (MMT)

In this test, the examiner counteracts the force of a subject manually. It is graded on a traditional six-point MMT scale proposed by the British Medical Research Council [31]. MMT is used to evaluate the strength of key muscles as a part of ISNCSCI motor examination. Upper extremity motor score (UEMS) is the sum of the MMT scores of five upper extremity key muscles on each side of the body. An overall motor score out of a possible 25 for each arm indicates normal motor function.

MMT depends on the examiner's judgment of the amount of resistance applied during the test [32]. The experience of the examiner can also influence the consistency of MMT scores [33]. Savic et al. [34] examined the interrater reliability of motor examinations performed according to ASIA standards and found out that the overall agreement in assignment of MMT grades was over 80% on both sides with the strongest agreement for grade "0" and the weakest for grade "3." Noreau et al. [35] stated MMT was not sufficiently sensitive to assess muscle strength, at least for grade "4" and higher, and to detect small or moderate increases of strength in SCI persons over the course of rehabilitation. On the other

hand, they found that measurement with dynamometry allows for greater accuracy.

Handheld Dynamometry (HHD)

Handheld dynamometries, also known as myometers, are small portable devices used to test isometric strength. Several HHDs have been used to test muscle strength in tetraplegics, for example, Penny and Giles and Jamar and Preston dynamometer [35, 36]. To test a muscle with a HHD, a minimum MMT score of 3 out of 5 is necessary [32].

They have several advantages including lower cost, greater ease of use, and better acceptability in clinical settings.

Marciello et al. [37] showed that HHD of wrist extensors appeared to be a better indicator than the MMT for some self-care activities in tetraplegic patients. All the other investigators [32, 35–38] emphasized that HHD may identify effects of therapeutic interventions, missed by MMT, especially for grades 4–5.

Disadvantages of the HHDs include that they are capable of measuring only one point in the range of motion (ROM) at a time. The examiner must be able to provide appropriate stabilization during the examination [38].

Grip and Pinch Strength Measurement

Grip dynamometers may be used to quantify strength changes in persons with lower cervical lesions who retain finger motion [38] as well as to measure outcomes in clinical trials of upper limb tendon transfers [39].

Pinch dynamometry appears to be useful to measure improvement in grip strength after hand surgery in tetraplegics [40].

The Preston pinch meter and the Jamar hand dynamometer (Jamar hydraulic pinch gauge) have been traditionally used for pinch strength and grip strength measurements, respectively [12]. Although most of them lack the sensitivity to record small changes in force, the digital dynamometer (digital pinch/grip meter) that can measure both pinch and grip strength has been shown to detect low forces generated [41, 42].

It is essential to follow a standardized test protocol that describes the positioning of the subject during the measurements as the magnitude of force that is recorded is affected by the upper limb posture [12, 42, 43].

Isokinetic Dynamometry

Isokinetic dynamometry is a method of measuring muscle strength that involves hydraulic or motor-driven devices that impose a constant velocity. Unlike HHDs that measure the force at one particular point in the ROM, isokinetic dynamometers measure torque produced at the anatomical joint throughout the available ROM [38].

However, it has a limited clinical use since it is expensive and it occupies a large space. Furthermore, a MMT grade of at least 3 is necessary to perform the desired movement, whereas muscles with MMT grade 2 and below cannot overcome gravity and therefore cannot move the dynamometer over the entire ROM [13].

While testing positions are standardized, some testing positions for persons with SCI are cumbersome. May et al. [44] measured shoulder strength of SCI persons with both handheld and isokinetic dynamometry. They concluded that while HHD can be used reliably to measure shoulder rotation in paraplegic and tetraplegic patients, the relationship between HHD and isokinetic measurement is poor for the participants with tetraplegia which may be a function of the method of isokinetic measurements. So further study with a modified isokinetic testing protocol is needed to clarify the results of the participants with tetraplegia.

Spasticity Assessment

Spasticity is encountered in 87–96% of individuals after C-SCI, and it is most frequent in incomplete injuries [45–48]. Spasticity in the upper limb typically involves shoulder adductors and internal rotators, forearm pronators, and elbow, wrist, and finger flexors [49].

Spasticity can be either functional or nonfunctional. For example, a patient with flexor pollicis longus muscle spasticity and voluntary wrist extension may have a desired strong lateral pinch. On the other hand, a patient with a closed fist because of severe finger spasticity may have dif-

ficulties in grasping, reaching, and releasing items [49]. Therefore, spastic muscles should be assessed for the degree of the spasticity and whether they are functional.

Many tests are used to assess spasticity, but the two most widely used are the Modified Ashworth [50] and Modified Tardieu Scales [51]. As these scales rate every specific muscle function, they are not suitable to describe the global consequences of spasticity in the upper limb. There is currently no grading scale that quantifies the upper limb spasticity in SCI [49]. There are some specific scales, namely, Spasticity Evaluation Tool (SCISET) [52] and Patient Reported Impact of Spasticity Measure (PRISM) [53], which measure the impact of spasticity on SCI patient's quality of life.

Graded Redefined Assessment of Strength Sensibility and Prehension (GRASSP)

Investigators: Kalsi-Ryan et al. [54] (2009).

Purpose: To assess the sensory, motor, and functional upper extremity changes in a manner that is sensitive to small neurological changes over the natural course of recovery or as a result of therapeutic intervention [55].

Target population: Individuals with acute and chronic C-SCI.

Test composition: The GRASSP is a clinical impairment measure that incorporates three domains vital to upper limb function: sensation, strength, and prehension. It consists of five subtests, palmar sensation and dorsal sensation, strength, prehension activity, and performance measured by observation of grasping and task acquisition.

The GRASSP Version 1.0 is a test kit with all of the standardized apparatus included along with a manual which details the instructions for administration.

Scoring Method: Each subtest renders a subtest score for the right and the left. The five subtest scores are used to characterize upper limb impairment.

The Strength domain is evaluated through manual muscle testing of ten upper extremity muscles, namely, the anterior deltoid, elbow flexors, elbow extensors, wrist extensors, extensor digitorum, opponens pollicis, flexor pollicis longus, finger flexors, finger abductors, and first dorsal interossei. Each receives a score from 0 to 5, for a total strength domain score between 0 and 50 for each of the right and left sides.

The Sensation domain is evaluated by testing three palmar and three dorsal finger locations with Semmes–Weinstein monofilaments. Each location receives a score from 0 to 4, resulting palmar sensation and dorsal sensation subtests between 0 and 12 each and a total sensation domain score of up to 24, for each side.

The Prehension Ability domain is evaluated by asking the individual to perform three prehension patterns (cylindrical grasps, lateral key pinch, and tip-to-tip pinch). Each is scored from 0 to 4, based on active vs passive positioning of the wrist and fingers. This results in a prehension ability subtest score between 0 and 12 for each side.

The Prehension Performance domain is evaluated based on six functional tasks: namely, pouring water from a bottle, unscrewing lids from jars, performing a pegboard task, using a key, manipulating coins, and placing nuts onto screws. Each task is scored from 0 to 5, for a total prehension performance subtest score between 0 and 30.

A total score is not calculated. Completion time is 45–60 minutes.

Psychometric properties: The GRASSP was found 50% more sensitive than the ISNCSI when defining sensory and motor integrity of the upper limb, and the subtests showed concurrence with the SCIM, SCIM self-care subscale, and CUE. The interrater and test–retest reliability for all subtests were above the hypothesized value of 0.80 [55]. Responsiveness, sensitivity, and minimally detectable difference of the GRASSP have also been studied [56].

The modified version of the GRASSP, GRASSP version 2, is now available. The new version allows for shorter assessment times in clinical studies without degrading metric properties [57].

Upper Extremity Outcome Tools Categorized According to the ICF Domain "Activities"

General Tests: Basic Activities

Action Research Arm Test (ARAT)

Investigators: Lyle et al. (1981) [58].

Purpose: To evaluate upper limb motor function recovery following a stroke or other brain injuries.

Target population: Hemiplegics.

Test composition: It is composed of 19 items that measure subject's ability to pick up and release objects of different size and shapes either vertically (30 cm high shelf), horizontally (forward) on the table or to perform whole arm movement by touching the back of head, top of head, and mouth. The test has been standardized by Yozbatiran et al. [59].

Scoring method: Four-point scale (0 ± 3) is used for grading the items. The scores are summed to give a total score. The maximum score is 57 points.

Psychometric properties: The ARAT has been validated and found reliable in stroke population. However, validity and reliability of the ARAT has not been studied in SCI individuals. Poor correlations were found between the ARAT, the neurological level of the lesion, and the ICSHT [60].

Sollerman Hand Function Test

Investigators: Sollerman et al. (1995) [61].

Purpose: To give a good measure of overall function of the hand.

Target population: Tetraplegics, rheumatoid arthritis patient, finger amputees, nerve injured persons, and persons with impaired range of motion of the arm [13].

Test composition: It includes 20 subtests, each comprising a task considered to be an ADL. These tasks represent four common grip (diagonal volar grip, transverse volar grip, spherical volar grip, extension grip) and four common pinch (pulp pinch, lateral pinch, tripod pinch, five-finger pinch) patterns.

Scoring method: Each subtest is scored on a five-point scale (0 ± 4), with a maximum score of 80 points for the dominant hand and 77 ± 79 points for the non-dominant hand. Each subtest is scored by the examiner on a scale from 4 to 0 and lasts 1 minute. The test is usually completed within 20 minutes.

Psychometric properties: It correlates well with the accepted ICHST. The test is reliable and reproducible [61].

General Tests: Complex Activities

Modified Barthel Index (MBI)

Investigators: The original BI was developed by Mahoney et al. [62] (1965); the modified versions of BI were investigated by Granger et al. [63] (1979) and Yarcony et al. [64] (1987).

Purpose: Measurement of severity of disability and monitoring of rehabilitation progress in severely disabled persons [63] or assessment of functional abilities [65].

Target population: Traumatic SCI persons.

Test composition: The MBI consists of 15 tasks, including drinking from a cup, feeding from a dish, upper body dressing, lower body dressing, donning a brace or prosthesis, bathing, grooming, bowel continence, bladder continence, chair transfers, toilet transfers, tub/shower transfers, walking, stair-climbing, and wheelchair propulsion (only if not walking). In Yarcony's investigation published in 1987, the item "donning brace or prosthesis" was not included [64].

Scoring method: The test is administered by observation of the individual's performance. It does not require special equipment or training. Items are rated as independent, assisted, or dependent. Items that are considered more important for independence, such as eating without assistance, are weighed more heavily than less important items, like grooming.

Psychometric properties: The MBI has been used mostly for cerebrovascular diseases. It has not been used extensively in SCI [66]. The MBI was able to identify statistically significant improvement from discharge to 3-year follow-up in both complete and incomplete tetraplegics [65].

Normative data: The MBI has construct validity, with the exception of the bladder and bowel

items [67]. The internal consistency and interrater reliability of the MBI in SCI patients are good [67]. Self-care and mobility subscores of the MBI at admission and discharge for patients with complete and incomplete tetraplegia are provided [64], as are mean MBI scores during 3-year follow-up [13, 65].

Functional Independence Measure (FIM)

Investigators: Hamilton et al. [68, 69] (1987).

Purpose: Rating severity of patient disability and the outcomes of medical rehabilitation.

Target population: Patients who undergo medical rehabilitation.

Test composition: Eighteen items, concerning self-care (eating, grooming, bathing, dressing upper body, dressing lower body, toileting), sphincter control (bladder and bowel management), mobility (transfers to bed, chair or wheelchair, to toilet, and to tub or shower), locomotion (walking or wheelchair propulsion, stair climbing), communication (comprehension and expression), and social cognition (social interaction, problem solving, memory).

Scoring method: The first version of the FIM used a four-point rating scale (0 ± 4) to score each item. In the revised version, the items are scored on a seven-point scale, varying from "1" total assistance to "7" complete independence [70].

The tasks are evaluated by a certified clinician who has a special training for administration of the FIM. The clinician first observes the patient performing the task and then rates according to his/her professional judgment.

Psychometric properties: The FIM is highly correlated with many outcome measures such as QIF [71, 72], SCIM-III [73], and CUE-Q [74]. The FIM appeared to have high interrater and intrarater reliability [70]. FIM scores were significantly lower in complete C4 tetraplegics than in C6 tetraplegics [75], which indicated that the FIM is sensitive enough to differentiate between different levels of injury. In incomplete tetraplegic persons, FIM scores appeared to change significantly between admission and discharge. In complete tetraplegics, no significant change was found [76]. The FIM is useful in detecting changes in function in time. FIM motor gains were greatest between admission and discharge for all neurologic levels.

Normative data: Mean FIM scores by injury level and age [75] and by injury level and Frankel grade over time [77] are available.

Canadian Occupational Performance Measure (COPM)

Investigators: Law et al. [78] (1990).

Purpose: To assess patients' perspectives about changes in activity limitations and participation restrictions.

Target population: Patients with a variety of disabilities and across all developmental stages.

Test composition: It is administered in a semi-structured interview where patients are required to identify specific activity limitations and participation restrictions. It is important that the therapist, the administer, has the specific training necessary to administer the COPM in a reliable and valid manner.

The therapist initiates the COPM process by engaging the patient in identifying daily occupations of importance that they want to do, need to do, or are expected to do but are unable to accomplish. Areas of everyday living explored during the interview include self-care, productivity, or leisure. After identifying the occupational performance problems, the second step is undertaken. In step 2, the patient is asked to rate the importance of each of the occupations to his/her life using a ten-point rating scale. In the third step, the patient chooses up to five of the most important problems identified in step 2 to be addressed in intervention. In step 4, the patient is asked to use a ten-point scale to rate their own level of performance and satisfaction with performance for each of the five identified problems. In the final fifth step, which is after an intervention, the therapist again asks the patient to self-rate performance and satisfaction for the problems addressed. The therapist then uses these scores to calculate the performance and satisfaction change scores [79].

Scoring method: The therapist calculates an average COPM performance score and satisfaction score. These typically range between 1 and

10, where 1 indicates poor performance and low satisfaction, respectively, while 10 indicates very good performance and high satisfaction [79]. The process can take up to 60 minutes to complete.

Psychometric properties: There are numerous types of validity studies, evaluated for the COPM, in various settings and populations. It has previously demonstrated sufficient internal consistency and test–retest reliability and validity across several populations, treatment sessions, and countries.

Duruöz Hand Index (DHI)

Investigators: Duruoz M et al. [80] (1996).

Purpose: To measure functional disability in the hand.

Target population: It was developed primarily to assess hand-related activity limitation in patients with rheumatoid arthritis [80].

Test composition: It contains 18 items related to the ability of the hand while performing kitchen tasks (8 items), dressing (2 items), maintaining personal hygiene (2 items), performing office tasks (2 items), and performing other general items (4 items).

Scoring method: Patients rate their ability from "0" (no difficulty) to "5" (impossible to do), and these 6 levels of answers allow a highly sensitive grading of hand-related activity limitation. The total score of the questionnaire, ranging from 0 to 90, indicates greater impairment or more difficulty with higher scores, whereas less impairment or difficulty with lower scores. No training is required prior to administration, and it takes less than 3 min to administer the whole questionnaire.

Psychometric properties: The DHI was found a valid method with high internal consistency in the assessment of hand functions in patients with tetraplegia [81]. It showed significant correlations with UEMS, AIS, QIF-SF, hand function VAS, physical functioning, and physical compound summary scores of SF-36. The scores showed a significant difference between patients with high and low level of tetraplegia, which indicated that the DHI was sensitive enough to differentiate between different levels of injury.

Future research is needed to establish test–retest reliability and responsiveness of the DHI in patients with tetraplegia.

Spinal Cord Independence Measure-III (SCIM-III)

Investigators: Catz et al. [82] (1997).

Purpose: To describe the ability of the patients with SCI to accomplish activities of daily living and also make functional assessments of this population prone to changes on the course of recovery and/or in the long-term life period.

Target population: Persons with SCI.

Test composition: Since the first publication of the SCIM in 1997 [82], two more versions named SCIM-II [83, 84] and SCIM-III [73, 85] were developed. SCIM-III is the latest version comprising 19 items in three subscales: [1] self-care (six items: feeding; bathing, upper body; bathing, lower body; dressing, upper body; dressing, lower body; grooming), [2] respiration and sphincter management (four items: respiration; bladder, sphincter; bowel, sphincter; use of toilet), and [3] mobility (nine items: mobility in bed; transfer, bed/wheelchair; transfer, wheelchair/toilet/tub; mobility indoors; moderate distances; mobility outdoors; stair management; transfer wheelchair/car; transfer, ground/wheelchair).

Scoring method: Nineteen items are scored on an ordinal scale varying from three to nine classes. The total score may range between 0 and 100. Higher score indicates that the patient is capable of accomplishing the activities of daily living with less assistance, aids, or health compromise. The time needed for the evaluation is 30–45 minutes.

SCIM-III is administered by observation. A self-report version of SCIM-III (SCIM-SR) is also available [86].

Psychometric properties: The interrater reliability of the total SCIM scores was good. Sensitivity of the SCIM appeared to be higher than the sensitivity of the FIM. In tetraplegic subjects, the FIM missed 22% of the functional changes detected by the SCIM [84].

Additional information: In a study of Rudhe et al. [87], the relationship between upper extremity

muscle strength tests, capacity tests, and the SCIM III in persons with tetraplegia was explored. A total of 29 individuals with tetraplegia (motor level between C4 and T1; sensory–motor complete and incomplete) participated. The total score, category scores, and separate items of the SCIM-III were compared to the upper extremity motor score, an extended manual muscle test for 11 upper extremity muscles, and hand capacity tests of the hand. The SCIM-III sum score correlated well with the sum scores of the three tests. The SCIM-III self-care category correlated better with the tests compared to the other categories. The SCIM-III self-care item "grooming" highly correlated with muscle strength and hand capacity items.

Valutazione Funzionale Mielolesi (VFM)

Investigators: Taricco et al. [88] (2000).

Purpose: To identify changes in patient's functional status over time.

Target population: Persons with SCI.

Test composition: It includes 65 specific tasks, including using fork, using spoon, using knife, pouring [a pitcher] out, using cup or glass, washing hands, washing face, drying hand/face, brushing teeth, shaving/putting on makeup, combing hair, writing in longhand, typing, turning page, using phone, using remote control, opening/closing door, using keys, and using elevator.

Scoring method: The items are reported on a five-point scale [1–5]. The duration of the test is 30–50 minutes.

Psychometric properties: VFM was found to be strongly correlated with independent clinical variables (diagnosis and lesion level) and with the Barthel Index. Most of its domains were able to document large and significant changes over time.

English version of VFM is not available.

Specific Tests: Basic Activities

Standardized Object Test (SOT)

Investigators: Thrope et al. [89] (1989).

Purpose: Evaluation of the minimal criteria of functional hand grasp necessary to use a functional nerve stimulation neuroprosthetic hand system.

Test composition: The test consists of six objects each having various weights, sizes, and textures, including a block, disk, videotape, pegs, cylinder, and fork. The subject is asked to acquire, transport, and release each object as many times as possible in a 30-s period.

Scoring method: Number of objects transported.

Psychometric properties: The test was sensitive enough to detect an increase in hand function in tetraplegics when using a hand system [13].

Vanden Berghe Hand and Arm Function Test

Investigators: Vanden Berghe et al. [40] (1991).

Purpose: Evaluation of the effect of reconstructive surgery in tetraplegic persons.

Test composition: Nine unilateral items, including transfer of bowls of different weights (50, 100, 150, 200, 250 grams), grasp and transfer of 10 daily objects (cup, knife, toothbrush, lighter, key, sharpener, nut and screw, and purse), 10 different objects of natural wood (ball, cube, beam, slat, disc, and triangle), 10 different painted objects (smooth surface), and writing a sentence of 18 letters.

Scoring method: Time necessary to perform each subtest. The duration of the test is dependent on the speed with which a subject performs the subtests.

Psychometric properties: Not available.

Normative data: Mean times necessary to perform each subtest for 13 tetraplegics were reported without distinguishing between subjects with different injury levels [13].

Grasp and Release Test (GRT)

Investigators: Wuolle et al. [90] (1994).

Purpose: Assessing the use of a hand neuroprosthesis in C5 and C6 level tetraplegic persons.

Test composition: It is a pick-and-place test that requires the participant to unilaterally acquire, carry, and release five objects (peg, paperweight, block, can, and videotape) of varying weight and size. A sixth object, the fork, is used for simulating pinching of a fork handle and stabbing of food. The objects peg, paperweight,

and fork have to be manipulated with lateral grasp, and the objects block, can, and videotape have to be manipulated with palmar grasp.

Prior to the test, a pretest is done. The patients are given at least 30 seconds of practice with each object. If the patient is not able to correctly grasp, move, and release the object during the pretest, the object is not included in the testing.

Scoring method: The score is comprised of the total number of completions achieved in a 30-second trial for all six objects. If a person fails to move an item, the score zero is given for that particular item. If a subject moves the item N times, the score N is given. Each hand is tested and scored separately. This test takes approximately 20 minutes to administer.

Psychometric properties: Wuolle et al. first reported on the psychometrics of the GRT, which were further established by Mulcahey et al. In Mulcahey et al.'s study, intraclass correlation coefficients were high for repeated GRT test measures; the GRT scores were stable over time for chronic stable hand-function measurement and were sensitive to changes in hand function via functional electrical stimulation (FES) and tendon transfers [91]. Clinically, the GRT has been an effective outcome measure for intervention studies of FES and tendon transfers [39, 91–96].

Like all tests of hand function, the GRT requires the person to sit upright in the wheelchair. This prerequisite limits GRT use in clinical trials involving persons with acute SCI who are not medically stable for sitting. Another limitation of the GRT may be that its original intent was the evaluation of changes caused by FES and lateral and palmar grasp; therefore, it may be insensitive to other grasp patterns and/or injury levels that typically do not use current FES systems (e.g., high and low cervical SCI) [92].

Capabilities of Upper Extremity (CUE) Instrument (Questionnaire) (CUE-Q)

Investigators: Marino et al. [97] (1998).

Purpose: To measure upper extremity actions without assistance or equipment and thus to evaluate capabilities of individuals with tetraplegia.

Test composition: It is a 32-item (15 unilateral—left and right—and 2 bilateral) questionnaire assessing 17 tasks.

Scoring method: Patients rate on a seven-point ordinal scale representing self-perceived difficulty in performing the action, varying from "1" unable to perform and "7" can perform without difficulty. Responses are summed to give a total score (ranges from 32 to 124). It takes 10–15 minutes to complete.

Psychometric properties: Internal consistency and test–retest reliability of the scale is high. Analysis of variance indicated that the CUE-Q distinguished between motor levels of tetraplegia more than one level apart. The CUE-Q was correlated highly with both UEMS and self-care FIM scores. Regression analysis indicated that the CUE-Q was better than upper extremity motor scores for predicting FIM scores.

Normative data: Mean CUE-Q values are provided for tetraplegic persons with different levels of injury and by best motor level.

The CUE-Q has been used to evaluate improvements after upper limb reconstructive procedures [93] and was used in a pilot study to predict the ability of patients with tetraplegia to self-catheterize after continent diversion [98]. This test has also been recommended as a valid measure of upper limb and hand function in a chronic SCI population [99].

Thorson's Functional Test

Investigators: Thorson et al. [100] (1999).

Purpose: Evaluation of hand functions when using a stimulation device, the myoelectrically controlled FES in individuals with tetraplegia.

Test composition: Eight unilateral tasks are divided into four groups, including moving flat objects, namely, CD covers of different weights and a thin book, moving cylindrical objects, drinking, and eating with a spoon. The total experiment, including preparation, takes less than 1.5 h.

Scoring method: The performance of the grip is rated on a three-point scale (0–2).

Psychometric properties: Not available [13].

Van Lieshout Test

Investigators: Van Lieshout G et al. [101, 102] (2000).

Purpose: To assess the upper extremity tasks that are associated with daily activities in patients with tetraplegia.

Test composition: It consists of 19 tasks that cover the majority of arm hand functions associated with ADLs. The test assesses positioning and stabilization of the arms; opening and closing of the functional hand, grasp, and release; and manipulation of objects using thumb and fingers.

Scoring method: The possible ways of performance of each task were described in six hierarchical levels, resulting in a score from "5," the highest level of accomplishment, down to "0," representing that accomplishment of the task is not possible at all. The score valuing principles of performance were ranging from low to high level of performance. Administration of the VLT provides a detailed and standardized assessment of tetraplegic hand function that allows therapeutic goal setting and monitoring of progress. Such an assessment takes about 60–90 min.

Psychometric properties: The VLT is responsive in measuring changes in AHSP during rehabilitation in persons with C-SCI. The VLT can be used to measure changes in AHSP in C-SCI persons with ASIA score A–D, as well as with a lesion C3–C6 or C7–T1. The responsiveness of the VLT is significantly correlated to the GRT, but not to the FIM and the QIF [103].

Van Lieshout Test-Short Form (VLT-SF)

Investigators: Van Lieshout G et al. [104] (2006).

Purpose: To reduce the total administration time and to be used in researches.

Test composition: The VLT-SF includes 10 of the 19 tasks. These tasks are forward reaching, arm extension against gravity, thumb closure, grip function of the thumb, thumb strength, finger closure, finger strength, pen grip, lighting a match, and opening a bottle. Some items involve basic arm skills like forward reaching, and other items involved hand and finger skills like thumb closure and finger strength. The items pen grip, lighting a match, and opening a bottle involve manipulation of objects.

Scoring method: The total VLT-SF score is the sum of the item scores, ranging from "0" (worst arm/hand function) up to "5" (best arm/hand function) with a maximum score of 50. Administration time of the VLT-SF is 25–35 min.

Psychometric properties: The VLT-SF highly correlates with the long version of the VLT. The criterion validity, the interrater reliability, the intrarater reliability, and the internal consistency of the VLT-SF are very good [104]. The VLT-SF is sensitive to detect changes in AHSP during rehabilitation in people with C-SCI [103].

Motor Capacities Scale (MCS)

Investigators: Fattal et al. [105] (2004).

Purpose: To focus on elementary motor abilities required to achieve ADL. It was specifically designed for tetraplegics who undergo a functional surgery of upper limbs.

Test composition: MCS includes 31 items classified in six functional categories: transfers, repositioning on Bobath's couch, repositioning on wheelchair seat, locomotion in a manual wheelchair and in an electric wheelchair, motor capacities of spatial exploration, and motor capacities for grasping and gripping.

Scoring method: Assessment is performed on the basis of an external evaluation and direct observation. A score, ranging from 1 to 5, is assigned for each task in the first four domains–transfers, repositioning on Bobath couch, repositioning on wheelchair seat, and locomotion. For motor exploration and for grasping and gripping, a two-point and four-point scales are, respectively, used. A total score is *calculated* by summing the subscores of each functional category. The completion time of the test is 20–50 minutes.

Psychometric properties: MCS displays a good apparent and content validity and an excellent reproducibility and constructible validity [106].

Capabilities of Upper Extremity-Test (CUE-T)

Investigators: Marino et al [107] (2012).

Purpose: It is intended to be used to detect changes in functional capabilities/limitations in the upper extremities of persons with tetraplegia.

The CUE-T was developed to find out the relationship between perceived difficulty in performing an action (CUE-Q) and actual ability to perform the action (CUE-T). It was developed as an objective measure of the ability to complete actions involving the arm and hand in persons with tetraplegia [107].

Test composition: Its items and procedures were developed based on the CUE-Q. It consists of 19 tasks, 17 unilateral (tested separately on the right and left sides) and 2 bilateral tasks, for a total of 38 items.

Scoring method: Depending on the item, scoring is based on completion of the action, the number of repetitions of the action, or time to complete the action. Raw scores are converted to a five-point scale (0–4) with 4 being best. Total scores are the sum of item scores; there is no item weighting. Right or left side scores can be obtained by adding the score of the unilateral items on each side.

Psychometric properties: It has excellent test–retest reliability and agreement, and there is some evidence of construct and divergent validity. CUE-T scores are highly correlated with UEMS, CUE-Q, and SCIM self-care score in persons with chronic SCI [108].

Toronto Rehabilitation Institute–Hand Function Test (TRI-HFT)

Investigators: Kapadia et al. (2012) [109].

Purpose: It has been designed to be used to assess the effectiveness of (a) hand therapies; (b) neuroprosthesis for grasping as an orthosis (i.e., as a permanent assistive device) in ADLs; (c) FES therapy for restoring voluntary grasping function; and (d) surgical restoration options such as tendon transfer surgeries. It has been designed to focus on an individual's ability to manipulate universally available standardized objects encountered in their daily lives and to evaluate the dexterity and strength of three specific gross motor hand functions—lateral pinch, pulp pinch, and palmar grasp [109].

Test composition: The TRI-HFT consists of 2 parts, including 14 items. The first part of the test assesses the individuals' ability to manipulate objects that they may encounter in their daily lives. To manipulate these objects, they are required to use one of the following: a lateral pinch, a pulp pinch, or a palmar grasp. The second part of the test measures the strength of their lateral pinch or pulp pinch and palmar grasp. The objects have been constructed to demonstrate the influence of different weight and texture on performance and to allow objective measurement of pinch force and circular torque.

Scoring method: A score, ranging from 0 to 7, is applied to items 1–11. The instrumented cylinder, credit card, and wooden bar are used to measure the torque generated by palmar grasp, the force that the pinch (lateral or pulp) grasp could resist, and the eccentric load that the palmar grasp could sustain, respectively (items 11–14). The TRI-HFT should preferably be administered by a hand or upper extremity specialist (physiotherapist or occupational therapist). The entire evaluation for both hands can be completed in less than 30 minutes.

Psychometric properties: The TRI-HFT is a reliable and sensitive measure to assess unilateral hand gross motor function in persons with tetraplegia, with moderate to strong construct validity when compared to the FIM and SCIM [109].

Specific Tests: Complex Activities

Rancho Los Amigos Hospital Functional Activities Test

Investigators: Rogers and Figone [110] (1980).

Purpose: To analyze the ability of individuals with high SCI to perform self-care activities.

Target population: Tetraplegic persons.

Test composition: Eight categories are included, namely, feeding, grooming, toileting and bathing, upper extremity dressing, lower extremity dressing, written communication, desk skills, and transfers. Three to seven items are tested within each category.

Scoring method: The items are rated on a three-point scale, namely, independent, assisted, or unable. The test also assesses the use of upper extremity orthotic and assistive devices.

Psychometric properties: Not available [13].

Quadriplegia Index of Function (QIF)

Investigators: Gresham et al. [111] (1980).

Purpose: To provide a more specific and sensitive instrument to document the functional improvements achieved during the rehabilitation of tetraplegic patients.

Target population: Tetraplegic persons.

Test composition: The index is composed of 10 variables and 37 items. These ten variables are transfers, grooming, bathing, feeding, dressing, wheelchair mobility, bed activities, bladder program, bowel program, and understanding of personal care. It is a clinician-administered questionnaire. Administration of the test takes 30 minutes or less when the assessor is familiar with the measure.

Scoring method: The items are graded on a five-point scale (0–4) in order of increasing independence. Each category of functional performance is calculated according to weighted scores.

Psychometric properties: The interrater reliability of the QIF was good [112]. The QIF appeared to improve significantly in both complete and incomplete tetraplegics between admission to and discharge from medical rehabilitation [71, 113]. Comparison of the total QIF to the total FIM resulted in a high correlation [71]. Comparison of subgroups of the QIF and FIM also resulted in high correlations between the subtests, except for the feeding subtest [72]. The QIF seemed to assess functional ability in the category of feeding more accurately than the FIM.

Normative data: Average scores on the QIF at admission and discharge are provided for persons with complete and incomplete tetraplegia [71].

Common Object Test (COT)

Investigators: Stroh [114] et al. (1989).

Purpose: Evaluation of the use of functional nerve stimulation.

Target population: Tetraplegic persons.

Test composition: The COT uses a task analysis approach to evaluate a person's ability to perform specific phases of an activity. Each ADL is broken down into phases, including acquire and release phases and several performance phases unique to each activity. For example, the performance phases of eating are stab, lift-lower, and bite.

Scoring method: The subject is scored on (1) independence of performance, (2) quality of performance, (3) preference, (4) frequency of an activity, (5) frequency of method, (6) frequency of method at the observed level of independence for both systems, and (7) importance of the activity to the subject. The scoring of independence of performance, i.e., physical assist, adaptive equipment, self-assist, or independent, is assigned for each phase of the activities [13].

Psychometric properties: Not available. In literature, this test was also used by Mulcahey et al. [115, 116].

Quadriplegia Index of Function (QIF)-Short Form

Investigators: Marino and Goin [117] (1999).

Purpose: To provide a sensitive global functional scale for measuring gains in individuals with tetraplegia during rehabilitation.

Target population: Tetraplegic persons.

Test composition: The test is composed of six items, which were selected from five of the functional performance categories of self-care and mobility. Items include wash/dry hair, turn supine to side in bed, lower extremity dressing, open carton/jar, transfer from bed to wheelchair, and lock wheelchair. It is a clinician-administered questionnaire like the original QIF. Administration time is under 5 minutes.

Scoring method: The items are graded on a five-point scale (0–4) in order of increasing independence like the original QIF. Contrary to the original QIF, the individual items in the QIF-SF were not weighted when determining the total score. Scores range from 0 to 24.

Psychometric properties: There is a high correlation between the QIF-SF score and the 37-item QIF score [13]. Its internal consistency is high for the total QIF-SF and is low to high for

QIF-SF items [117]. There is a significant difference in QIF-SF scores across the three measurement times (start of rehabilitation, 3 months after start of rehabilitation, and discharge) for groups C3–C6 and C7–T1 [103]. No values were reported for the presence of floor/ceiling effects in the QIF-SF for the SCI population.

Tetraplegia Hand Activity Questionnaire (THAQ)

Investigators: Land NE et al. [118] (2004).

Purpose: To construct a disease-specific questionnaire to evaluate interventions to the arm–hand of tetraplegics in terms of gained and lost activities relevant to the patient.

Target population: Tetraplegic persons.

Test composition: It is a questionnaire consisting of 9 subscales and 153 items. These subscales are self-care, dressing, continence, mobility, eating and drinking, work/admin/telecom, leisure, household, and miscellaneous.

Scoring method: Items are scored based on three dimensions: performance or doing (without difficulty (0) to help from others (3)); use of an aid (never (0) to always (3)); and importance of performing activity independently (not important (0) to very important (2)).

Psychometric properties: The expert panel found activities relevant for evaluation in individuals with tetraplegia, not covered in other literature, to be used as THAQ items (69%), particularly within the domains leisure, work/administration/telecom, and continence with 100%, 88%, and 87% new items, respectively.

Although there are many outcome measures to evaluate hand functions in patients with tetraplegia, none of them could reach an international acceptance so as to be referred to as a gold standard. The reason for this is that none of them meet the criteria for the ideal outcome measure in tetraplegics. The necessary criteria for choosing an appropriate test have been stated and include the following:

1. Activities appropriate for tetraplegic individuals representing their ability to perform actual ADLs requiring hand function
2. Insensitivity to learning
3. Standardized administration
4. An unambiguous scale that does not combine too many aspects of function (i.e., level of independence and time for completion scored concurrently)
5. Multiple trials to help ensure reliability
6. Sensitivity to changes provided by treatment or intervention to restore upper extremity function [13, 119]

Currently, there is no single test that meets all the above criteria. Therefore, before deciding which test to use, the most important issue is to decide whether the examiner wants to evaluate isolated hand function or overall body function in the level of activity and/or participation. So, as no patient is similar, the most appropriate test should be chosen for each individual tetraplegic.

Among the upper extremity outcome tools categorized according to the ICF domain "body function and structure," ISNCSCI is the most commonly used motor and sensory assessment. GRASSP is also a valid, reliable, and responsive outcome measure to evaluate upper limb function at the level of "body structure and function."

At the level of basic activities, general tests that are commonly used are "Action Research Arm Test" and "Sollerman Hand Function Test." Among them, only "The Sollerman Hand Function Test" has been showed to have reliability and validity in tetraplegics [61].

At the level of general complex activities, SCIM is the most widely used outcome measure to document change in ADLs in individuals with SCI. It is the only comprehensive skill test that is specifically designed for people with spinal cord injury [33, 73]. Since the original version, it was lastly revised in for the third time [33, 73]. The importance of SCIM seems to increase gradually, and its reliability and validity studies are carried out at international extent. Self-care activities of SCIM-III have been showed to reflect the upper extremity performance of tetraplegics successfully [87].

The Capabilities of Upper Extremity Questionnaire "Grasp and Release Test" and "Van Lieshout Test" are mostly used general outcome measures at the level of basic activities. Currently, the GRT maintains its popularity as an outcome

measure especially after arm/hand surgery in tetraplegia [49, 120]. "Van Lieshout Test" is a test of ADL, specifically designed for tetraplegics [33, 102, 104]. Although "Van Lieshout Test-Short Version" has been found to be valid and reliable, its use is limited to Holland [33, 103].

Among the tests specifically designed for tetraplegics, the most commonly used test at the complex activity level is "Quadriplegia Index of Function." Its validity, reliability, and responsiveness have been well documented [66, 113]. "Quadriplegia Index of Function-Short Version" is also preferred because of its high correlations with the long version and easy applicability [117].

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Hand Function in Parkinson's Disease

11

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Physiology of Hand Function

Parkinson's disease (PD) is a chronic, neurodegenerative disease whose primary pathophysiology is the loss of the dopamine-containing cells in the basal ganglia [1]. Deprived of their normal dopaminergic inputs, nuclei within the basal ganglia become dysfunctional leading to abnormal neural oscillations and synchronization within multiple basal ganglia-thalamic-cortical circuits [2]. These circuit disturbances lead to the clinical manifestations of the disease, which include such motor impairments as bradykinesia (slow movements), muscle rigidity, resting tremor, and postural instability. The impairment in voluntary movement in PD is characterized by a number of specific sensorimotor processing deficits, including a generalized slowness of movement [3]; a difficulty in carrying out sequential movements [4]; a reliance on sensory input, particularly visual input, to guide and correct movement [5, 6]; and difficulties in timing, synchronizing and coordinating movements [7–9]. Control of hand function can be quite compromised. This portion of the chapter will review the behavioral manifestations of impaired hand function in PD established by experimental data, and will discuss insights gained from these and related studies into neural control of hand function.

Role of the Basal Ganglia in Grasp Function

The fine motor skills of the hand, specifically for grasping and object manipulation, are thought to involve interactions among networks that include the anterior intraparietal area (AIP) of the posterior parietal lobe, the rostral portion of the ventral premotor cortex (PMrv), and primary motor cortex (M1) [8, 10, 11]. The basal ganglia receive massive inputs from most parts of the cortex, including inputs from AIP, PMrv, and M1, and project back to AIP [12], PMv [13, 14], and M1 [13, 15, 16]. The basal ganglia are strategically connected to cortical regions responsible for the planning and execution of hand movements and thus play an important role in coordinating activity within this network. The basal ganglia have been implicated in the control of predictive grasp planning during goal-directed movements and scaling of parameters such as grip amplitude and rate in precision grip (for review, see [11]). The loss of dopaminergic cells in the basal ganglia disrupts the discharge patterns of important neural signals across entire basal

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ganglia-thalamic-cortical circuits [17], thus compromising the functionality of many cortical areas important for skilled hand function.

Sensorimotor Deficits of Hand Control in PD

The coordination of sensory information with motor planning is crucial for appropriate execution of hand movements. The regulation of force control, an important parameter for proper hand function, relies on appropriate activation of the basal ganglia [18, 19]. In PD patients, the latency and rate of isometric force generation is impaired during both the generation and release phases of force production [20, 21]. Isometric force control in PD is also associated with increased variability in grip force with increased force magnitude or with the removal of visual feedback ([22]). Specifically, amplitude of corrective responses to visual feedback of force production is found to be greater for PD patients, which in turn corresponds to a greater variability of force output during the task. This variability may be due to increased response of long-latency stretch reflex processes [23, 24], delayed long-latency cortical inhibition of the motor potentials [25], and/or abnormal motor unit recruitment as seen in subjects with action tremor [26, 27]. However, it is not a function of decreased muscle strength [22]. Motor dysfunction in PD is also related to a dissociation between sensory feedback and motor output [28]. Sensory information about the hand in space is vital for the maintenance of dynamic goal-directed movements [29]. PD patients exhibit sensory deficits such as decreased spatial [30] and temporal [31] tactile discrimination thresholds of the fingertips, and deficits in proprioceptive acuity [32–34]. The integration of sensory information for the planning of an expected motor output is also impaired in PD [33, 35, 36]. Deficits of sensorimotor integration in PD have been proposed to underlie patients' reliance on external cues, such as visual feedback, to perform motor tasks [5, 33]. Impaired sensorimotor integration may also be responsible for PD deficits in hand dexterity [37]. For instance, when asked to produce a repetitive finger movement, PD patients have difficulty maintaining a synchronous response to an auditory tone [38], exhibit a decrease in movement amplitude over time [39], and an increase in finger lift duration [40]. Maintenance of a repetitive tapping rhythm also relies heavily on visual feedback of the hand during the task [41]. The spatial and temporal accuracy with which subjects are able to tap varies with medication [42–45] and is not a result of muscle fatigue [46]. This lends support to the idea that difficulties with sensorimotor control are a function of impaired central processing rather than faulty peripheral signals.

Grasping and Functional Hand Control

Much of what we know about hand function in PD stems from studies on grasp control. Although a seemingly simple task, to grasp an object one must appropriately shape the hand to the object by spatially and temporally coordinating multiple digits to the shape, size, and orientation of an object during reach ("preshaping") and choose contact points on the object allowing successful grasping and lifting of the object. After interacting with the object, it is imperative that the force exerted on the object is large enough to avoid slip but at the same time not so large as to result in destruction while also allowing the freedom of individual digit modulation to successfully manipulate the object to meet task demands. There are many facets within the process of grasping where small deficits could lead to major adverse consequences.

Reach-to-Grasp Impairments of reach are seen from the very start as patients exhibit difficulty in movement initiation to a target [47–49]. During the reach, PD patients exhibit deficits in hand preshaping to object geometry. Unlike healthy individuals where hand shaping to object geometry begins early after reach onset [50, 51], PD is associated with a delayed preshaping of hand configuration [8, 52, 53]. When objects are positioned in various locations in the workspace, PD patients correctly specify the movement direction while

simultaneously mis-specifying hand shape [53]. Grip aperture closure also is delayed [53–56], and the amplitude of maximum grip aperture is reduced [56–58]. In addition to grip aperture, abduction between the index and middle fingers which increases with grip aperture in control subjects is essentially nonexistent in PD patients until the end of the reach [8, 53]. In other words, PD patients do not open their grasp to the same extent that of control subjects while also waiting to close their hand until it is near the object. This is indicative of a dissociation between the timing of the reach and grasp components [59] and can affect the ability to manipulate objects properly. This is partially due to the loss of predictive control of voluntary movements in PD patients [60, 61]. Grasp planning for object manipulation is also impaired as seen as lack of adjustment of hand shaping to meet the task goals. For instance, healthy individuals produced different grasp configurations depending on whether a liquid was to be poured out of a bottle or whether it was to be thrown [62]. However, PD patients do not modulate hand shaping during the reach to meet task demands [52]. Corrective responses to object perturbations are also impaired in PD as seen by delayed motor adaptations to online changes in object size [63]. Consistent with their overall dependence on visual cues to control movement, PD patients also rely heavily on visual feedback to guide the movement of the hand to the object [8, 53, 55]. This over-reliance on vision may well be due to an impaired ability to extract critical proprioceptive information and integrate it with vision and motor commands [5, 36]. Thus, when visual feedback of the object and/or the hand is removed during the reach, PD patients take significantly longer to transport the hand to the object, especially at close range to the target, while producing a greater than normal grip aperture [64]. Removal of visual feedback of the hand during the reach also exacerbates inappropriate hand preshaping and results in significantly more failed grasps [8].

In addition to hand transport during reach, choice of digit placement on an object is important for successful manipulation [65, 66]. PD patients exhibit impairments in the planning of where to place their digits resulting in suboptimal performance of object manipulation compared to health controls [67]. Specifically, when lifting an object whose center of mass is shifted to the left or right side (Fig. 11.1a), PD patients exhibit poorer modulation of digit placement to counteract the distribution of the object's weight. Furthermore, PD patients exhibit less independence of contact points across digit pairs (Fig. 11.1b), suggesting impairments of fine motor control of digit individuation. Impairments in the planning of digit placement in PD patients are combined with an inability to anticipate appropriate forces in order to lift the object vertically. Figure 11.1c shows the average trial-by-trial performance of peak object roll for the PD and control groups tested in Lukos et al. [67]. Although the PD patients exhibited the ability to learn to anticipate the object weight distribution to some extent (i.e., object roll decreased over trials), they still failed to implement a grasp with the same degree of effectiveness as the control group. Thus, PD patients generated systematically greater object rolls across the entire block of trials. These data suggest impairments in the acquisition and/or utilization of the sensorimotor memories associated with the planning of digit placement and force coordination for object manipulation (for more details, see [67]).

Force Control During Object Manipulation

Force control when interacting with objects entails complex coordination between the magnitudes of the force used to squeeze the object (grip force) and the force used to lift the object (load force), as well as in the temporal transitions between grip, lift, and manipulation. Many studies have looked at PD coordination across these grasp phases. The temporal coupling of grip and load force development prior to lift is delayed in PD [54, 68–70]. This latency not only affects the force production but also increases the lift duration, thus slowing movement. Concurrently, the scaling of multi-digit force-sharing patterns to object properties during whole-hand grasp is impaired during grasp development [71]. Specifically, differentiation of the force-sharing patterns of the digits prior to lift was not adapted

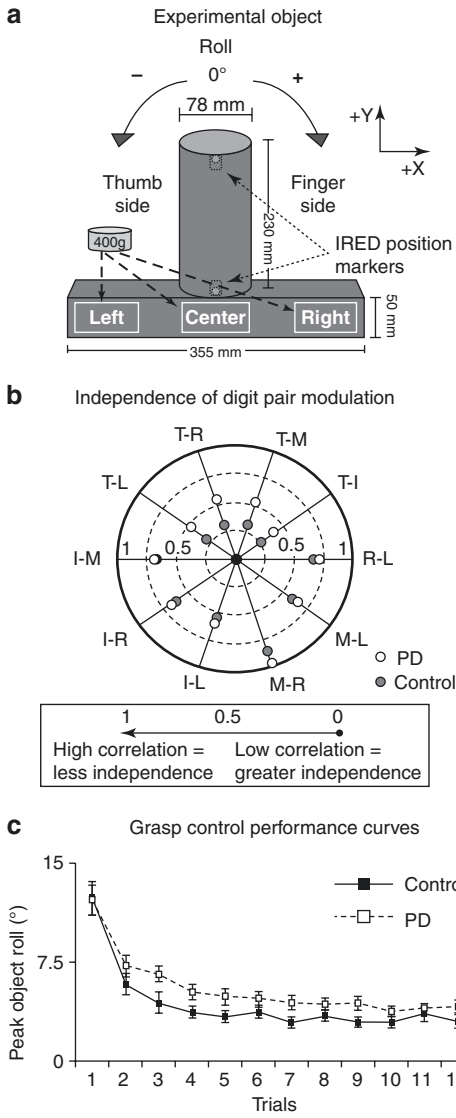

Fig. 11.1 Anticipatory control of digit placement is impaired in PD
Panel A is an illustration of the object used in Lukos et al. [67]. The graspable object (frontal view) was affixed to a horizontal base where a mass was added to the left, center, or right slots. Markers were placed on the object to record object roll, a measure of task performance caused by incorrect planning of digit placement and/or forces to counteract the added mass. Panel B is a polar plot with each solid line representing the axis of magnitude a digit-pair correlation. The correlation coefficient (Pearson's r) of each digit pair is shown as white and grey circles for the PD and control subject groups, respectively. Values near the center of the plot (closer to zero) are indicative of greater independence of digit-pair planning. T, I, M, R, and L denote thumb, index, middle, ring, and little fingers, respectively. Panel C shows the performance curves of peak object roll across trials for the PD and control groups (white and black symbols, respectively). This figure was adapted from Lukos et al. [67].

to the object weight distribution to the same extent as age-matched controls. However, after lift, subjects were able to use sensory feedback grasp performance (i.e., visual feedback of the object's position and haptic feedback of the forces exerted) to correct force-sharing patterns. This suggests impairment in anticipatory force modulation to meet task demands. It is hypothesized that predictive force control deficits are a result of central impairments associated with the generation and/or retrieval of sensorimotor memories for movement planning [71, 72]. However, these deficits in anticipatory grasp control are variable in PD and depend on task complexity, patient severity, and whether or not patients were tested on or off anti-Parkinsonian medication [73, 74].

Once an object is lifted, PD patients tend to produce greater grip forces than healthy age-matched controls [68, 75], regardless of whether they have explicit knowledge of how heavy the object is [74]. This may be due to impairments in tactile discrimination [30, 31] or sensorimotor integration [33, 35] described above, since cutaneous information from peripheral afferents has been shown to be vital for normal force production during precision grip (for review, see [76]). However, the coordinated relationship between grip force and load force which is present in healthy controls [77] is also apparent in PD patients during object manipulation [68, 74]. Force-sharing patterns across digits during the hold phase of whole-hand grasp are also maintained in PD [78]. Multiple factors including inappropriate generation and/or retrieval of sensorimotor memories, deficits in the coordination of multiple effectors, and impairments in sensorimotor integration likely contribute to the observed deficits in grasping and object manipulation in PD.

Pathophysiology of Motor Dysfunction in PD

Neuroimaging studies in healthy individuals have shown that activation of the basal ganglia is associated with multiple grasp functions, including

planning [19, 79, 80], execution [81, 82], and coordination [83]. Activation of brain networks in PD patients both at rest and during movement is altered and reorganized. During the execution of complex movements, PD patients show hypoactivation of rostral supplementary motor area, which has been proposed to underlie akinesia ([84–87]; see also [88]). Abnormal hyperactivity of motor cortex [85, 89], sensorimotor cortex, dorsal premotor cortex, and cerebellum [90] has been proposed to underlie bradykinesia and difficulties with movement amplitude and velocity. Decreased activation of the medial frontal cortical areas is also thought to underlie an inability for PD patients to initiate motor actions [91–93]. The reorganization of brain networks in PD also involves increased activations in parietal and premotor cortices [85–87, 94], as well as hyperactivity of cerebellar circuits [95] as mentioned above. The abnormal activation of many cortical regions in PD patients, especially those associated with motor planning of hand actions, reflects the importance of the functioning of the basal ganglia in maintaining the integrity of the entire circuit responsible for hand function.

As a general consideration, the basal ganglia output could be abnormal in PD either due to the amount of output or its pattern [96]. Constant hyper- or hypoactivity could act as a constant facilitator or brake upon target structures. One leading current view is that the output of the basal ganglia becomes excessively synchronized at low frequencies in PD or the MPTP model of PD [97–101]. Excessive synchronization means that abnormal network properties reduce responsiveness to the specific signals related to a particular context or action. In addition, the output may lose topographic specificity, with a loss of finely differentiated parallel processing [102]. In most general terms, the signal-to-noise ratio of basal ganglia function is impaired in Parkinsonism [103]. In addition to abnormal activation of many cortical regions, PD patients exhibit distorted and slowed oscillations of brain activity as observed through electroencephalography (EEG) recordings of scalp potentials [104]. There is distorted cortical and subcortical activity that is thought to result from disruptive activity and abnormal rhythmic synchrony within the basal ganglia circuitry, particularly in the beta frequency band (10–30 Hz) [105]. Abnormal synchronous firing patterns of neurons in the basal ganglia are present in parkinsonian monkeys [106–108] and human patients [109–111]. A recent study recorded scalp EEG in PD patients while modulating the subthalamic nucleus activity via deep brain stimulation [112]. Therapeutically stimulating the subthalamic nucleus at high frequency improved the ability of patients to inhibit a motor response, while at the same time modulating task-related beta band activity recorded over (right) frontal cortex toward the pattern seen in controls. One current hypothesis of the pathophysiology of PD is that increased "neural noise" in the basal ganglia underlies motor variability, movement delays, difficulties with prehension, and other motor actions [113, 114].

The reorganization of firing patterns in the cortical circuits of PD patients favors externally guided feedback of motor control as a compensatory alternative to the dysfunctional internally guided anticipatory control circuits. The behavioral correlates of this neural reorganization include: increased reliance on visual feedback for movements of the arm; a reduced ability to preshape the hand while reaching for an object reflects impaired internal prediction in mapping dynamically changing hand configurations onto object properties; and a reduced ability to coordinate multiple body parts (hand and arm) during movement. Such deficits in PD have been well documented (e.g., [5, 7, 8, 53, 115]).

Deep Brain Stimulation Recently, there has been a significant shift in the therapeutic strategies in common use to treat PD. After a period dominated almost entirely by the use of pharmacologic treatments, relying for the largest part on dopaminergic medications (the dopamine precursor levodopa and varied dopamine agonists), surgical interventions have come back into favor. Beginning with targeted lesions (pallidotomy and subthalamotomy), there has now been a substantial shift towards the use of deep brain stimulation (DBS). Most recently unilateral or bilateral subthalamic stimulation (STN) has become the surgical procedure of choice [116–120], more effective even than optimal pharmacotherapy in

the advanced patient [121]. Invasive procedures, such as DBS of the subthalamic nucleus show improvements of motor performance in many patients (for meta-analysis, see [122]). A recent study by Schettino et al. [123] showed that STN DBS resulted in a more normal pattern of hand preshaping when reaching to grasp an object, a pattern not seen with dopaminergic therapy in a previous study [8]. Specifically, when reaching towards an object that was convex on one side (Fig. 11.2a), healthy control subjects tended to generate temporally coordinated trajectories of grip aperture (between the thumb and index finger) and abduction (between the index and middle fingers). This is shown in Fig. 11.2b (top plot) as an increase and decrease in the aperture and abduction at similar times throughout the reach. This pattern was not true for PD patients without DBS. Although changes in the aperture were present, abduction remained static throughout the reach (Fig. 11.2b, bottom plot). However, when stimulation was turned on, coordination between aperture and abduction was partially regained (Fig. 11.2b, middle plot). The temporal synchrony of the aperture and abduction trajectories can be assessed through cross-correlation analyses. Figure 11.2c displays a peak in the correlation curve at the midpoint (100th point) for the control subject (dashed line), which corresponds to zero latency in the coordination

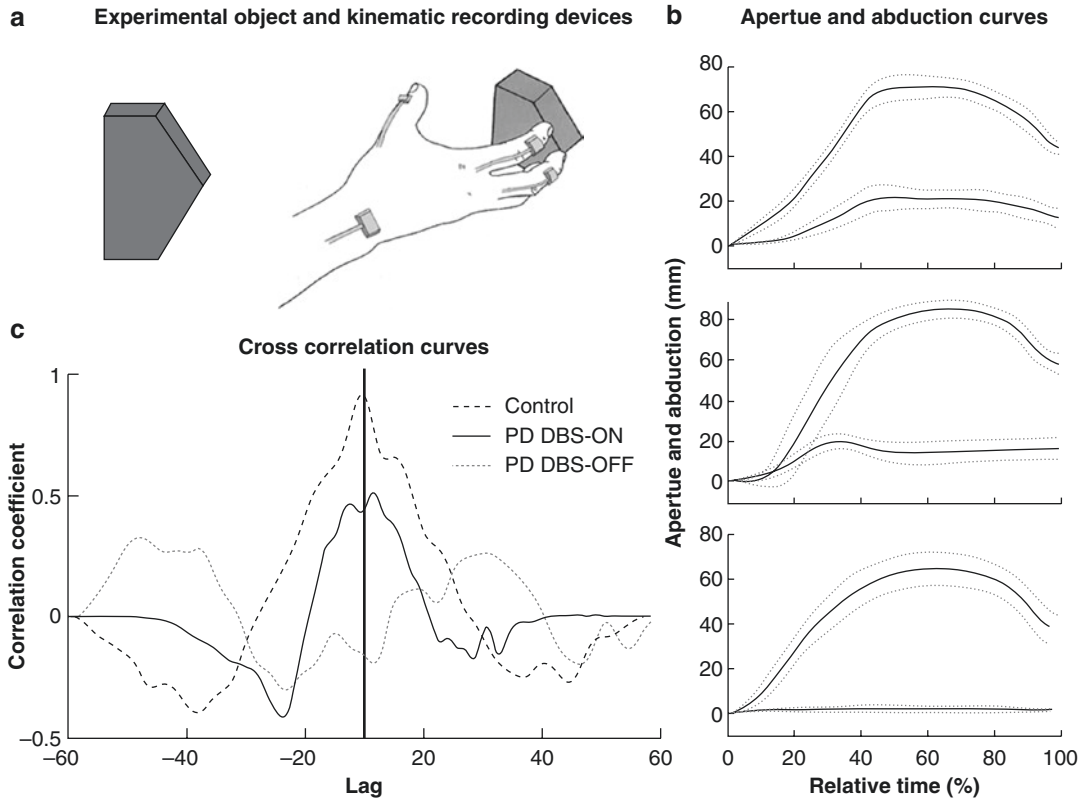

Fig. 11.2 Deep brain stimulation improves coordination of hand preshaping during reach
Panel A shows the object used in (right) and motion capture sensor positioning of the subjects' hand (left) in Schettino et al. [123]. Panel B displays the mean (± standard deviation) curves for aperture and abduction (higher and lower amplitude curves, respectively) for a representative age-matched control subject, a PD patient with DBS on, and the same patient with DBS off (top, middle, and bottom plots, respectively). Panel C shows the cross-correlation curves for a representative age-matched control subject, a PD patient with DBS on, and the same patient with DBS off (dashed, solid, and dotted lines, respectively). A temporal lag of zero between the coordination of aperture and abduction is centered around 100 on the horizontal axis. This figure was adapted from Schettino et al. [123].

between the aperture and abduction curves. Conversely, there is no significant correlation between the trajectories for the PD patient off DBS (dotted line), thus no temporal synchrony between aperture and abduction. Yet, the curve when DBS was turned on shows a peak at the midpoint (solid line). Although the peak was not as high (i.e., the correlation was not as strong), the PD patient(s) with DBS on exhibited temporal synchrony for the coordination of the aperture and abduction. Therefore, DBS resulted in increased spatiotemporal coordination of hand shaping during grasp. For more details, see Schettino et al. [123]. Other groups have looked at force regulation with DBS and have shown improvements of force regulation during grasp [124, 125]. Specifically, the overexertion of forces on an object traditionally associated with PD was partially remedied with DBS. However, others have noted improvements in hand mobility and dynamics, but with minimal enhancement or even worsening of performance during grasping tasks [126, 127]. Thus, this method deserves further investigation to reveal the processes by which improved motor function is obtained. With continual improvements of medical devices for the localization of optimal insertion of electrodes for stimulation of the basal ganglia, better understanding of the ideal parameters with which to provide stimulation, and the increasing knowledge of the neural circuitry responsible for motor function, the mechanisms by which the basal ganglia are affected by DBS and its efficacy could be greatly enhanced in the future.

Noninvasive Electrocortical Stimulation Cortical electrical stimulation has become an experimental treatment of PD motor symptoms aimed at altering the output of the brain networks through the application of an electrical current. Noninvasive brain stimulation techniques, such as transcranial magnetic stimulation (TMS), electroconvulsive therapy (ECT), and transcranial direct current stimulation (tDCS), have shown to modestly improve motor deficits in PD [128, 129]. Repeated rTMS therapy sessions (eight sessions over 4 weeks) have also shown gradual improvement of complex hand movements with after effects lasting 1 month posttreatment [130]. Others have combined techniques by following tDCS by repetitive TMS (rTMS) over the motor cortex and found improvements of bradykinetic hand movements, yet no influence on hand coordination [131]. Still, more work needs to be done to determine the appropriate stimulation sites, duration of the treatment and intensity of the stimulus, as well as determine effectiveness. For instance, rTMS can cause either excitation [132] or inhibition [133] of cortical excitability depending on the stimulation frequency. Thus, noninvasive stimulation has the potential to be a means of PD therapy; yet, the particular methods by which to transmit the appropriate signals are still under investigation.

Clinical Aspects of Hand Function

Tremor

Tremor in one hand is often the initial manifestation of Parkinson's disease that is obvious to the patient or family. It usually is present at a frequency of 4–6 per second and may be confined to a small part (for example one finger). Some patients note that the tremor begins in the index finger or the thumb. Typically, the tremor occurs when the affected hand is at rest. The shaking is regular and rhythmic. A simple, small to-and-fro motion of the arm may be all that is obvious. . More often, there is a complex movement, with slight turning of the forearm and a back and forth movement of the thumb and fingers reminiscent of a hand counting coins or of rolling a marble between the thumb and forefinger. Hence, the tremor has been described as "pill-rolling" in quality [134].

The tremor disappears during sleep or when the patient is relaxing quietly. Thus, it may be present only intermittently, and its presence reflects the patient's state of mind. Nervousness or stressful situations or even the alertness induced by concentrating on a mental task regularly enhances the tremor. The patient may be sitting at home reading a book until some excitement

in the storyline or the arrival of a visitor makes the tremor reappear. Resting tremor is often more embarrassing than functionally problematic for many patients because it tends to disappear with action. [134]

A characteristic feature of tremor in PD is its variability. It seems to come in bursts and then subsides. The tremor in one part need not be synchronous with that in another. In fact, tremor may appear in one hand for a few minutes or less and then quiet down only to appear in the other hand or another limb. Most patients are able to stop the tremor by an act of will. Many learn various tricks to stop it. A slight movement or change of posture may arrest the tremor for a while; eventually it reappears after some minutes or longer. Other patients keep the tremulous hand in a pocket, moving it slightly to keep the tremor at bay [135].

Tremor in one hand while walking disappears if the patient remembers to swing the arm. It reappears when the patient forgets and allows the arm to hand idly at the side- as if the tremor were a substitute activity. Holding something in the hand can also stop the tremor. We have seen patients who carry a package in the hand while out walking, just to stop the tremor. [134]

So far, we have discussed the resting tremor of PD. Nearly half of all patients, however, have a postural and/or action tremor. Many patients have both a resting and action/postural hand tremor, but some patients have only the latter. Like the resting tremor, postural and action tremors may be unilateral or, if bilateral, are usually worse on the more involved side. They are generally more functionally disabling than the resting type, since they become most prominent when the patient is doing something with the involved hand. Simple activities such as using a screwdriver, eating a bowl of soup or even holding a newspaper can become major sources of discomfort or disability. [136] There seems to be a subset of Parkinson patients who have prominent action/postural tremors, often in conjunction with a prominent resting tremor, who have a slower progression than the usual patient. This group can be labeled "benign tremulous parkinsonism." These tremor types can unfortunately be relatively unresponsive to anti-parkinsonian medications (vide infra).

Patients may feel a tremor that they describe as internal to the affected hand or arm. Sometimes, it is a tremor that is simply too fine to be noticeable to either the patient or the family. It may be felt as a quivering or vibrating sensation. Some patients say it is a tremor that is felt in the muscle but many patients describe a feeling of quivering in the bone of the limb. The sensation is usually felt in the forearm or the upper arm and rarely in the hand itself. These internal tremors are often more uncomfortable and therefore more disabling than outright resting or postural/action tremors. [137]

Bradykinesia and Rigidity

Strictly speaking, rigidity of the hand or arm is not a symptom the patient feels but an objective sign that can be appreciated only by another person examining the patient for evidence of resistance to passive motion of the limb. Patients with rigidity, however, often complain of a feeling of stiffness, which is perhaps the subjective appreciation of rigidity. It is surprising that many patients with clear-cut rigidity do not complain of stiffness. To examine the arm for rigidity, the physician takes the patient's arm and gently bends and straightens it a number of times while asking the patient to relax. Rigidity can be tested best at the elbow or the wrist. When testing at the elbow, the movements can be increasingly rapid flexion and extension maneuvers. At the wrist, a slow, gentle rotational movement is best to elicit signs of rigidity. If there is no rigidity noted after a number of trials, facilitation strategies are employed to elicit it. The usual way to facilitate the chances of finding a rigid arm is to ask the patient to open and close the other hand. This should immediately bring out the rigidity in the arm under examination. A persistent resistance to passive motion of the wrist or elbow with a plastic or lead pipe quality is what is meant by rigidity. There is often a regular, jerky quality to the resistance as if

there were a ratchet gear or cogged wheel in the joint being manipulated. That feeling represents the underlying tremor acting on the rigid limb and is known as "cogwheel rigidity." One can also look at rigid muscles and note that they are tensed constantly in a state of sustained contraction. The tightness and firmness of the muscles can be palpated.

Rigidity in the arm needs to be distinguished from the increased tone associated with spasticity. Arm spasticity is best elicited if the examiner passively pronates and supinates the forearm. The resistance tends to increase with movement and then gives way (the clasp knife reaction). This is in marked contrast to the plastic rigidity of Parkinson's disease.

Rigidity certainly slows movement, but bradykinesia in Parkinson's disease is a phenomenon that should be separated from mere rigidity. Slowness of movement can be seen in an arm that is not rigid at all, and fairly rapid movement can be seen in limbs that have significant increased tone. One of the commonest manifestations of bradykinesia in the arm is loss of automatic, associated movements. The patient does not swing the affected arm or swings it less than the unaffected arm. Furthermore, a normal person does not keep the arms perfectly still while sitting. We tend to move the arm, perhaps even tapping the fingers or fidgeting a little. A patient with Parkinson's disease, on the other hand, may leave the arm perfectly still at his side or in his lap for long periods of time. There is an extreme poverty of spontaneous movement in the arm and hand. This poverty of motion can lead to frozen shoulders, elbows, or even wrists in the untreated patient and even in some patients who are being treated with antiparkinsonian medications.

Another aspect of bradykinesia is hesitation on initiating movements with the affected arm. There may be rapid fatigue that severely limits the amount and type of manual activity that a patient can do. Repetitive movements with the fingers or the whole arm tend to be difficult to accomplish. It can be difficult for a patient to do two things in succession such as putting an arm into a sleeve and then using the same arm to button the coat. This in part may be due to concomitant problems with executive function but can simply be related to bradykinesia. At any rate, it makes ordinary activities that require the use of the arms, such as dressing or eating, take longer and give them the appearance of being done in a too deliberate manner [134].

Bradykinesia varies considerably from moment to moment and in different circumstances. The phenomenon is especially striking in severely affected patients. A patient who can barely use his arms suddenly and inexplicably is able to dress himself. In general, automatic acts of daily life are most affected by bradykinesia and learned acts less so. This has been called paradoxical kinesia. Hence, a severely bradykinetic patient may play the piano tolerably well but does not swing the arm at all while walking [134].

Hand Function in Activities of Daily Living

Characteristic changes in handwriting occur in Parkinson's disease patients. These changes may be of diagnostic value to the physician and are often early and problematic for the patient. The handwriting tends to get smaller (micrographia). The letters are generally well formed but get progressively smaller as the patient continues to write; by the end of a sentence or phrase, the letters may be so small as to be difficult to read. In addition, if one looks closely, tremor may be evident in the writing in the form of small squiggles in each letter [134].

With the increasing importance of computers in everyday life, difficulties with keyboard operations have become important to patients with Parkinson's disease. The most frequent early complaint is that patients tend to hold down a single key with the affected hand for much longer than they might wish. This leads to multiple, repeat letters in the text they are working on. Patients also miss keys, hit the wrong key, or are unable to move easily from one key to another. Speed of typing is severely affected.

There are many other problems with living activities that are impacted by the abnormal

hand and arm function of Parkinson's disease. Deficits in fine motor coordination lead to problems getting wallets or other objects out of coat or pants pockets. Extricating money from a purse or wallet may be nearly impossible. Toileting and shaving become a chore and putting on makeup can be messy at the very best. To tie a shoelace may take forever, as can buttoning. Poverty of movement, stiffness, and movement initiation difficulties, may make it difficult for a patient to get his arm into a coat or jacket sleeve without help from another person.

Examination of the Hand and Arm

Hand function is assessed best using reproducible and organized rating scales. The most widely used ratings scale is a modification of the Unified Parkinson's Disease Rating Scale (UPDRS). [138] Part II of the UPDRS measures activities of daily living. The two most relevant questions ask about hand writing and cutting food or handling utensils. The ratings are on a scale of 0–4.

Handwriting
- 0 = Normal
- 1 = Slightly slow or small
- 2 = Moderately slow or small; all words legible
- 3 = Severely affected; not all words legible
- 4 = The majority of words are not legible

Cutting food and handling utensils
- 0 = Normal
- 1 = Somewhat slow and clumsy, but no help needed
- 2 = Can cut most foods, although clumsy and slow; some help needed
- 3 = Food must be cut by someone but can still feed slowly
- 4 = Needs to be fed

Two other more indirect measures of hand and arm function are the ability to dress oneself and hygiene. The dressing question covers the ability to button and to get the arm into a sleeve.

Dressing
- 0 = Normal
- 1 = Somewhat slow but no help needed
- 2 = Occasional assistance with buttoning, getting arms into sleeves
- 3 = Considerable help required but can do some things alone
- 4 = Helpless

The question on hygiene covers bathing, brushing of teeth, washing, combing of the hair and going to the bathroom

Hygiene
- 0 = Normal
- 1 = Somewhat slow, but no help needed
- 2 = Needs help to shower or bathe; very slow in hygienic care
- 3 = Requires assistance for washing, brushing teeth, combing hair, or going to the bathroom
- 4 = Requires mechanical aids or Foley catheter

Direct examination of motor hand function is accomplished by Part III of the UPDRS, which includes sections devoted to tremor, rigidity, and motor coordination of the hand and arm.

Tremor at rest
- 0 = Absent
- 1 = Slight and infrequently present
- 2 = Mild in amplitude and persistent or moderate in amplitude, but only intermittently present
- 3 = Moderate in amplitude and present most of the time
- 4 = Marked in amplitude and present most of the time

Action or postural tremor of hands
- 0 = Absent
- 1 = Slight, present with action
- 2 = Moderate in amplitude, present with action
- 3 = Moderate in amplitude with posture holding as well as action
- 4 = Marked in amplitude; interferes with feeding

Rigidity
- 0 = Absent
- 1 = Slight or detectable only when activated by mirror or other movements
- 2 = Mild to moderate
- 3 = Marked, but full range of motion easily achieved
- 4 = Severe, range of motion achieved with difficulty.

Rigidity should be measured with the patient sitting and relaxed and should ignore cogwheeling which is an indication of underlying tremor rather than rigidity.

Finger taps (patient taps thumb with index finger in rapid succession with widest amplitude possible, each hand separately)
- 0 = Normal
- 1 = Mild slowing and/or reduction in amplitude
- 2 = Moderately impaired. Definite and early fatiguing. May have occasional arrests in movement
- 3 = Severely impaired. Frequent hesitation in initiating movements or arrests in ongoing movement
- 4 = Can barely perform the task

Hand movements (patient opens and closes hand in rapid succession with widest amplitude possible, each hand separately)
- 0 = Normal
- 1 = Mild slowing and/or reduction in amplitude
- 2 = Moderately impaired. Definite and early fatiguing. May have occasional arrests in movement.
- 3 = Severely impaired. Frequent hesitation in initiating movements or arrests in ongoing movement
- 4 = Can barely perform the task

Rapid alternating movements of hands (pronation/supination movements of hands, vertically or horizontally, with as large an amplitude as possible, each hand separately)
- 0 = Normal
- 1 = Mild slowing and/or reduction in amplitude
- 2 = Moderately impaired. Definite and early fatiguing. May have occasional arrests in movement
- 3 = Severely impaired. Frequent hesitation in initiating movements or arrests in ongoing movements
- 4 = Can barely perform the task

In addition to poverty of spontaneous hand and arm movements such as a diminished unilateral or bilateral arm swing when walking, Parkinson patients have a typical hand posture that is evident even early in the disease. The outstretched hand is held flexed at the metacarpal/phalangeal joints and is also slightly flexed at the elbow. Full range of motion at the shoulder is often not possible and the shoulder may be lower on the more involved side in comparison to the less involved side.

Sensory Symptoms

Various types of pain syndromes can interfere with hand function in Parkinson patients. [139]. Diminished spontaneous movement of the arm, as described in the previous section, often leads to frozen shoulders or less frequently frozen elbow. This condition not only causes poor movement of the involved joint but also causes significant and sometimes disabling pain. Dystonia, usually drug induced from levodopa preparations, but sometimes spontaneously, can cause painful cramps [140]. These dystonias can involve any combination of hand and arm muscles and sometimes resemble those seen with writer's cramp or other occupational dystonias. Another not uncommon complaint is pseudoradicular pain mimicking cervical radiculopathy [141]. The pain may start

in the elbow and radiate both distally and proximally to the shoulder or may start in the shoulder and radiate to the hand. Finally, a host of nonspecific symptoms cause functional hand problems. These include numbness, soreness or the muscles or bones, aching, tightness and feelings of abnormal temperature sensations in the arm or hand (cold or hot) [142]. As with many symptoms of Parkinson's disease, the hand or arm on the more affected side is usually more likely to display these sorts of symptoms.

Dyskinesias Associated with Treatment

Choreiform movements and dystonic hand postures often are the consequences of treatment with dopaminergic agents for Parkinson's disease [143]. These most commonly occur with peak dose concentrations of levodopa (high dopa dystonia) but also can occur with inadequate levels of levodopa during "off" periods (low dopa dystonia) [144]. Both types of involuntary movements interfere with fine motor tasks such as eating, shaving, buttoning, writing, keyboard maneuvers, etc. Occasionally, they are more disabling than the bradykinesia and poor motor coordination directly related to the Parkinson motor signs [145].

Future Directions

Studying PD patients is an important way to understand the role of dopaminergic pathways originating in the basal ganglia for the regulation of hand function. Although our knowledge on hand function in PD has been greatly enhanced in the last few decades, there are still many aspects of PD hand dysfunction that are yet to be understood. Technological advancements are now allowing a more detailed examination of the behavioral deficits and the neural processes responsible. For instance, improvements in signal extraction in EEG through the use of high-density recordings with active electrodes and advanced signal processing techniques during movement now permit the recording of dynamic brain activity simultaneously with kinematic movements during motor tasks to gain a better understanding of how the hand is controlled [146]. Furthermore, combining EEG with functional magnetic resonance imaging (fMRI) provides both temporal and spatial resolution of cortical activity [147–149], which will greatly increase our knowledge about the reorganization of the basal ganglia circuitry. Directly recording from the STN and other brain regions in humans during surgery is providing direct evidence of altered neuronal firing in key circuits underlying PD (e.g., [150]). These and other methods are leading to new insights into the pathophysiology of PD and effect of current pharmaceutical and surgical therapies on the control of movement.

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Hand Function in Cerebral Palsy

12

Evrim Karadağ Saygı

Cerebral palsy, the most common cause of neurological disability in childhood, is a developmental disorder that results from a nonprogressive lesion in the developing brain but creates activity limitations changing depending on the age. Marked loss of motor function, posture, and movement disorder are some of the symptoms [1]. More than 50% of children have upper limb problems, with significant wrist and hand involvement. Upper limb contracture was reported in 36% of these patients and decreased hand control in 69% [2, 3]. A common problem associated with poor hand function as a consequence of spasticity is the difficulty of the child with fine motor tasks such as grasping objects and manually writing or cutting. Also these patients have difficulties in coordinating movements against spasticity. The performance of hand tasks in these patients requires gross and fine hand movement coordinated with visual perception and postural control to reach, grasp, release, and manipulate objects [1, 3]. The motor disorders seen in these children are complex. Muscle tone abnormalities changing depending on the position, posture and motion, balance and coordination disorder, decreased muscle strength with loss of selective motor control, and contractures and deformities are often seen. Persisting from infancy, affected children may have abnormal hand postures such as thumb adduction and/or flexion with limited wrist extension [4, 5].

Although there is various type of cerebral palsy, spastic, dyskinetic, or a combination of these can occur. Spastic cerebral palsy is the most common subtype. It is further classified as unilateral (hemiplegic) bilateral (diplegic and quadriplegic) spastic cerebral palsy. Upper limb problems vary according to the type of cerebral palsy, the degree of spasticity, the severity of muscle weakness, and the size of sensory loss [3]. Most diplegic children have slight fine motor disorders but gross motor functions are usually good. Hand involvement is more severe in hemiplegic and quadriplegic patients, affecting varying degrees of severity from fine motor skills to severe deformities [3, 6]. Especially in hemiplegic children, sensory dysfunction is present in half of the patients, and stereognosis and two-point discrimination are the most important sensory problems. All of these problems prevent proper positioning of the hand in space and functions such as proper grip and release [5, 7]. In the following period, in addition to functional limitations, the body image perception may also deteriorate. Cosmetic worries can even come to the forefront over time. Maceration and infections can occur in skinfolds in severe deformities. In addition, difficulties in using assistive devices can also lead to ambulation problems [2, 8]. Dyskinetic type is marked with jerky, uncontrolled movements that may be slow or

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rapid. These may occur in any number of regions of the body but are most likely to occur in the hands, face, neck, arms, legs, and sometimes in the trunk. Dyskinetic patients may have twisting and repetitive movements (dystonia), slow and stormy movements (athetosis), and dance-like irregular movements (chorea). These involuntary movements often cause trouble holding writing implements, utensils, and other items. Moreover, they tend to be greater whenever the patient is upset, excited, or tired.

Since cerebral palsy is a lifelong disability, its main objective is to maximize the child's functional potential and to ensure independence as much as possible in life. However, it is not easy to determine the effective treatment method because clinical presentation creates a wide heterogeneity. At this point, detailed examination, follow-up of the patient, and recording the symptoms are significant [9]. Although the literature suggests that the clinical assessment of sensorimotor function alone is not sufficient, it may be complemented with information about neural, structural, and functional integrity. Diversity of brain lesions in patients is also the main determinant of clinical picture [10]. The location and extent of the lesion detected on cranial imaging can be combined with time-point of insult to clarify the clinical picture. However, the presence of different imaging findings of two children with similar sensorimotor function can only be explained by early neuroplasticity [10, 11]. Just at this point, the patient should consider seeking care at the earliest signs of disease. Accordingly, recording the combination of detailed examination findings and imaging methods should be emphasized once again, and the appropriate treatment plan should be started immediately. It should be borne in mind that each patient is unique, and it's essential not to lose time while searching for the most suitable one.

What Kind of Hand Functional Troubles Exist in Cerebral Palsy?

The impact of cerebral palsy on a child's hand functioning may be more easily explained through the framework of the International Classification of Functioning, Disability and Health (ICF). The ICF consists of two parts: "functioning and disability" and "contextual factors." The first part concerns more about the health status of the individual and is divided into "body functions and body structures" and "activities and participation" sections [12]. Body structures are anatomical pieces and correspond to components such as muscles, joints, and bones. On the other hand, muscle strength, control of rapid coordinated movements, touch-pressure detection, and recognition of common objects and shapes are defined as body functions [12, 13]. Upper limb deformities resulting from the imbalance between the spastic and paretic muscles are mostly seen in hemiplegic and quadriplegic children. In the upper extremities of diplegic, fine motor skills such as using pencil, cutting with scissor, and holding spoon have more difficulty, but no significant deformity is detected [2]. Shoulder adduction, internal rotation, and flexion contracture may occur in quadriplegic patients due to spasticity of the subscapularis and pectoralis major muscles in shoulder [2, 14]. Two-jointed biceps and pronator teres muscles are the main muscles responsible for the development of deformity in the upper limb. It is also stated that the first muscle that develops contractures in the hemiplegics is the pronator teres and the botulinum toxin injections to the upper extremity are frequently applied to this muscle [15].

The pronation of the forearm and thumb in palm deformity is the most common upper extremity problem in children with cerebral palsy [14, 16]. The parents seeing their newborn's movements to reach and catch something notice distinctive hand preference. During this period, thumb-in palm deformity where the thumb is in adduction and flexion makes the grip difficult [17]. Together with dislocation in metacarpophalangeal joints, hypermobility and swan-neck deformity in the proximal interphalangeal joints can also be observed which disrupts opposition [2, 14]. If the spasticity is intense, shortening of the finger flexors starts and the hand function is severely impaired unless rehabilitation is initiated. Even in the early stages, bimanual activities become impossible due to children ignoring plegia [5, 6, 7]. The presence of more

proximal problems of the upper limb also makes hand use more difficult. Because of the spasticity in pronator teres and flexor muscles of the wrist, the active supination and wrist extensions are limited. Accompanied by the elbow flexor spasticity, the upper limb and hand functions are even more deteriorated (Fig. 12.1). Limited passive range of motion and poor selective motor control result in abnormal posture and joint positions at hand. Limb growth in plegic side deteriorates with spasticity and weakness. Bimanual use is markedly limited by difficulty with selective muscle control and/or co-contraction as well as developing contracture and finally a daily life with a single extremity starts [5].

Due to spasticity, involuntary movement control, muscle weakness, the activity limitations and participation restrictions are frequently seen in children with cerebral palsy [12]. The activity symbolizes the life of the individual and participation means integration in the society [13]. While especially fine works are done by the help of the dominant hand in daily life, non-dominant hand helps the dominant hand to do fast and skilled work by assisting to hold and grasp. Many children with cerebral palsy experience difficulty in reaching, grasping, releasing, or manipulating objects due to hand-eye coordination disorders, tactile dysfunction, or sensory problems. For this reason, many children need help in routine daily activities such as eating, drinking, grooming, or dressing. This creates difficulties in social life, including the long-term upper limb and primarily the school. When children try to finish the works that need to be done bimanually with just one extremity, they have difficulty in completing the mission or just finishing it in time. At this point, overprotective attitude of parents goes into effect. The individual with cerebral palsy is isolated from his/her peers and friends. Even they don't want to leave home. It is crucial that teachers and parents are more patient and encouraging at this point in terms of patient participation in society [5, 13, 18].

Fig. 12.1 The spasticity in pronator and biceps muscles is very important for the hand functions of children with unilateral cerebral palsy

Pathophysiology of Impaired Hand Function in Cerebral Palsy

The voluntary motor movement of the upper limb is provided by the contralateral primary motor cortex. If the movement is complex, the premotor area and the complementary motor cortex also come into play. The movement-related information collected from the cerebral cortex is transmitted to the spinal cord with corticospinal tract. The information that comes out of the motor cortex goes down to the brainstem and proceeds through the brainstem over medulla. At the base of the pyramids, about 90% of the fibers in the corticospinal tract decussate, and they will then enter the spinal cord where they originated as part of the lateral corticospinal tract. The other 10% of the fibers will continue into the spinal cord on the same side of the body where they originated as part of the anterior corticospinal tract. The lateral corticospinal tract controlling the movement of more distal muscles like those of the hands, and the anterior corticospinal tract controlling the movement of more proximal muscles like those of the trunk [10, 19].

White matter development during brain maturation occurs between the 24th and 34th weeks. Association tracts and afferent/efferent projection tracts arise from the neuroepithelium surrounding the lateral ventricle. The projections of the corticospinal tract are initially bilaterally crossed and uncrossed. Over time, the ipsilateral uncrossed projections gradually weaken and the contralateral crossed projections strengthen. This situation, defined as "competitive withdrawal," results in a markedly contralateral control of the upper limb [20].

The severity of impaired hand function in children with unilateral cerebral palsy closely relates to the integrity of the corticospinal tract innervating the affected hand. At this point, time of insult as well as the location and extent of the lesion is of critical importance. Periventricular lesions occurring between 24th and 34th weeks cause less motor and tactile deficits and better arm and hand function than cortical-subcortical lesions occurring after 34 weeks or immediately postnatally or postnatal acquired lesion [21]. In patients with periventricular lesions, corticospinal projections are often damaged in white matter around the ventricle as they go to the internal capsule from primary motor cortex. In this case, the crossing fibers in the affected hemisphere are interrupted, and the ipsilateral projections are strengthened. In patients with cortical-subcortical lesions, the crossing corticospinal projections are often preserved, as the lesion is distant from the periventricular white matter. However, if the early lesion is large and causes the affected upper limb to "rewire" as it provides input from the lesion-free ipsilateral hemisphere, this results in worse performance with contralateral control at the affected upper extremity compared to the children with periventricular lesions [10, 19, 22].

Assessments Tools and Classification Systems Evaluating Hand Function in Cerebral Palsy

The assessment of the function and performance of the upper limb is important in defining the level of skill in the person's daily life activities, the effectiveness of the rehabilitation and the role skills of the person. Hand assessment tests are important approaches in determining the functional capacity of the upper limb [6, 7]. Because inadequacies in hand functions influence daily living activities and performance in work and leisure activities. The functionality of the hand, which has a rather complex structure to fulfill various functions as gripping, holding, touching, and catching, depends on its anatomical integrity, muscle strength, sensory function, skill, and motivation. Factors such as age, gender, mental status, and dominant hand can influence functional abilities [5, 9, 12]. The development of hand functions depends not only on the motor control of the upper limb but also on sensation-perception-motor, cognitive, and visual development. The most basic motor activities of hand functions are various concepts, gripping and dropping patterns. These activities contribute to the development of gross motor activities in supine, prone, sitting, standing, and walking position [9, 23]. The development of the upper limb function also depends on the posture of lying, sitting, and standing. Hand use is also very helpful tool for cognitive-perceptual development and emotional happiness in children [6, 24].

Criteria used in evaluating hand and wrists generally focus on joint range of motion, strength, and sensation, and these evaluation methods ensure that the results are objective. The passive-active ranges of motions are evaluated by goniometric and visual measurements. The Upper Extremity Rating Scale used for this purpose is also a simple, reliable, and reproducible method. Modified Aschworth and Tardieu scales are often used for tonus evaluation. With the Zancolli Classification, voluntary isolated movements of the wrist and fingers are assessed by gripping and releasing movements [25, 26]. Selective motor control test has been frequently used for these patients in recent years, whose selective motor control is often impaired [27, 28]. However, these methods do not assess the subjective factors that affect the result such as pain, skill, participation in daily life activities and return to work, which enable the person to continue his/her daily life. As a result, evaluation of tonus, range of motion and strength is under the heading of body structure/function. On the other hand, in recent years, outcome measures developed specifically for individuals with cerebral palsy aim to measure the level of participation in daily life activities and the degree of strain during activities [6, 25].

When the literature is examined, it is seen that there are more than 50 tests available for upper limb assessment in children with cerebral palsy, but some of these tests are frequently used (Table 12.1). The ICF emphasizes the impor-

tance of measuring or addressing hand function in children/youth with cerebral palsy not only in terms of body structure and function but also in terms of activities, participations, and environmental factors (Table 12.2). Hand function can be assessed according to the individual's functional performance (what the child usually does) or by testing what a child is able to do on request (capacity) [6]. Since these two conditions cannot always be equal, it is important that the patient has either a functional assessment or that the test involves both concepts in follow-up treatment. The scales used should be suitable for the purpose and also should be sensitive to the development process of the children, the cultural structure in which they are involved, and the changes in the general level of life. For this reason, validated and reliable scales should be preferred [6, 25, 29].

Manual Ability Classification System is a simple classification system used frequently in everyday clinical practice that classifies how children use their hands while holding objects in everyday activities (Table 12.3). It is used as of 5 years of age and mini-MACS have been developed for the smaller age group (1–4 years) [30]. The House Classification is also used for thumb-in-palm deformity, the most common thumb deformity. Starting from the Type 1, the metacarpal adduction contracture, it continues up

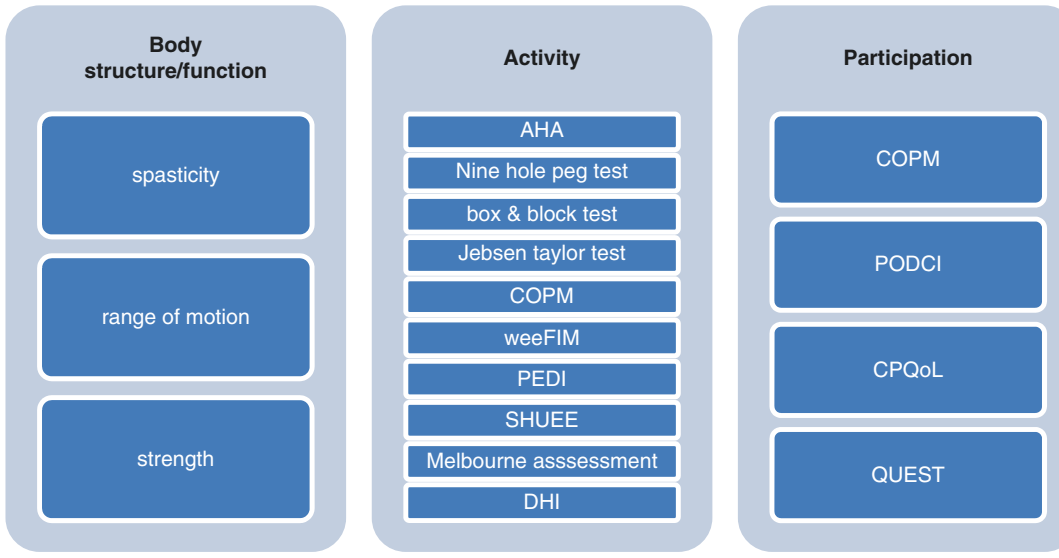
Table 12.1 Hand assessment tools in cerebral palsy

Questionnaires
ABILHAND-Kids
Cerebral palsy quality of life (CPQoL)
Duruöz Hand Index (DHI)
Pediatric Outcomes Data Collection System (PODCI)
Performance-based tests
Assisting Hand Assessment (AHA)
Box and Block Test (BBT)
Jebsen Taylor Hand Function Test (JTHFT)
Melbourne Assessment of Unilateral Upper Limb Function (Melbourne Assessment)
Nine-hole Peg Test (NHPT)
Pediatric Evaluation of Disability Inventory (PEDI)
Quality of Upper Extremity Skills Test (QUEST)
Shriners Hospitals Upper Extremity Evaluation (SHUEE)
WeeFIM/FIM

Table 12.3 The manual ability classification system (MACS)

Level 1	Handles objects easily
Level 2	Handles objects with reduced quality and speed
Level 3	Handles objects with difficulty requiring modifications
Level 4	Handles objects only in adapted situations
Level 5	Does not handle objects

Table 12.2 Assessment tools categorized by ICF Model



to Type 4 (the cortical thumb), which ends with the flexion deformity of the metacarpal and interphalangeal joints with the metacarpal adduction contract on the thumb [25].

Assessments tools are either clinician-based observations or patient/family reports. Pediatric Evaluation of Disability Inventory (PEDI) and WeeFIM can be used in either fashion. PEDI is a comprehensive clinical evaluation tool that evaluates the functional ability and performance of children aged 6 months to 7 years. It consists of three main parts: self-care, mobility, and social function. The application period is approximately 45–60 minutes and usage is charged. WeeFIM, which evaluates the self-care, mobility, and cognitive functions of the child from birth to 7 years, requires certification, and its usage is also charged [25, 29].

The other functional performance tests Assisting Hand Assessment (AHA), Box and Blocks Test, Nine-hole Peg Test, Jebson Taylor Hand Function Test, Melbourne Assessment of Unilateral Upper Limb Function Test (Melbourne Assessment), Quality of Upper Extremity Skills Test (QUEST), and Shriners Hospitals Upper Extremity Evaluation (SHUEE) are all clinician-based. Assisting Hand Assessment is more prominent with its use in researches. It is a video-based review and takes 10–15 minutes. It is applied during the game between 18 months and 5 years and as a board game during 6–12 years. There are 22 items and each item is scored out of 4 points. Twenty-two points indicate that the hand can never be used, and 88 points indicates functionality as dominant hand. It requires post-training certification with a 3-day workshop, and the use of the test is charged [25, 31]. Duruöz Hand Index, which is used in our clinic and has validity in hemiplegic cerebral palsy, also shows significant correlation with MACS. This index including 18 questions tests the daily use of the hand and activities requiring bimanual use such as eating, dressing, and writing. The application used in the 7–16 age group is simple and short [32].

Manual dexterity (hand and finger, respectively) skill can be evaluated by box and blocks test or nine-hole peg test. They imitate many actions required to perform everyday tasks such as grasping, carrying, and releasing. Box and Block Test kit consists of a large wooden box with a center divider. The patient grasps a block and moves it toward the other side of the box to release it (Fig. 12.2). The score is the number of blocks carried in 1 minute. In the Nine-hole Peg Test, the patient is asked to place the wooden bars in the holes in the panel as quickly as possible. It is then required to remove the entire bars from the holes again. The measured time to complete the NHPT in seconds is recorded [25, 33]. If the patient cannot complete the test, pegs are calculated using the number of pegs placed relative to the 300 second time period. Calculation of the pegs has the advantage of avoiding floor effects in persons with severe upper extremity dysfunction [34].

Fig. 12.2 Box and block test

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13 Hand Function in Children with Congenital Disorders

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Congenital Upper Limb Differences

Congenital differences of the upper limb are relatively common. Their prevalence is estimated at 16 per 10,000 live births, but varies within different populations and ethnic groups. In frequency, they are second to congenital heart malformations. In approximately 75–80% of cases, the difference is unilateral. Associated anomalies are seen in up to 53% of cases, with musculoskeletal defects found most frequently. Several other congenital associated abnormalities occur in about one-third of all cases affecting different systems, including defects in the head and neck, cardiovascular, gastrointestinal, and genitourinary tract systems [1].

The precise causes of congenital upper limb differences are unknown in 60%, but in 20 per cent of cases, a genetic cause exists, and in the remaining 20%, the difference is due to an environmental cause [2].

The upper limb difference can either be isolated (confined to the upper limb, possibly bilateral) or part of a syndrome. Most isolated differences are not caused by genetic factors. Although occasionally a genetic cause is found for an isolated difference, most differences that are genetically based are part of a multiple congenital syndrome.

Most upper limb differences are isolated, and in most cases other affected family members are absent. This suggests that most of these differences are caused by vascular problems during embryogenesis, either from vasoconstriction, haemorrhage, thrombosis or embolization, especially when transverse terminal defects are present [1].

A number of different classification systems have been proposed. In former scientific studies, the most frequently used classification of congenital differences of the upper limb was based on the Swanson classification [3]. The latter was modified by the Congenital Malformations Committee of the International Federation of Societies for Surgery of the Hand (IFSSH) in 1983 (Table 13.1) [4]. This classification scheme consists of seven main categories that are divided into subcategories, level of anomaly, diagnosis and sub classification [3]. Most differences can be classified using this classification [5], but in cases of occurrence of different types of differences within the same limb, classification may be difficult. Failures of differentiation and duplications are the most common differences [6].

Currently, the Oberg, Manske, and Tonkin (OMT) classification replaces the modified Swanson classification (short version displayed in Table 13.2). It is a framework that classifies congenital anomalies of the hand and upper limb using dysmorphological terminology. It places the

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Table 13.1 Modified Swanson classification

I. Failure of formation of parts (arrest of development)
A. Transverse arrest (common levels are upper third of forearm, wrist, metacarpal, phalangeal)
B. Longitudinal arrest (including phocomelia, radial/ulnar club hands, typical cleft hand, atypical cleft hand otherwise referred to as part of the spectrum of symbrachydactyly)
II. Failure of differentiation of parts
A. Soft tissue involvement
B. Skeletal involvement
C. Congenital tumorous conditions (includes radio-ulnar synostosis, symphalangism (stiff PIPJs with short phalanges), camptodactyly, arthrogryposis, syndactyly)
III. Duplication
IV. Overgrowth
V. Undergrowth (thumb hypoplasia, Madelung's deformity)
VI. Congenital constriction band syndrome
VII. Generalized skeletal abnormalities

Table 13.2 Oberg, Manske, Tonkin classification of congenital hand and upper limb anomalies

I. Malformations.
A. Abnormal axis formation/differentiation – entire upper limb
1. Proximal-distal axis
2. Radial-ulnar axis
3. Dorsal-ventral axis
4. Unspecified axis
B. Abnormal axis formation/differentiation – hand plate
1. Proximal-distal axis
2. Radial-ulnar axis
3. Dorsal-ventral axis
4. Unspecified axis
II. Deformations
A. Hypertrophy
1. Whole limb
2. Partial limb
B. Tumorous conditions
1. Vascular
2. Neurological
3. Connective tissue
4. Skeletal
III. Dysplasias
A. Constriction ring sequence
B. Trigger digits
C. Not otherwise specified
IV. Syndromes
A. Specified
B. Others

anomalies in one of three groups: Malformations, Deformations and Dysplasias. The main group, Malformations, is further subdivided according to whether the whole of the limb is affected or the hand plate alone and whether the primary insult involves one of the three axes of limb development and patterning or is non-axial.

Although classifications can be useful to analyse groups of patients, they are of little practical value in the everyday management of these differences, because each case stands on its own and should be analysed and treated with a client-centred approach.

Impact of Congenital Hand Differences on Hand Skills Development

A century of research on infant motor development has provided a detailed description of the sequence of hand skills development and conceptual knowledge of how normal infants develop their handfunction. However, the impact of having a congenital hand difference on the development of handskills has rarely been studied. Understanding the normal sequence of hand skills development helps to identify the problems that children with congenital hand differences may encounter.

Hand motor function is of extreme importance to the developing child. The child's desire to understand and master his surrounding world results in exploration and manipulation of objects and different materials [7], and therefore the child's hand function is important for the child's total development. It is not only important for babies and toddlers, but it has also a major impact on the child's school performance. McHale and Cermak found that children in kindergarten spend almost one half (46%) of their in-class day in some type of fine motor activity [8], and later in school life, that percentage even increases. Due to a continued learning process, it takes a very long time for hand motor function to achieve its final state. Global gripping patterns that emerge in the first 12 months of life change gradually in fine manipulatory patterns, which fine-tuning continues into adolescence.

This is a traditionally based view on motor development, which has been practised for decades. Now, there is much debate regarding this basis for intervention approaches. A paradigm shift towards the Dynamics Systems Theory of motor development has brought new insight in the treatment of children, although it is not extensively tested for children with congenital hand differences. The Dynamic Systems Theory (DST) is a theoretical framework in paediatric physiotherapy. It views movement as resulting from the interaction of many subsystems within the individual, features of the functional task to be accomplished, and the environmental context in which the movement takes place. These subsystems are interdependent and work together, for example, strength in one system (e.g. visual) can support the weaknesses in others (e.g. kinaesthetic). In children with congenital hand differences, the underlying pathology (e.g. aberrant anatomical structures) causes functional problems, and this so-called mechanical disturbance can normally be compensated through other subsystems.

Normally, children with congenital hand differences alone overcome their handfunction problems very well, sometimes using alternative strategies sometimes with surgical treatment or with the help of aiding tools. Psychological problems that arise from emotional problems with the hand difference are harder to overcome.

When treatment of the functional problems is not as successful as expected, one should be aware that some of these children next to their congenital hand difference might suffer from developmental coordination disorder (DCD). Even in the overall population of children, the prevalence of DCD is 13% [9]. This comorbidity may affect the functioning of the child with the congenital hand difference. Children with DCD manifest motor deficits in virtually every motor domain. They tend to work more slowly than their typically developing peers [10, 11] and display deficits in gross motor (i.e. balance, gait) [12, 13] and fine motor skills.

Although the DST is very promising, no sufficient descriptions of hand skills development exist yet. Therefore, we will describe it based on the reflex, hierarchical and maturation theories.

A distinction can be made in two different stages of hand skills development:

1. Basic hand skills: reach, grasp, hold, transport, controlled release and support
2. Development of more complex hand skills: complementary two-hand use, 'in-hand manipulation', and the use of utensils [14]

Basic Hand Skills

Reaching

Although the first swiping at objects tends to be unilateral, bimanual reach towards an object may be observed as early as 2 months after birth [15]. Children suffering from, for instance, arthrogryposis multiplex congenita (AMC) or a severe ulna dysplasia (UD) will already have difficulties with only reaching for objects.

Grasping

An infant's earliest grasping is a reflexive grasp, which relates to the physiologic flexor muscle tone characteristic of the full-term neonate. Between 4 and 6 months, the infant starts to develop control of grasping, using both tactile and visual information. Visual input is used to prepare the hand for grasping. This first ability to grasp, orient, and adjust is the beginning of the purposeful grasp. In clinical practice, treatment of grasping problems is interwoven with treatment of 'voluntary release' problems, and 'in-hand manipulation' problems.

The first purposeful grasp to be developed is the palmar grasp. This grasp is described as a pronated underarm with flexion of all fingers and thumb holding the object. Although in past research, ulnar palmar grasp was said to emerge first, more recent research shows that the index finger is active first [16]. At the stage of developing a radial palmar grasp, an infant already starts to differentiate in function between the radial and ulnar sides of the hand and the forearm will be positioned in more supination. This radial palmar grasp is a milestone in the development of grasping [15].

Between the age of 6 and 7 months, manipulating an object is done more with the fingers,

than with the palm of the hand. At the age of 12 months, the infant can use a pincer grasp with the tip of the thumb and index finger.

Grasping in Children with a Transverse Arrest

In children with a transverse arrest, when thumb and fingers are completely absent, the affected hand can participate in grasping bilaterally only by assisting the bilateral hand. In children with a transverse arrest distal to the carpal bones, sometimes grasping is possible between the wrist and forearm. The affected hand can be very useful in fixating objects, stabilizing the object by weight or support, while the other hand manipulates the object. If the level of amputation is more distal and there are rudimentary fingers and a rudimentary thumb, grasping and holding may be possible with this hand, but manipulation skills will be very limited.

Grasping in Children with a Longitudinal Arrest: Radial Dysplasia

Radial dysplasia is the name given to a wide variety of abnormalities on the radial side of the arm, and the spectrum varies from a mild hypoplasia of the thumb to a complete absence of the radius with complete absence of the thumb and accompanied by stiff fingers (the ulnar fingers having the best ROM). This anomaly can be either unilateral or bilateral.

Children with a minor degree of thumb hypoplasia will not be impeded in grasping or releasing activities in early childhood. The thumb hypoplasia may affect 'in-hand manipulation skills' later on in life. Children suffering from a severe kind of radial dysplasia, e.g. type 4, will most certainly have major problems with grasping and releasing objects because of stiff fingers and thumb absence. Grasping in these children is very often performed with the ulnar fingers. The child develops deviant grasping patterns such as an interdigital grasp to compensate the absence of an opposable thumb. Because there is diminished ability to grasp with one hand, the child will grasp bimanually if necessary. These children develop grasping by using it in all kinds of activities, not only for self-care, but also in playing and learning, while they discover ever so quickly an efficient method to accomplish their tasks.

Grasping in Children with Syndactyly

Syndactyly has diverse forms of severity. The most severe form is part of a syndrome as in Aperts syndrome or acrocephalosyndactyly (ACS). This is a rare syndrome characterized by severe syndactyly and craniosynostosis. Upton has classified the Apert Syndrome hand into three types for ease of clinical decision-making [17]. In the type 1 hand, there is a radially deviated small thumb with a shallow first web, and the index, middle, and ring fingers are joined by a complex distal syndactyly and the little finger by a simple syndactyly. In the type 2 hand, the thumb is included in a simple syndactyly, and there is splaying of the central metacarpals of the long and ring fingers. In the type 3 hand, skeletal union of all digits exists which is often complicated; radial deviation of the thumb may not be present. Very often, the mid-digital bony mass has a confluent nail, and therefore, only movement in the MP joint is possible [1]. The range of motion of the both the shoulder and elbow joints is also limited. In types 2 and 3, without surgical intervention, grasping is only possible bimanually, and holding can be performed using a stabilizing surface (table or body). Surgery normally is performed before the end of the first year of life. Normally the thumb is released firstly, followed by the border digits. After all surgical procedures, the best-case scenario is that the hand will be a four-fingered hand, with mobility only in the MP joint, and a radially deviated thumb despite the surgical adjustments. Due to early surgery, grasping possibilities are obtained, and the infant is able to perform all kinds of prehension activities in early childhood. The in-hand manipulation will not be possible or will be very difficult. The acquisition of self-care, for example, holding a cup for drinking or grasping a spoon for eating, will be delayed.

"Controlled Release" or Voluntary Release

Release is an integral part of prehension and manipulation; as with the grasp, the first object release is based on reflexes. Finger extension and

a slight withdrawal is observed in response to the touch of the neonate's hand, which is called an avoiding reaction [18]. From 5 to 6 months, the transition begins from a reflexive release to purposeful release. The infant begins to release objects from one hand to pass it to the other. This object transfer first takes place by pulling the object, and later, it becomes a coordinated release. At the age of 10 months, the infant will drop food and toys from his highchair and will take great pleasure in this new acquired skill [15]. Object-releasing activities are now reinforced by auditory and visual consequence of the object. Gesell et al. in 1947 already stated that release is one of the most difficult activities to master in early life [19]. They pointed out that a child's ability to release a cube with the exact timing of force and position made this child successful in its attempt to build a tower, whereas the child who cannot regulate this force or position will drop the cube or may press rather than place the cube and the structure will fall.

Controlled release is an important component of the in-hand manipulation. In many in-hand manipulation tasks, an object is grasped and repositioned by delicate grasp–release movements of the fingers.

When grasping is difficult, controlled release will also be diminished. The compensation strategy that is most often used for this problem is to release the object with the help of the other hand [20].

Children will use this strategy automatically and quickly and one must be a trained observer to notice this behaviour. Another strategy is to drop the object, but the result of this is unpredictable and not precise, so therefore not very often used in daily activities.

Controlled Release in Children with a Longitudinal Arrest: Radial Dysplasia

Children with a radial dysplasia will mostly have to release their objects from an interdigital grasp. Release from this grasp can be quick and effective. If the object is larger than the active range of the interdigital grasp permits, and the object is pushed into this space passively, releasing the object becomes difficult. In radial dysplasia with a pollicized index, releasing an object after a whole-hand grasp can also be constrained, because of the reduced opening of the hand. However, this also depends on the object's size.

Controlled Release in Children with Failure of Differentiation of Parts with Soft Tissue Involvement: Finger Flexion C

Children with extreme flexion contractures of the fingers, which might be the case in a windblown-deformity (e.g. Freeman-Sheldon syndrome, severe cases of camptodactyly, or arthrogryposis), will have functional problems in developing an adequate active release of objects.

Complementary Two-Hand Use

Complementary two-hand use is an important skill that develops between 12 months and 2 years of age [21]. At first, the child picks up a toy, holds it with one hand, and just explores it with the other hand. Bilateral hand use implies that the child is capable to initiate and control two different motor programs for the hands. This ability means much more than performing simultaneously holding and doing, but there is a continuous monitoring of the interaction between hands and the movements of the hands complement each other in this performance.

A task that requires complementary use of the two hands is bead-stringing. Almost all studies place the successful accomplishment of this task around 2 years of age [7]. For example, for development of the Peabody developmental scales, the ability to string 3 beads was examined. The authors found that 16% of the 18- to 23-month-old children were able to string three beads, in contrast to the 70% of the 24- to 29-month-old children. This represents a significant change in behaviour over a relatively short time. Probably, this change is caused majorly by the development of successful two-hand use. Bimanual actions are more complicated than unimanual actions as the movements of both arms and hands must be coordinated temporally and spatially to complete a task or achieve a desired goal [22].

Many children with congenital hand differences will have problems with bilateral hand skills. They will have problems stabilizing an object with one hand, while manipulating it with the other hand. Problems can be seen in stabilizing the object with a grasp or stabilizing the object without a grasp.

Complementary Two-Hand Use in Children with a Transverse Arrest

Depending on the level of amputation, the object will be held in the hand, or stabilized on a surface. The efficacy of a performance depends on the stability of the object in the hand and readjustments possibilities of the grip.

Complementary Two-Hand Use in Children with a Longitudinal Arrest-Radial Dysplasia

Many children with a severe form of radial dysplasia have limited range of motion of the elbow. Most surgeons will not surgically correct radial deviation of the wrist in children with a stiff elbow joint, because the hand–hand, and hand–mouth interaction will be hindered if the wrist deviation is surgically corrected.

The forearm will often be positioned in pronation, because supination is impossible or limited. Hand–hand orientation in many activities needs some supination in the elbow and therefore the ability to position the hand in the right position will be difficult. In children with a unilateral difference, the bilateral hand will use compensation movements in order to enable the task.

Complementary Two Hand Use in Children with a Syndactyly: Apert Syndrome

Many two-hand activities, for example, buttoning, tying shoes, and stringing beads, demand a lot of in-hand manipulations skills. To accomplish these tasks, readjustment of the grip is continuously necessary. Therefore, children with Apert's syndrome, who lack movement in the IP joints and only have possibility to move the MP joint, will have problems with these readjustments. They will more often lay down the object and recapture it in the right position to continue the action, which influences the bimanual skills. The lack of in-hand manipulation affects the success of the bimanual task performance.

In-hand Manipulation

Exner defines in-hand manipulation as the capacity to manipulate objects in the fingers and in the hand [23]. The purpose of these adjustments is to allow more efficient placement of an object in the hand for use or voluntary release [7]. In-hand manipulation skills seem to be the most complex of all fine motor skills.

A 12-month-old infant can very well pick up one pellet and bring it to its mouth. But when the infant is placed before a heap of pellets, it will grasp a lot of pellets, bringing the entire hand to the mouth, rather than moving the pellets in the hand and eat the pellets one by one. Exner has called this ability the in-hand manipulation of which three components have been described:

1. Translation movement, which is the ability to move an object from the fingers to the palm, or reverse to move an object from the palm to the fingers.
2. Simple or complex rotation movement, which is the ability to rotate an object in the pad of the fingers. This movement requires independent movements of the fingers and the thumb.
3. Shifting the object that moves in a linear direction on the finger's surface. This movement is performed by the thumb and radial fingers.

In addition to these three different components, one more form of 'in-hand manipulation' exists, which is accomplishing one of these three components while stabilizing another object in the ulnar side of the hand. The hand performs two different actions at the same time, which is the most complex form of in-hand manipulation and requires control of both sides of the hand.

Another important factor for the development of in-hand manipulation is the development of the regulation of grip strength. The coordination of manipulatory forces in 1-year-old children is poorly developed. For example, a 1-year-old

child easily squashes an ice-cream cone, whereas a 2-year-old child can handle the ice cream-cone without crushing it.

In-hand Manipulation in Children with Congenital Hand Differences

It goes without saying that children with a severe congenital hand difference, such as Apert syndrome or radial dysplasia (type 3 and 4), normally never develop in-hand manipulation skills, while others with a moderate congenital hand difference will develop in-hand manipulation, but with delay.

In general, children who lack in-hand manipulation skills will compensate this by using different strategies. For example, a child who picks up a pencil to draw, and cannot bring the pencil into an efficient dynamic tripod position to stabilize the pencil, will quickly use the other hand to manipulate the pencil into the right place and starts drawing.

Function-, Activity-, Participation-Reported Problems

Diagnosis does not predict function. Congenital hand differences are associated with compromised or altered functional status that may be indicative of more significant health problems.

The International Classification of Functioning, Disability and Health (ICF) provide a common framework and terminology to describe human functioning at three levels: body function, activity, and participation. In October 2007, International Classification of Functioning, Disability and Health-child and youth version (ICF-CY) was published, which is designed for use with children and youth and allows for coding of more developmental aspects of functioning.

A person's functioning and disabilities, including his/her participation, are considered to arise from the interaction among health conditions and contextual or environmental factors and personal factors. The ICF provides a model of functioning and disability in which the interactions among these concepts are visualized (Fig. 13.1).

The ICF has adopted a biopsychosocial model of disability to capture the complexity of disability that involves both appreciation of the medical and social aspects of the individual and society [24]. According to this model, functioning is classified as all body functions, activities, and participation. The ICF-CY has two parts (health condition and contextual factors), each consisting of two separate components: [1] body functions and structure and activity and participation and [2] environmental and personal factors. The ICF-CY provides codes that represent categories to describe: the child's integrity of body functions and structures, the ability to perform daily life activities and the scope of the individual's participation, and environmental factors that might facilitate or impede functioning and personal factors.

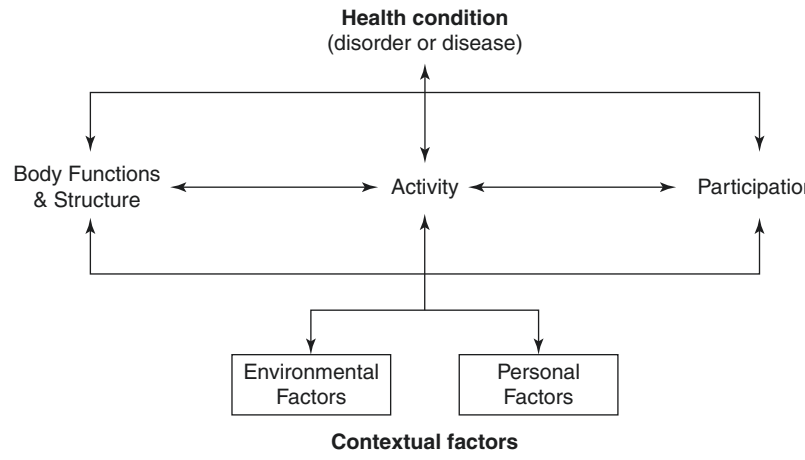

Fig. 13.1 The WHO model of functioning and disability

Children with congenital hand difference can experience problems in all domains of the ICF-CY. It is therefore important to evaluate functioning of these children on all these domains.

It is impossible to mention all possible problems in all kinds of congenital hand differences on all ICF-CY levels. This even becomes more difficult if children suffer from a congenital hand difference that is part of a syndrome.

Beside the levels of functioning, there is also the distinction between capacity and performance. Capacity reflects what a child can do, and performance what a child does do in daily life. The difference between what a child can do and what it actually does is well known [25].

Assessment of Function

Assessment of function is essential as the base for interventions to reduce functional limitations and improve well-being. Evaluation of a child's hand function is different from that of an adult. Clinicians require expert knowledge in fine motor and developmental milestones to identify whether the child's deficits are true or reflective of developmental skill. Functional expectations change with maturation, and the child's age determines what they are expected to do. Therefore, the evaluation must reflect the child's age and developmental level, as well as the diagnosis [26].

Among children with chronic conditions, variability occurs in their ability to perform individual activities as well as in the ways that they participate in society. Moreover, the contexts in which children live, that is, their physical, social, and psychological environments, influence their functioning [27, 28].

History and Status Praesens

After referral of a child and its parents, the hand therapist or physician performs an interview. Hereby, they obtain information obtained about the child's medical, family, emotional, educational, and social history, but also developmental, environmental, and personal aspects should be addressed.

Outcome Measures at Function Level

Range of Motion

Precise numerical documentation of active and passive range of motion of upper extremity joints is essential. At the time of initial assessment, documenting active and passive range of motion is of importance, because changes can occur as a result of therapy but also as a result from growth and development [29]. Measuring hand range of motion in a child is technically not different from measuring an adult's hand, because it is performed with a finger goniometer using the dorsal measurement technique. In younger children, only the passive range of motion can be assessed.

Thumb range of motion is a special domain of measuring children with congenital hand differences. The opposition can be measured by the Kapandji Thumb range of motion, and recently a device for measuring palmar abduction was developed and validated in children with congenital thumb differences [30].

Strength

Grip and strength should be assessed with standardized, commercially available dynamometers. Normative values are available to compare the children's performance with their peers. However, using these normative data as reference values can be difficult, because when measuring a child at follow-up, the outcome is influenced by both the intervention and growth. Therefore, Molenaar et al. suggested growth diagrams for grip strength in children between 4 years and 12 years of age [31].

Besides grip strength, pinch strength should be measured whenever correct positioning of the fingers and thumb is possible. Assessment of pinch strength should include tip-tip pinch and lateral pinch to evaluate thumb opposition strength. In some congenital hand differences, tripod pinch strength may be included in the evaluation.

In the case of grip or pinch strength, a combination of extrinsic and intrinsic hand muscle

strength is used and a large number of joints are involved. At present, there are tools capable of assessing intrinsic muscles strength of the child's hand and of which Molenaar et al. presented growth diagrams in which strength is plotted against age [32].

Measurement of muscle strength around the larger joints of the upper extremity can be obtained by handheld dynamometers. These measurements should include elbow flexion and extension as well as wrist flexion and extension force.

Sensibility

Sensibility can be tested in different ways and much controversy exists concerning the neurophysiologic basis of sensory testing. This fact combined with the lack of control of certain variables in our testing which comprises accuracy together with the young age of the children tested, the results should be interpreted with care.

Threshold tests as Semmes Weinstein monofilaments for touch and pressure or vibration can be used in children with congenital hand difference. Functional sensibility can be measured through established tests that have normative data on the population tested [33].

Dexterity

Dexterity is described as the ability to manipulate objects with the hands. Accuracy and speed can be measured through established tests that have normative data on the population tested. Clinical observation of the child picking up and manipulating different objects is also a way to obtain information on dexterity.

Although there is a need for a classification system for hand functions, to date, no valid and reliable one is available.

Outcome Measures at Activity Level

In contrast to the worldwide accepted core set for hand function measurement on the ICF-function level, selecting the assessment tools for measuring limitations on activity level with congenital hand difference is extremely difficult and undergoing a lot of research at the moment. Several functional tests and questionnaires have been developed on this domain, but to date, there are no disease-specific tools for children with different kinds of congenital hand differences. Therefore, it is impossible to give the golden standard in testing limitations in the activity and participation of children with congenital hand difference. The observer should also keep in mind the difference between capacity and performance. Observational assessments show an individual's capabilities, but they may not reflect typical performance of the diverse activities performed in real life. Therefore, both aspects should be measured [34].

Tests to measure limitations in activity level can be divided into different groups: performance tests, questionnaires, or semi-structured interviews.

The below-mentioned questionnaires and functional tests were all developed for children with hand disorders, including cerebral palsy and congenital transverse reduction deficiencies.

Children with bilaterally affected hands as well as unilaterally affected hands encounter the most problems in daily life when performing bimanual activities. Examples of questionnaires used in children with congenital hand difference that measure bimanual activities are Prosthetic Upper Extremity Functional Index (PUFI) [35], AbilHand-Kids [36], Children's Hand-use Experience Questionnaire (CHEQ) [37], and Child Occupational Self-Assessment (COSA) [38]. The Unilateral Below Elbow Test (UBET) [39] and University of New Brunswick Test of prosthetic function (UNB Test) [40] are examples of performance tests, and the Canadian Occupational Performance Measure (COPM) [41] and Goal Attainments Scale (GAS) [42] are examples of semi-structured interviews.

Outcome Measures at Participation Level

As in measuring activity limitations in children with congenital hand differences, no disease-specific

tools for measuring limitations in participation in these children exist.

However, if information on participation is needed, general participation measures could be used. An example of participation measures is the CAPE (Children's Assessment of Participation and Enjoyment) [43].

Research in children and youth with CP has shown that manual ability (classified according to the Manual Ability Classification System – MACS) was related to participation in leisure activities [44]. Better handling of objects and better fine motor function were associated with greater participation in leisure activities. Further research is needed in children with congenital hand differences.

Aesthetics

Many parents of children with congenital hand differences are concerned about the aesthetics of their child's hand. It is important that this is recognized. However, surgical interventions for aesthetics should never compromise function and, if possible, vice versa. Visual analogue scales (VAS) can be used to measure the appearance objectively by the children if they are old enough or by the parents.

Psychological Implications of a Congenital Hand Difference

Due to advances in prenatal detection of congenital differences, along with the evolving technology and widespread use of ultrasonography in prenatal screening, congenital hand differences are increasingly detected before birth. Parents whose child is diagnosed to have a congenital hand difference on prenatal testing, or whose child is born with a visible congenital hand difference, may go through a process that is akin to bereavement. The early responses differ from denial and anger to distress, but they also have questions on how this happened. Although the mother may have done everything to live healthy during the pregnancy, she is not able to prevent a birth defect.

Many emotions are focused on themselves and on their babies and most parents are concerned mostly about the child's psychological and social development. Parents respond differently on coping with the congenital hand difference. Some parents are able to accept the congenital difference rapidly, but some need more time to adjust to an unexpected situation. When parents seem to get lost in their grief, and the physicians treating the child feel like the reaction is no longer in relation to the difference of the child, they may consider psychological help for the parents and their children. The emotional development of the child and their parents should be followed up over the years [45].

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Hand Involvement in Juvenile Idiopathic Arthritis

14

Erbil Ünsal

Juvenile Idiopathic Arthritis (JIA) is the most common chronic rheumatic disease of childhood. It is an important cause of short- and long-term disability. JIA is an umbrella term for both "juvenile rheumatoid arthritis" and "juvenile chronic arthritis." Brewer et al. published the Juvenile Rheumatoid Arthritis classification criteria in 1972 [1]. European League Against Rheumatism criteria used the term Juvenile Chronic Arthritis [2]. The latter classification included Juvenile Psoriatic Arthritis, Juvenile Ankylosing Spondylitis and Inflammatory Bowel Disease. Pediatric Standing Committee of ILAR (International League Against Rheumatism) proposed a new classification in 1993, which was discussed in Durban (1997) [3] and Edmonton (2001) [4]. The term JIA is the final form following the related meetings. It includes oligoarthritis, systemic arthritis, polyarthritis, enthesitis-related arthritis, and psoriatic arthritis.

Hands are mainly involved in systemic arthritis, polyarthritis, and psoriatic arthritis. This chapter will focus particularly on these subtypes, regarding hand involvement.

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Physical Examination in the Differential Diagnosis of Rheumatic and Non-rheumatic Hand

There are several non-rheumatic conditions mimicking arthritis in the hand. The fingers might be shorter than usual in severe polyarthritis, but achondroplasia should be kept in mind. There is diffuse edema of the hand in some patients with polyarthritis; it might be a feature of myxoedema on the other hand. Juvenile psoriatic arthritis sometimes presents itself with sausage-like finger as asymmetrical arthritis; this is a similar finding in neurofibromatosis and local arteriovenous fistula causing hypertrophy of the related finger. Typical fusiform swelling of the proximal interphalangeal joint (PIP) is commonly a finding of chronic arthritis; however, collateral ligament tears as a result of trauma and less commonly tuberculosis, sarcoidosis, and syphilis are the other possibilities. Loss of active extension in the thumb (mallet finger) is usually the result of rupture of extensor pollicis longus tendon, a complication of distal radius fracture, rarely the result of rheumatoid arthritis. Boutonniere deformity presents as the flexion of the PIP joint and extension of the DIP joint. Wound of the dorsum of finger, traumatic avulsion, or rheumatoid arthritis are the causes. Symmetrical flexion of the fifth fingers in the PIP joints is seen in congenital contracture of the related fingers, rather than chronic arthritis

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deformity. Similarly, flexion of interphalangeal joint of the thumb in infants and young children is due to tenovaginitis involving flexor pollicis longus. Tenosynovitis of the flexor tendons at the wrist level in chronic arthritis causes flexion deformity of the thumb and fingers; however, it is also the result of damage of the brachial artery in supracondylar fracture, leading to Volkmann's ischemic contracture. Rarely, familial camptodactyly, congenital synovitis of the PIP joints with fibrosing serositis, causes flexion contractures of the hands. In severe polyarthritis, there are numerous nodules palpated over the dorsum of the hand as a result of synovial swelling; enchondroma, one of the commonest bone tumors of the hand, might be the other cause [5].

Systemic Juvenile Idiopathic Arthritis

It is one of the most difficult diseases among childhood arthritides. The diagnosis requires exclusion of a detailed list of diseases listed in the differential diagnosis of "fever of unidentified origin." The diagnosis requires arthritis in any number of joints together with a fever of at least 2 weeks duration that is documented to be daily for at least 3 days. The following signs/symptoms are usually found: erythema circinatum (Fig. 14.1), hepatosplenomegaly, serous inflammation (pericardium, pleura), and generalized lymphadenopathy. Regarding arthritis, any number of joints can be affected at onset or during the course, but eventually, most of the children have polyarthritis. The knees, wrists, and ankles are the most involved joints, but hips, temporomandibular joints, and small joints of hands have inflammation in more than half of the patients (Fig. 14.2). In a group of children, they have severe arthritis leading to destruction of joint space, loss of function leading to marked disability in the first 2 years of the disease. Schneider et al. showed that about one-third of patients demonstrated destructive poly-

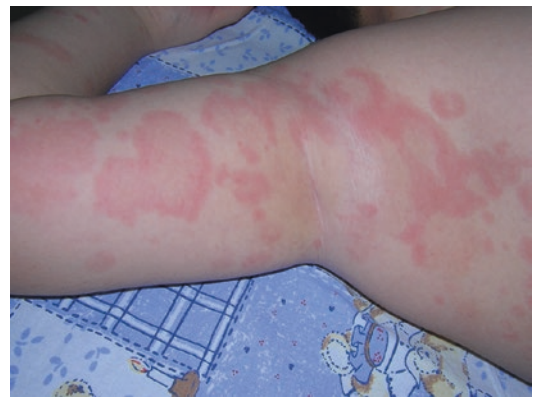

Fig. 14.1 Systemic JIA – erythema circinnatum

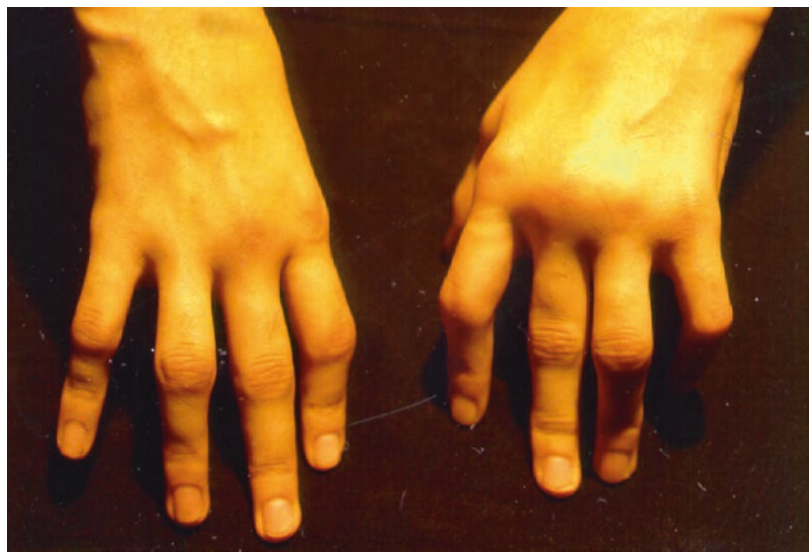

Fig. 14.2 Systemic JIA – polyarthritis

arthritis after a mean follow-up of 5 years [6]. In others, the disease can go to clinical remission with mild joint involvement. Bekkering et al. [7] studied the relation between impairments in joint function in 21 children with systemic arthritis. The relationship between loss of joint motion in the leg and disabilities in leg activities appeared to be strong. However, the relationship between impairments and disabilities in the arm appeared to be moderate. The author explained the lesser impact of loss of motion to disability in the hand in terms of coordination in daily activities such as eating, grasping, writing. Tenosynovitis is a frequent and important finding, particularly in polyarticular course in systemic arthritis. Extensor tendon sheaths in the dorsum of the hand and finger flexor tendon sheaths are the sites that are commonly involved in the hand. Some children develop synovial cysts in communication with the wrists [8].

Polyarticular Juvenile Idiopathic Arthritis

It is defined as chronic arthritis in children affecting more than four joints in the first 6 months of the disease. It accounts for approximately 20% of all JIA subgroups. ILAR classification categorizes this subgroup as rheumatoid factor (RF)-positive and RF-negative arthritis [4]:

Rheumatoid Factor-Negative Polyarthritis

This subtype is predominant in children regarding polyarthritis as 85% of them are RF-negative [9]. The incidence has two peaks in age: 1–3 years and adolescence. It affects girls four times, and up to ten times more during teenage years.

Clinically, RF-negative polyarthritis has less severe extraarticular manifestations when compared to RF-positive polyarthritis, i.e., fever, fatigue, and weight loss. Regarding joint disease, the onset of arthritis is often insidious. Morning stiffness typically lasts for hours. Symmetrical involvement of the joints is the result. Swelling due to intraarticular fluid and synovial hypertrophy with warmness are the usual symptoms, and the joints are rarely tender or red. Small joints of hands are typically involved; the most commonly affected are the second and third metacarpophalangeal (MCP) and proximal interphalangeal joints. Distal interphalangeal joint involvement is unusual (Figs. 14.3, 14.4). Temporomandibular joint is more likely to be involved compared to RF-positive patients; the reason might be the earlier age onset of the former subtype [10].

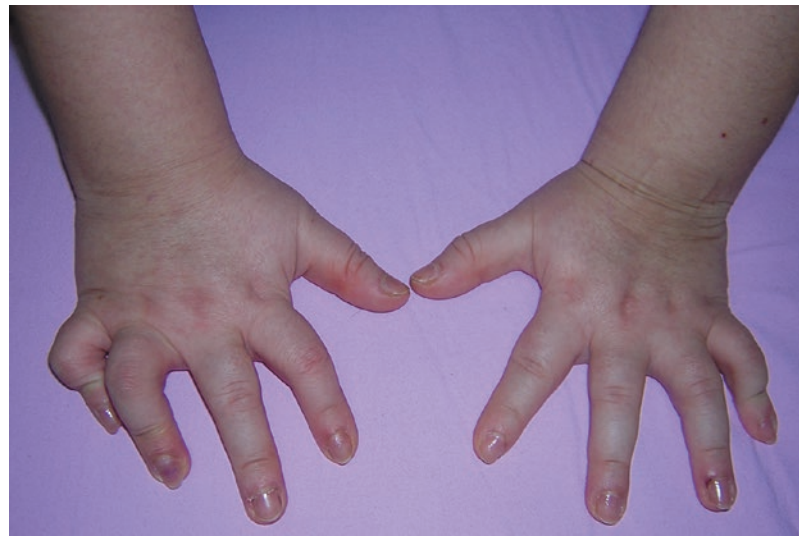

Fig. 14.3 Polyarthritis

Fig. 14.4 Polyarthritis – flexion contractures

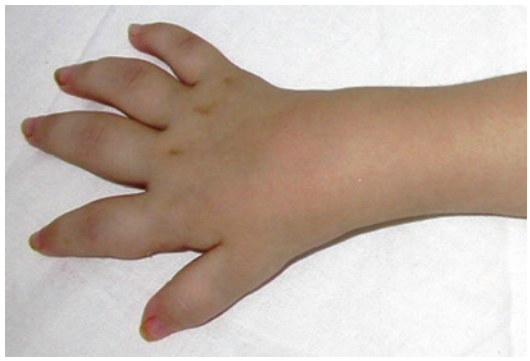

Fig. 14.5 Diffuse polyarthritis

Rheumatoid Factor-Positive Polyarthritis

This subtype differs from the RF-negative polyarthritis by the presence of rheumatoid factor positivity. RF is defined as positive when its presence is demonstrated in two positive tests performed at least 3 months apart. It forms about 15% of children with polyarthritis, and 3% of all JIA patients [8]. It has similar characteristics with adult rheumatoid arthritis as immunogenetic profile, serology, and clinical phenotype. Its mean age is 10 years, and girls outnumber boys from 4 to 13 in large series [8]. Arthritis is mainly found in large as well as small joints, which are symmetrically involved. Micrognathia does not occur in contrast to RF-negative polyarthritis because of the late age development of the former. Only cervical spine is affected, and sacroiliac joints and thoracolumbar vertebrae are spared. Rheumatoid nodules similar to that of adults are found on the bony prominences. Hand involvement is serious and mostly destructive leading to multiple deformities. The characteristic pattern is the symmetrical arthritis affecting MCP and PIP joints and the wrists (Fig. 14.5). Ulnar deviation, boutonniere, and swan neck deformities are typical for this subtype as in adults. Systemic symptoms accompany arthritis, fatigue, and weight loss.

Juvenile Psoriatic Arthritis

Juvenile psoriatic arthritis (JPsA) is defined as chronic arthritis with psoriasis or two of the following: dactylitis, nail pitting, onycholysis, or psoriasis in a first-degree relative (Fig. 14.6). Skin manifestations are subtle, mostly diagnosed as eczema. Typical psoriatic lesions are found in 0.5–1% of children, up to 2 and 3% in adults [11]. The lack of dermatological findings makes the diagnosis difficult and challenging. Regarding all subtypes, JPsA represents about 7% of JIA. Etiopathogenesis is somehow different, and environmental factors are shown to play a role. Streptococci is a known precipitant factor for guttate psoriasis, and these sorts of factors seem to trigger the joint inflammation, as well as enthesitis, a typical finding found in enthesitis-related arthritis [10].

JPsA is clinically heterogeneous. The peak age distribution is around age three and adolescence. Younger girls tend to have dactylitis and antinuclear antibody positivity. Dactylitis is the sausage-like swelling of any digits of hand or feet. Distal interphalangeal joint is involved as well as the proximal one. Regarding hand involvement, oligoarticular onset finally leads to progressive, destructive, bilateral wrist, and small joints of the hand involvement, a typical polyarticular course in about 60–80% of untreated children. Nail changes such as pitting, onycholysis, horizontal ridging, and discoloration are found in approximately 30% of children. They are almost always found with distal interphalangeal involvement. However, the relation of nail pitting with severe arthritis in adults is not found in children [10].

On the other hand, adolescent onset has the equal sex ratio, and axial involvement with enthesitis predominates the articular features

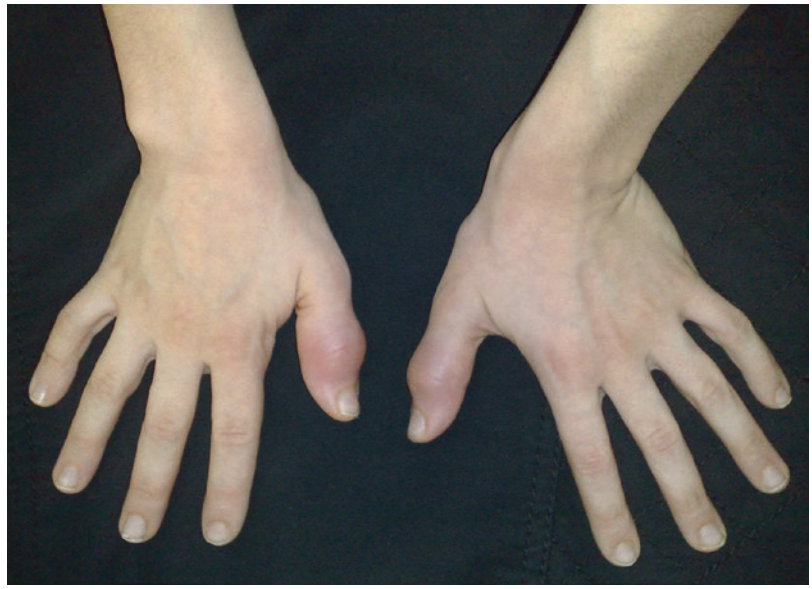

Fig. 14.6 Juvenile psoriatic arthritis – dactylitis

[12]. This type resembles adult psoriatic arthritis. Fortunately, the "arthritis mutilans" type which often leads to serious destructive arthritis in adults is rarely found in children. However, this does not mean that JPsA has relatively a benign course; it has worse outcome than oligoarthritis and polyarthritis. There are discrepant results regarding the course and prognosis. Roberton et al. followed patients at least for 5 years and demonstrated 70% ongoing arthritis and restricted joint movement in one-third [13]. A more recent study by Stoll et al. documented achievement of remission on medication in about 60% of children, both for the early onset and for the late onset [14].

Interpretation of the Joint Involvement in JIA

The Wrist

It is one of the most involved joints in JIA, 36% at the beginning, and 63% in the course of the disease. It is the most secondly involved joint. Severely affected areas are the intercarpal, radiocarpal, and second and third carpometacarpal joints [15]. In the early phase, there is a limitation of the extension, early as several months before the onset of radiologic changes. As the synovitis progresses, extension is severely limited. Distal radioulnar involvement might lead to the ulnar shortening, eventually exerting a traction force on the ulnar aspect of the wrist and may be responsible for deformity of the wrist. Granberry and Mangum reported 200 patients with JRA, with ulnar shortening leading to wrist deformity [16]. Patients with systemic onset, polyarticular course and the RF-positive and RF-negative polyarticular disease have bilateral and symmetric wrist involvement in the first year of the disease. Dorsal and flexor tenosynovitis are also common findings [17]. In psoriatic arthritis, there is asymmetric involvement of the large and small joints, leading to wrist and hand pathology and dactylitis.

Metacarpophalangeal (MCP) Joints

The polyarticular JIA has the greatest propensity to affect MCP joints, namely 50%. In contrast with deformity in adults with RA, who typically demonstrate ulnar deviation and loss of extension, deformity of MCP joints in patients with JRA tends to cause radial deviation and loss of MCP flexion. The index and

middle MCP joints are involved first, with synovitis and radial drift, typically followed by the fourth and fifth fingers [16].

Interphalangeal Joints

Patients with JIA usually have proximal interphalangeal joint involvement, up to 49%. In others, especially in psoriatic arthritis, distal interphalangeal joints are affected. Marked flexion with loss of extension is seen, and there is flexor tenosynovitis. Trigger finger may result from the formation of tendon nodules [15].

Recently, Hoeksma et al. conducted a study with 152 children with JIA [18]. Impairment of hands and/or wrists were detected in 40%; in the hands in 40% and in the wrists in 30%; most frequently on the dominant side. There was a marked impairment of the fingers than the wrists, despite a marked limited range of motion of the wrists. Proximal interphalangeal joints were the most involved parts, as expected. During daily life, almost half of the patients had writing difficulties at school.

The Role of Hand in Quality of Life and Functional Assessment of Hand in JIA

Hands are the most frequently used instruments of the body during daily life. Their restricted use due to arthritis has a major impact on the quality of life. Quality of life is defined as individuals' perceptions of their position in life in the context of culture and the value systems in which they live and in relation to their goals, expectations, standards, and concerns. Children with arthritis have longer life span when compared with the last century, particularly following the development of the disease-modifying drugs and biologic agents. Most of the pediatric arthritides is not fatal; however, they have a negative effect regarding the quality of life. As there is not a unique way of understanding the etiopathogenesis of JIA, the term "cure" cannot be used. The disease could only be put into remission. The World Health Organization (WHO) developed the International Classification of Functioning and Health (ICF) in order to provide a common vocabulary for the consequences of the disease [19]. The framework of ICF is particularly applicable to chronic arthritis. The ICF model defines the health condition in a child's life in three domains: structural and functional anatomy, activities in daily life, and social participation. A child with JIA has to overcome the difficulties in daily life which are mainly caused by the circumstances of his arthritis, and he has to cope with his peers. In the last 20 years, specific instruments have been developed in order to measure the effects of all the related conditions on the child with arthritis, namely, Health-Related Quality of Life (HRQoL). One of the most widely used is the "core outcome variables." They comprise physician global assessment, patient/parent global assessment, number of joints with active arthritis, number of joints with limited range of motion, ESR as acute-phase reactant, and childhood health assessment questionnaire (CHAQ). Improvement is defined as at least 30% improvement in three of the six items and no worsening of any of the items for more than 30%. This is called as ACRpedi30, which can be increased to ACRpedi50 or ACRpedi90. There are numerous important instruments for measuring the physical function and health-related quality of life other than CHAQ:

Juvenile Arthritis Assessment Scale (JAFAS) and Report (JAFAR) measures physical function. JAFAS requires a health professional, who measures the child's performance on 10 physical tasks [20]. It has limitations because of requiring professional and standardized equipment.

JAFAR contains 23 items when measuring physical function, and a 3-point scale (0–2) is used [21].

JAFAS and JAFAR have good reliability and validity, the limitation being applicable to children over 7 years of age.

Juvenile Arthritis Self-Report Index (JASI)
JASI is used mainly for rehabilitation purposes [22]. It measures physical function in 5 categories, with 100 items, higher scores reflecting better function. It can be completed in about 50 minutes.

Juvenile Arthritis Quality-of-Life Questionnaire (JAQQ)
JAQQ measures health-related quality of life [23]. It measures gross and fine motor functions, psychosocial functions, and pain on a 100 mm visual analogue scale. It is found as responsive as CHAQ, CHQ (Childhood Health Questionnaire), and Peds QL (Pediatric Quality of Life Inventory).

Childhood Arthritis Health Profile (CAHP)
CAHP is a parent report which consists of three modules [24]. It measures gross and fine motor function along with role activities between friends and family members.

Quality of My Life Questionnaire (QoMLQ)
QoMLQ is short and easy to use, measuring disease-related as well as generic difficulties, thus, demonstrating the differences between both factors [25].

Child Health Questionnaire (CHQ)
CHQ has numerous forms of which parent form 50 is used for JIA [26]. It measures global health, physical activities, daily activities, pain, behavior, well-being, general health, and family. Two scores are found, for physical and psychosocial activities, respectively. It is chosen for JIA patients along with CHAQ, for its widespread use (32 languages) and good reliability and validity.

Pediatric Quality-of-Life Inventory (Peds QL)
Peds QL is applicable to patients between ages 2 and 18 years [27]. It has 23 items including physical, emotional, social, and school functioning. It has separate parent and patient forms. It has a definitely positive contribution to studies with JIA patients.

Composite Disease Activity Scores for JIA
A composite disease activity score (JADAS) is developed [28], because JIA core set and pediatric response criteria only describe the improvement or deterioration in disease status. It includes four of the core set criteria (active joint count, physician's global assessment of disease activity, parents'/patient's assessment of overall well-being, and ESR as acute-phase reactant). There are three assessments of joint groups, measuring 10, 27, and 71 joints, respectively. It has a great contribution to the studies with JIA.

Childhood Health Assessment Questionnaire (CHAQ)
CHAQ [29] has two parts: disability and discomfort. Disability Index assesses functions in eight areas (dressing and grooming, arising, eating, walking, hygiene, reach, grip, and activities) distributed among a total of 30 items. In each functional area, there is at least one question that is relevant to children of all ages. Each question is rated on a 4-point scale of difficulty in performance, scored from 0 to 3. The Disability Index is calculated as the mean of the eight functional areas. Discomfort is determined by the presence of pain, as measured by a 100-mm visual analogue scale (VAS). In addition, a 100-mm VAS measures patient or parent global assessment of arthritis. CHAQ is translated into several languages and it is one of the most widely used instruments in JIA. It lacks psychosocial measuring in its current form. Regarding measuring hand functions, the questionnaire measures hand functions to an extent. For example, dressing and grooming part includes "tying shoelaces and doing buttons"; eating part has "open a new cereal box"; grip part includes "push open a doorknob." It does not have a particular assessment for hand including every aspect of hand functions.

Current literature does not have a specific instrument for measuring hand functions in children with arthritis. There are numerous items for adults, which will be discussed briefly:

Arthritis Hand Function Test (AHFT)
AHFT is an 11-item performance-based test designed to measure hand strength and dexterity [30]. The items include grip and pinch strength, pegboard dexterity, lacing a shoe and tying a bow, fastening/unfastening 4 buttons, fastening/unfastening 2 safety pins, cutting putty with a knife and fork, manipulating coins into a slot, lifting a tray of tin cans, and pouring a glass of water. It is mainly used for rheumatoid arthritis, osteoarthritis, and systemic sclerosis.

Basically, AHFT is a performance-based test which measures unilateral and bilateral hand functions, opposite to most of the other related tests. However, predictive validity and responsiveness to change have not been documented. Another disadvantage is that it does not have a summative score [31].

Grip Ability Test (GAT)
It is modified from a general test for hand function [32]. It includes only 3 items: putting a sock over one hand, putting a paper clip on an envelope, and pouring water from a jug. Patients with rheumatoid arthritis having the test are informed to complete in a timed session. A GAT score is formed by the sum of seconds while performing 3 items. A total score less than 20 seconds is normal. GAT test is used for only rheumatoid arthritis, and it has not been validated with other standardized performance-based tests for hand function. There are no reliability or validity studies performed with other forms of arthritis [27].

Jebsen Test of Hand Function
This test aims to measure a broad spectrum of hand functions [33]. Target groups are children over 6 years and adults with hand impairment. There are seven subscales: writing, turning over 3 by 5 inch cards (simulated page turning), picking up small common objects, simulated feeding, stacking checkers, picking up large light cans, and picking up large heavy cans. Each subscale is scored by recording the amount of time it takes the person to complete each task. Scores can be summed to obtain a total score. Subscale scores are evaluated according to the same sex and age normal results. The score range depends on the severity of the disability. The test is easy to administer; however, the norms should be revised using the commercially available version of the test. More studies about validity and sensitivity are needed [27].

The Juvenile Arthritis Functionality Scale (JAFS)
JAFS is a short and simple scale for the assessment of physical function for JIA patients [34]. It is superior to CHAQ by means of being shorter. It consists of 20 items. Three main functional areas are identified (lower limbs (pattern 1), hand/wrist (pattern 2), and upper segment (pattern 3)), which are designated to have an equal weight in the instrument scoring system. The discriminative ability of the JAFS is shown as comparable to that of the CHAQ. It was compared with CHAQ in 206 patients. Among patients with Pattern 1, the JAFS revealed the greatest ability to capture and discriminate functional limitation, whereas impairment in the CHAQ was more diluted across several subdimensions. Both CHAQ and JAFS appeared to be less reliable in detecting functional impairment in the hand and wrist (Pattern 2) than in other body areas [35].

Duruöz Hand Index (DHI)
The aim of this test is to measure the functional ability of the hand [36]. It includes 5 subscales with a total of 18 items: Kitchen tasks include holding a bowl, a plate full of food, pouring liquid, cutting meat, and peeling fruit. Dressing items include buttoning and opening/closing a zipper. Hygiene items include squeezing a tube of toothpaste and holding a toothbrush. Office items include two writing tasks. Items in the "Other" category include turning a doorknob, cutting with scissors, and turning a key in a lock (Fig. 14.7). Time to complete the test is less than 3 minutes. It is administered to patients with rheumatoid arthritis (RA), osteoarthritis (OA), and systemic sclerosis (SSc), patients in hemodialysis, and patients with stroke.

DHI is a promising test for research purposes in adults. Adequate reliability and validity have

Fig. 14.7 Duruöz Hand Index (DHI)

Answers to the questions:
0 = Yes, without difficulty,
1 = Yes, with a little difficulty,
2 = Yes, with some difficulty,
3 = Yes, with much difficulty,
4 = Nearly impossible to do,
5 = Impossible.

Answer the following questions regarding your ability without the help of any assistive device.

C1 – In the kitchen.
1. Can you hold a bowl ?
2. Can you seize a full bottle and raise it ?
3. Can you hold a plate full of food ?
4. Can you pour liquid from a bottle into a glass ?
5. Can you unscrew the lid from a jar opened before ?
6. Can you cut meat with a knife ?
7. Can you prick things well with a fork ?
8. Can you peel fruit ?

C2 – Dressing.
9. Can you button your shirt ?
10. Can you open and close a zipper ?

C3 – Hygiene.
11. Can you squeeze a new tube of toothpaste ?
12. Can you hold a toothbrush efficiently ?

C4 – In The Office.
13. Can you write a short sentence with a pencil or ordinary pen ?
14. Can you write a letter with a pencil or ordinary pen ?

C5 – Other.
15. Can you turn a round door knob ?
16. Can you cut a piece of paper with scissors ?
17. Can you pick up coins from a table top ?
18. Can you turn a key in a lock ?

been established for RA and OA, and preliminary reliability and validity tests have been done with SSc patients [27]. It is also found as valid and reliable in children with cerebral palsy [37].

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15 Functional Assessment in Geriatric Hand

Nurgül Arıncı İncel

Focus on Aging Hand

Prolonged longevity with an increase in the numbers of elderly and disability-free life expectancy focused the impact on geriatric population [1]. In the United States in 2005, one out of ten persons was 60 years and older, and it is predicted that one person out of five will be 60 years or older by 2050 [2]. Apparently a larger geriatric population will result in a greater proportion of geriatric hand therapy patients.

The elderly population (persons 65 years old and over) is classified for specific purposes, and these proportions are labeled as "old" age 65–75 years, "older" who are 75–85 years of age, and "oldest old" for 85 years of age or older.

The normal aging process involves gradual decreases in organ system capabilities and homeostatic controls that are relatively benign in the absence of disease. However the end result of these age-related declines is an increased vulnerability to disease and injury. Characteristic features of aging are reviewed in the table (Table 15.1):

Functional ability seems to remain stable until age 65 years, after which it diminishes slowly. It has been reported that a 15% loss in strength per decade occurs in 50- to 70-year-old individuals. Also hand function seems to remain stable until age 65 years. After age 75 years, age-related differences in performance are most apparent [3]. Aging has been reported to have a negative effect on hand function, including declines in hand and finger strength, ability to control submaximal pinch force and maintain a steady precision pinch posture and manual speed. The decline in hand function has been postulated to be due to deterioration in muscle coordination, finger dexterity and hand sensation and degeneration of the central nervous system [4]. Studies on hand function have reported increased difficulties in performing everyday tasks such as tying shoelaces, fastening buttons, manipulating earrings, retrieving objects from a purse, and writing a note. Deterioration in hand function reduces quality and independence of life of senior citizens [4]. The degree of frailty in older adults is modifiable with the help of appropriate strategies to allow these individuals to live longer without severe disability [5]. So, early determination of present or future risks with an easy-to-apply indicator is a very

Table 15.1 Major changes in aging

Decreased reserve capacity of organ systems, which is apparent only during periods of maximal exertion or stress
Decreased internal homeostatic control
Decreased ability to adapt in response to different environments
Decreased capacity to respond to stress

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important issue. Hand assessment tools may serve for this purpose as a predictor of negative outcomes.

Hand assessment in elderly has special issues for both the physiatrist and the hand therapist. This chapter is supposed to highlight these specific conditions and to bring in an insight to the older hands. We must not forget that geriatric issues refer to problems not only affecting the aged but to the whole society as well.

In general, the four principal domains of comprehensive geriatric assessment are functional ability, physical health, psychologic health, and socioenvironmental factors. Assessment of each can be achieved by using certain assessment instruments. They make the process more reliable and easier. They also aid communication of clinically relevant quantitative information among health care providers and permit tabulation of clinical data and measurement of change over time. Several issues need to be considered in selecting an assessment instrument for a specific population: instrument reliability and validity, patient acceptance, time and personnel needed to administer the tests, and relevance and usefulness of the data to be collected.

Functional performance can be viewed as a measure of overall impact of health conditions in the context of a patient's environment and social support system. Participation restriction formerly known as handicap is defined as limited fulfillment of an individual's role based on age, sex, and social-cultural factors. A loss or decline in hand function is a major cause of activity and participation restriction with a negative impact to the quality of life.

It is essential to assess the geriatric patient's functional status at the initial visit, and any change in functional status should prompt further investigation. This can be assessed at three levels: basic activities of daily living (BADLs), instrumental activities of daily living (IADLs), and advanced activities of daily living (AADLs). The BADLs are the tasks that patients need to be able to complete on their own, or have assistance to complete, in order to be able to live in their own residences: transferring, toileting, bathing, dressing, continence, and feeding. The IADLs are the abilities one needs to maintain an independent household: shopping for groceries, driving or being able to use public transportation, telephone skills, meal preparation, housework, home repair, laundry, taking medications, and handling finances [6].

Changes Associated with Aging

Some of the physical changes and decline in function most affecting the hand in the elderly population are:

- *Neuromuscular changes*
- *Sensibility changes*
- *Skin and wound healing*
- *Cognitive changes*

Neuromuscular Changes

With increasing age, declines in strength, speed of movement, and coordination occur, and all are related to a decline in neuromuscular function. Nervous system changes include decreases in nerve conduction velocity, sensory activity, rate and magnitude of reflex responses, and arousal threshold. The decline in motor control with age, which results in part from age-related changes in cortical control of voluntary movement, is particularly pronounced for fine hand movements [7]. Sarcopenia, defined as the slow, progressive, and apparently inevitable loss of muscle mass and strength, is one of the most important physiological changes that occur with advancing age [8]. Sarcopenia is clinically defined as two standard deviations below the mean appendicular muscle mass of young healthy adults of a reference population, similar to osteoporosis [2]. It is estimated that aging is associated with 20–40% of the decrease in muscle strength and power at 70–80 years of age and with still greater reductions (50%) at 90 years of age [8]. However, this diminution is not linear and does not occur at the same rate and age in both sexes. Muscles that are most frequently used have less loss in strength.

Also changes in the contractile properties of muscle (e.g., normalized force, contraction time, half relaxation time) cannot explain the entire age-related decline in strength. Rather, some features of muscle activation also seem to contribute to the decrease in strength. Older adults, for example, exhibit greater levels of antagonist coactivation compared with young adults, which, while helping to stabilize the joint, also reduces the net torque exerted about a joint. Therefore, age-related differences in strength are due not only to changes in the size and quantity of muscle but also to changes in muscle activation [9]. Fifteen extrinsic muscles and 11 intrinsic muscles are associated with hand function. Extrinsic muscles directly contribute to the gross motor motion of the upper extremity and gripping force, while intrinsic muscles regulate fine motor coordination of the digits. Aging affects muscle strength of the upper extremity with the decline rate of strength being more pronounced in intrinsic muscles than in extrinsic muscles. In addition to losing muscle strength with age, older adults have poor force control. Force control may be as important as grip strength to older adults because most daily objects require the correct amount of force to maneuver; not maximum force. Moreover, aging has an adverse effect on steadiness with older adults having less control of force output [10]. Steadiness is defined as the ability to exert a constant submaximal force, and it is more strongly associated with fine motor coordination and precision than is grip strength. In summary, the literature suggests that hand function in older adults is influenced by three factors: force generation (muscle strength); force need (force control); and force consistency (steadiness). Therefore, measures of steadiness comprise an adequate index of hand function and, when complemented by other neurophysiological recordings, can provide insight into the mechanisms responsible for age-related differences in motor performance [9].

Another point of interest for the elderly population effecting motor function is the "laterality." Laterality is a phenomenon in which an organ with bilateral symmetry contains one half that is superior to another half in achievement of motor or cognitive tasks. The hand in which laterality is found is the dominant hand, and it is generally superior in muscle strength, quickness, accuracy, and dexterity. The degree of difference between the dominant and non-dominant hands may differ between young adults and the elderly [11]. In their study Saimpont et al. showed that elderly subjects were less accurate and slower than their younger counterparts in their left-right hand judgments which is positively correlated with task difficulty (coarse versus fine motor performance) [12]. As the HAROLD (Hemispheric Asymmetry Reduction in Older Adults) model states that prefrontal cortex activity tends to be less lateralized in older adults than in younger adults. Indeed, a number of studies have demonstrated bilateral prefrontal activations in older subjects, whereas in younger subjects, the activations were clearly lateralized. In other words, during the same tasks, older subjects activate both hemispheres, whereas younger subjects preferentially activate only one hemisphere [13]. This hemispheric asymmetry reduction in older subjects can be interpreted in two ways: either by a compensatory phenomenon which allows older subjects to maintain their performances, or by a phenomenon of dedifferentiation, meaning that older subjects have more difficulty recruiting specialized neuronal mechanisms [13].

Desroiser and coll. study pointed out that a gender based difference is observed in the hand preference of elderly too. The dominant and non-dominant arm-hand usage of 40 older adults was quantified according to gender, and women demonstrated a significant preference of using the dominant hand, whereas men presented more bilateral usage of their hands of using their non-dominant hand [14].

Changes in Special Senses

Warabi et al. suggested that impairment of sensory processes is a key component of decreased motor coordination and function [15]. Visual changes that can affect hand function include decreased acuity, accommodation,

color differentiation, sensitivity to light, depth perception, impaired eye-hand coordination, and accommodation to light and dark.

Screening for hearing loss is strongly recommended for all elderly persons. Decreased auditory acuity frequently develops. With hearing loss progression the lower frequencies are affected also, making it difficult to understand what is being said especially in a loud setting. Besides old persons often hide their hearing loss, embarrassed by it and equating it with aging [16].

Hearing or vision aids to improve functioning are often available, and elderly people must be encouraged to use them to improve their hearing- or vision-related quality of life.

Skin and Wound Healing

During the aging process, influenced by extrinsic and intrinsic factors, the three-layer skin system changes markedly. These changes provoke the skin to lose its ability to act as a physical and mechanical barrier against exogenous factors. Because of its decreased mechanical properties, aged skin not only shows typical signs of aging, like wrinkles and furrows, but also tends to a higher violability by mechanical exposure and skin diseases. A reduction of the water content in the outermost layer of the skin makes the skin drier and may in turn decrease the friction at the object-digit interface. The consequence of these skin changes is an increased slipperiness of the fingers during object handling, increasing the likelihood of dropping the object. This proposal is supported by studies showing that the slip force (i.e., the minimum force required to prevent an object from slipping) is increased in the elderly. The lower the friction at the object-digit interface (due to either a slippery object surface or increased skin slipperiness), the higher the grip forces necessary to maintain object stability [17].

Tactile thresholds in the elderly are also significantly increased. This is thought possibly to be attributable to a decrease in the density and distribution of Pacinian and Meissner corpuscles and Merkel's discs in the skin causing decreased spatial acuity. The spatial acuity of skin at the fingertip deteriorates noticeably with age as assessed by two-point threshold measurement. Tactile acuity thresholds in the finger are on average about 80% higher in the older subjects (age> 65 years) than in the younger subjects (age 18–28 years) [18]. For all these reasons skin aging has to be understood not only as a cosmetic problem but also, especially in an aging population, as a serious medical problem [19].

Cognitive Changes

Some researchers have assumed that there are little or no age relations on cognition until age 65 or older [20]. About 3% of community-dwelling elders between ages 64 and 74, 14% between 75 and 84, and >20% over 85 have moderate degrees of cognitive impairment. To evaluate cognitive impairment, the physician can use the Mini-Mental State Examination Test (MMSE). The MMSE is useful in quantitatively estimating the severity of cognitive impairment, in serially documenting. Age-related declines in cognitive functioning might be expected to have a greater role in decreases in quality than in decreases in quantity [20].

Frequent Problems to Deal with in Elderly Population

Apart from the clinical conditions irrespective of age like traumatic conditions, elderly population suffers from various pathologies in their hands. Age-related changes are often accompanied by underlying pathological conditions that are common in the elderly population. There are conditions a physiatrist/clinician must take into account while dealing with a geriatric hand patient. Assessment of hand function and prehension patterns is needed in order to determine specific treatment approaches [21]. For adults aged over 55 and 50 years in two different studies, respectively, the 1-month and 1-year period prevalence of hand pain was estimated at 17% and 30% with reports of loss of hand function and difficulty in completing everyday tasks [22].

Comorbid diseases or conditions not directly related to the primary upper extremity problem but negatively affecting the patients general health status or the therapy period, can be present, like a patient with flexor tendon repair accompanied by a severe dementia. These problems not only interfere with the evaluation and diagnostic process but seriously and negatively affect the therapy and rehabilitation period, especially in the absence of social support.

Some systemic pathologies common in the elderly population have marked impact on hand function. Parkinson's disease with rigidity and tremor, type II DM with neuropathy and Dupuytren's contracture, and stroke with flask or spastic extremities are the most recognized ones. Impairment of hand function in such conditions also overlap with the concept of "accelerated aging" in patients with chronic physical conditions and disabilities.

Below are the examples of medical conditions resulting in with functional deterioration of hands:

Fractures

Fractures in the elderly may result in prolonged pain and disability. Especially fracture of the distal radius in postmenopausal women is a well-known entity with multiple complications, ending up with a decline in upper extremity functional status. A different aspect of the fractures in the geriatric group is that they may tolerate greater degrees of residual deformity because of a more sedentary lifestyle [23].

Osteoarthritis

Primary osteoarthritis (OA) is characterized by a slow progression of intermittent or constant joint pain that may be accompanied by limited movement and joint deformity. Changes both intrinsic to the joint and those extrinsic (such as sarcopenia, altered bone remodeling, and reduced proprioception) contribute to the development of OA. The concept that aging contributes to, but does not directly cause OA, is consistent with the multifactorial nature of this condition and the disparity in which joints are most commonly affected [24].

Hand OA primarily affects the distal and proximal interphalangeal joints, and first carpometacarpal join. Hand OA has an enormous socioeconomic impact because it affects 60–70% of the population above the age of 65 and in particular, women already above the age of 47. Since almost 80% of the population can expect to live through most of their seventh decade of life, the socioeconomic impact of OA is likely to increase even further in the future. Hand osteoarthritis has considerable functional consequences in terms of pain, reduced hand mobility, reduced grip force, and problems in many domains of activity and participation. As a consequence, rehabilitation programs should be both multidisciplinary and multidimensional, aiming at reducing hand impairment, improving occupational performance, and enhancing the self-efficacy and coping strategies of the individual [25]. Also the European League Against Rheumatism (EULAR) recommends a combination of non-pharmacological and pharmacological treatment modalities for the optimal management of hand OA, with a preference for local treatments over systemic treatments. Local treatment could be an attractive treatment modality, especially in elderly patients with more comorbidities [26].

Diabetes Mellitus

Diabetes mellitus (DM) is a chronic disease characterized by hyperglycemia with various complications including diabetic hand syndrome, a condition characterized by association of distinct entities, and limited joint mobility also known as diabetic cheiroarthropathy, Dupuytren's disease, flexor tenosynovitis, and carpal tunnel syndrome resulting in significant morbidity and mortality [27]. Age and duration of diabetes are clearly related to these changes. The association between rheumatic disorders and diabetes mellitus is gaining attention, and with recent data showing that more than 30% of patients with type 1 or type

2 diabetes have some hand or shoulder diseases, the magnitude of this problem is becoming more evident. The exact mechanisms by which the specific metabolic abnormalities of diabetes impact on the pathogenesis of its rheumatic manifestations are not clear [28]. Also symmetrical distal sensorimotor polyneuropathy (PNP) is important in patients with diabetes interfering with hand function [29].

Recognition of the association between DM and musculoskeletal complications facilitates their correct diagnosis in the setting of DM and prompt initiation of appropriate treatment, which may include optimizing glycemic control. Conversely, awareness and identification of the characteristic musculoskeletal manifestations of DM may facilitate earlier diagnosis of DM.

Stroke

Stroke is the second leading cause of death in the world and the leading cause of serious, long-term disability in adults. The incidence of stroke increases dramatically with advancing age, doubling with each decade after the age of 45 years. Over 70% of all strokes occur above the age of 65 [30]. Progressive carotid atherosclerosis, cardiac arrhythmia and emboli, and vascular changes all contribute to this increasing incidence of stroke in the elderly [31]. About half of those who survive are dependent on others for assistance with personal activities of daily living. This disability is mainly due to loss of hand and/or upper extremity function [32]. Apart from the expected hypotonic and spastic states of hand during the disease course, it is not uncommon to have severe pain, neglect or dystonia of upper extremity and hand for these patients.

Rheumatic Diseases

Aging and arthritis has two main conflicting aspects. Aging with a rheumatic disease and having rheumatic diseases frequently affecting older people. The former group mostly covers the rheumatoid arthritis patients. Suffering from a rheumatic disease is related to negative perceptions with regard to the physical aspect of aging earlier in the life course. This group of patients suffer from hand functional disturbances resulting from their primary disease and as they get older their disease get older too. So secondary deformities and expected complications appear in early periods of their old age. As a result for these patients feeling physically old starts in the middle of their life [33]. Rheumatic disorders mainly affecting older patients are late-onset RA, polymyalgia rheumatica, giant cell arteritis, crystal arthropathies, etc. Hand joint involvement is fortunately scarce for these patients [34].

Parkinson's Disease

Parkinson's disease is present in 1% of people older than 65 and clinically manifests with tremor, and rigidity where upper extremities and hands are mostly affected. The tremor is present at rest and increases with stress. Voluntary movement is slow. All of these negative symptoms result in loss of hand functions and difficulties in everyday tasks [35].

Dementia

Dementia is found in 1.5% of people aged 65–70 years and increases to 25% of people 85 years age and older [36]. Patients with dementia experience difficulties for both the diagnostic and rehabilitative periods of hand management. Also severe dementia itself is a risk factor for trauma or self-destruction for all body parts including hands if left unattended.

Pain

The elderly deserve adequate pain management no less than any other age groups. Older adults

represent a subgroup of the general population with a greater risk of hand pain [37]. Risk factors for progression of hand pain and functional difficulty in older adults may differ from those in younger adults [38].

Unique characteristics for geriatric pain include difficulty in completing one of the most widely used pain measures, prolonged and impaired recovery from tissue and nerve injury, and age-specific interrelationships of psychosocial factors important in adjustment to chronic pain [38].

Senile Tremor

Senile tremor refers to cases in which essential tremor begins in old age, yet despite its name senile tremor is not a normal concomitant of aging. Most patients develop the tremor in the seventh decade. At first it occurs only with voluntary movements, later it becomes more constant and even occurs at rest. This can be embarrassing even debilitating with daily living activities and upper extremity tasks [39].

Evaluation of the Geriatric Hand

Clinicians should be prepared to spend more time interviewing and evaluating elderly patients and should tailor the interview to the individual patient [40]. Aphasia, cognitive dysfunction or sensory deficits such as hearing or vision loss can interfere with the interview process. Aids to improve functioning are often available to the patient but may not be consistently or appropriately used. If the patient uses a hearing aid, ensure it is worn and working; ensure glasses are worn [40]. As the presence of comorbidities increases markedly with age, to collect data without these medical conditions becomes extremely challenging. Also such a population would not be a real representative of the norm in older population [41].

Interviewing with geriatric patients requires attention as they may omit important symptoms, rationalizing them as an inevitable consequence of aging or fearing that admitting to problems may lead to placement in a care home. Clinical features of diseases may differ from those seen in younger patients; disease may manifest as functional decline. While exploring activities of daily living, make the distinction between what the patient wants to do, what they can do, and what they actually do—with the last descriptor being the most important [40]. Assessment of hand function and prehension patterns is needed in order to determine specific treatment approaches [21].

Inspection Heberden and Bouchard nodes occur in patients with OA. Nails may represent many abnormalities due to systemic conditions like clubbing, spoon nails, pitting, color changes, etc. Nails are thicker in the elderly so thin brittle nails can be a feature of metabolic abnormality. Palm examination may reveal Dupuytren's contracture, callus formations, or unusual color change as in cyanosis, pallor, rash, or palmar erythema. Petechia, livedo reticularis, or telangiectasias must not be underestimated. General sarcopenia may manifest as thenar or interosseal atrophy in the aged men and women (Fig. 15.1).

Range of Motion The range of motion examination is very important in the elderly. All upper extremity should be thoroughly checked. Even relatively minor losses in range of motion can

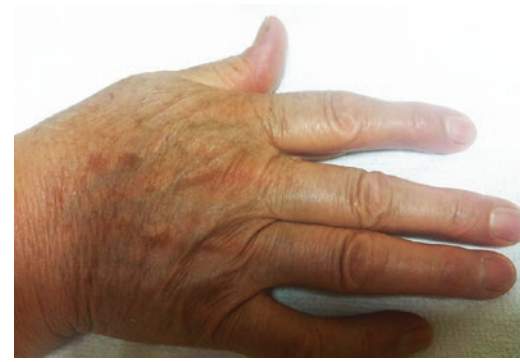

Fig. 15.1 Elderly hand

affect function. In hand OA limitations in range of motion can go unreported in some instances, because the older person might be unaware that range of motion has declined due to its gradual progression. Examiner must record both active and passive range of motion and note the presence of contractures for every joint. Wrist extension and flexion, finger flexion and extension limitations can have important ramifications.

Grip Strength Grip strength measures only one component of musculoskeletal performance and requires little cognitive function. However it is accepted to be the major predictor of hand function and with a high correlation to daily living activities. An advantage of handgrip strength could be that it is easy to use in clinical practice [42].

Further, grip strength affects the ability to perform tasks like dressing and holding small items. 9 kg of total grip strength is required to perform everyday functional tasks [43]. In fact, hand grip strength has been suggested as a better single marker of the frailty of an individual than their chronological age [44].

It was clarified that muscle strength in the elderly generally decreases with age. Maximal handgrip strength and controlled force exertion (CFE) in the elderly were about 70% and about 50% of young adults respectively [11]. The number of muscle fibers, the number of recruitable units and a firing rate of motor units, nerve impulses conduction velocity, and shortening velocity in single skeletal muscle cells decrease with age [45]. In addition, the information processing time in the central nervous system becomes longer. From the above, it is inferred that both maximal handgrip strength and CFE decrease with age, but the CFE which is affected by a decrease in nerve function and other factors besides muscle function shows a larger decrease than the maximal handgrip strength which is primarily influenced by a decrease in muscle function [11]. The decline in overall muscle in the geriatric population might also be responsible for fading away of both age and side-based variations as reported [46].

Relative Hand Strength Indexes:

Relative HS indexes are ratios of hand grip strength to body composition measurements body weight, BMI, fat mass, skeletal muscle mass, upper limb muscle mass, etc. Relative indexes proved to be a more useful tool to identify persons with increased risk for mobility limitation than hand strength alone [47].

Grip strength is measured with different types of dynamometers (e.g., Jamar®, a prototype of manual dynamometer). Pinch strength is also determined by manual hydraulic pinchmeters in different types of pinch positions (pulp, lateral, key, three-point pinch).

It is widely accepted that grip strength measurement could be substituted for the physical exam-based joint impairment measure to predict impairment as hand function has a high correlation to ADL. Lower hand grip strength predicts an accelerated decline in ADL, disability, and cognition, thus contributing to increasing dependency in old age.

However, for very frail elderly people, measuring hand grip strength might be difficult to perform, and general results could not be applicable to this group of patients. Grip strength is not only a determinant of a present impairment but a predictor of future decline in abilities with new studies considering this concept for preventive and rehabilitative purposes [44]. Here it is important to highlight the importance of population-specific norms. Most recent studies increasingly focus on that issue. Also these population-based studies may reflect the changes in the socioeconomic structure of countries within decades [41].

Laterality As mentioned in previous sections, a functional right and left difference called laterality is found in each body part with bilateral symmetry like hands. This asymmetry is expected to be diminished in the aged population. Hand preference can be determined with the Edinburgh Handedness Inventory which classifies handedness on the basis of a short interview on hand preference in the performance of routine practical tasks [48] (Table 15.2).

Table 15.2 Edinburgh Handedness Inventory used for assessing laterality

Edinburgh Handedness Inventory			
Task/object		Left hand	Right hand
1.	Writing		
2.	Drawing		
3.	Throwing		
4.	Scissors		
5.	Toothbrush		
6.	Knife (without fork)		
7.	Spoon		
8.	Broom (upper hand)		
9.	Striking a match (match)		
10.	Opening a box (lid)		
Total checks:		LH =	RH =
Cumulative total		CT = LH + RH =	
Difference		D = RH – LH =	
Result		R = (D/CT) × 100 =	
Interpretation: (Left handed: R < −40) (Ambidextrous: −40 ≤ R ≤ +40) (Right handed: R > +40)			

Functional Evaluation

The relation between grip strength is test-specific. Grip strength becomes a significant factor when test requires grip strength to successfully complete the task. Second, in addition to grip strength, arm curl strength independently contributes to hand function in both time-based and self-report assessments. Hand function relies on coordinated extrinsic and intrinsic muscles to provide mobility, stability, and dexterity. This finding highlights the important influence of extrinsic muscles, as measured by arm curl strength, on hand function. Lastly, a time-based assessment measures only one dimension of motor performance, which is speed. Older adults may compensate impaired movements with speed instead of slowing down [10] Functional evaluation gives us a chance to document the reflection of these different aspects to hand function.

Jebsen Test of Hand Function

The Jebsen Test of Hand Function is a commonly used standardized test for assessing a person's functional hand use. Both the dominant and non-dominant hands are evaluated using a series of seven subtests related to activities of daily living. The Jebsen test may be a useful means of quantifying any decline in hand function with age. Normative values for adults have been published for ages 20–59 and 60–94 years. It is reasonable to assume that changes in hand function could occur at varying rates between the ages of 60 and 94 years; this large age grouping therefore may be a poor representation for clinical comparison. In general, the elderly subjects had lower mean peak acceleration. Also, the elderly persons' movements were slower and less automated.

It appears that gender has only a minor influence on the decrease in hand function. In each age group, men and women were not significantly different for the majority of tasks. Women in their 60s and 70s, however, did perform the "writing" subtest with the dominant hand significantly faster than did men in the same age groups. Perhaps this may be attributed to a tendency for women to perform writing tasks more frequently than men [49]. Because another factor that might influence the relationship between age and task performance is familiarity with the task. Notably, the difference between elderly and younger people was less evident when it came to signing their names, a highly automated task [50].

Upper Extremity Performance Test for the Elderly (Test d'Evaluation des Membres Supérieurs de Personnes Agées-TEMPA)

The TEMPA was developed to evaluate strengths and weaknesses in the upper extremity function of patients aged 60 and older. Because normal aging may contribute to an increase in the length of execution of the tasks, normative data were developed to help clinicians using the TEMPA differentiate between normal and pathological aging. This test is composed of 9 standardized tasks representing daily activities: 5 tasks are bilateral (open a jar and take a spoonful of coffee; unlock a lock, open a pill container; write on an envelope and stick on a stamp; shuffle and deal playing cards); and 4 are unilateral (pick up and

move a jar; pick up a pitcher and pour water into a glass; handle coins; pick up and move small objects) for a total of 13 different items. All the test material is placed in precise, predetermined positions on a set of shelves designed to ensure a high level of standardization in performing the tasks. Each task is measured according to three criteria: length of execution, functional rating, and task analysis. For length of execution, each task is timed to the nearest tenth of a second, beginning as soon as the subject's hands leave the table and ending the moment the task is completed. The functional rating refers to the subject's independence on each task; it is measured using a 4-level scale: 0, the task is successfully completed, without hesitation or difficulty; -1, some difficulty with the task; -2, great difficulty in completing the entire task; and -3, the individual could not complete the task, even when assistance was offered. The task analysis section quantifies the difficulties experienced by the subject according to five dimensions related to upper extremity sensorimotor skills: strength, range of motion, precision of gross movements, prehension, and precision of fine movements [51].

According to normative data obtained from TEMPA results, the length of execution is shorter for women on the tasks more related to fine dexterity than the other tasks. In contrast, men are faster on the tasks least related to fine dexterity and sensibility and most related to grip strength. Age is the best predictor of upper extremity performance in this elderly sample. Other predictors vary according to the task requirements. Current activity level plays an important role in the performance of many tasks [51].

Pegboard Tests

For a comprehensive assessment of upper extremity function, dexterity is an important component that must be considered. Dexterity has been defined as "the fine, voluntary movements used to manipulate small objects during a specific task, as measured by the time to complete the task and considered as essential for successful performance of tasks of daily living, work, school, play, and leisure [52]. Most commonly used tools for determination of dexterity are pegboards. Purdue pegboard and nine-hole pegboard tests are the most frequently studied ones in the literature in different pathologies regarding the elderly population [53]. A decline in scores for elderly adults has been recorded up to 7–8% in studies indicating a loss of fine dexterity [14].

Functional Reach (Maximal Safe Standing Forward Reach)

This is an easy-to-perform test and an indicator of frailty for the aged population.

According to the measuring method devised by Duncan et al., participants stand with their feet together, their bodies perpendicular to and with one shoulder adjacent to, but not touching, a wall which had a measuring yardstick affixed to it horizontally [54]. They raised their arms in front of them to a horizontal position with their tips of the middle fingers positioned at the zero end of the measuring yardstick. They reached forward as far as possible, bending as necessary but keeping their arms straight and horizontal and their feet in the starting position. The distance from beginning position to ending position as measured at the tips of the middle fingers was the FR value. Although the FR test was originally developed as a measure of dynamic balance, not hand function, it involves movement of the upper extremities and is required for many upper body tasks. FR can be accepted as a determinant of independency for the elderly [55].

Finger-Nose Test

Upper extremity motor coordination can be estimated by the finger-nose test. The subject has to move her/his upper extremity in a specific trajectory as quickly as possible in 20 s. A high score indicates a good performance [14]. In Courtesier's study the decline in this test in the elderly is comparable to the decline in the pegboard test, which is a fine dexterity test (loss of 7–8% depending on the subtests) [14].

The 20 Cents Test (20-C-T)

The 20-C-T [54] was validated in geriatric subjects to assess the finger dexterity and fine motor skills of hand relevant to everyday life which is also feasible for patients with intermediate impairment of cognition or vision. It takes less than 5 minutes and uses coins as standardized objects. Validation was done with European as well as US-American one cent coins. The assessor lays a sketch paper on work surface and spreads 20 coins in an area. He places a tin or other vessel (diameter at least 8 cm, height not more than 4 cm) directly behind that (from the patient's perspective). He instructs the patient to take the coins and place it in the tin one by one as quickly as possible.

Questionnaires

In contrast to the so-called hand function tests, which require trained observers and a specific setting in time and place, self-reported questionnaires may be considered more feasible in busy clinical settings because they do not need the presence of professional staff when administered. But, it must be kept in mind that self-report does not directly measure musculoskeletal or cognitive function; rather the questionnaire measures the subject's perceptions of hand function.

With regard to length of questionnaires, some are relatively long, whereas others are relatively short. In the elderly, it may be hard to maintain concentration for a prolonged time. This can be an issue for the observer too, since time is a precious commodity in health care today, Another factor is the time it takes to score the scale. Also other important aspects to consider selecting a scale are the overall dimensions of the scale and the specific items it contains. The clinician and researcher first need to identify what dimensions they are interested in assessing in their patients and then select the scales that include those domains [56].

GERI-AIMS-Dexterity Scale

The self-measure report of hand function, GERI-AIMS, is a modification of the Arthritis Impact Measurement Scale (AIMS) for use in geriatrics (GERI-AIMS) [57]. GERI-AIMS is an interview-administered comprehensive measure of functional status and consists of 44 health status items arranged into 8 scales of functional status, 1 of which is the dexterity scale. The dexterity scale contains five questions about the ease with which the person can write, turn a key, button clothing, tie shoes, and open a jar [58].

Duruöz Hand Index (DHI)

This scale was developed by Duruöz et al. as a practical functional disability scale for rheumatoid hand [59] and it validated for assessment of hand function in many hand involvements. It was already validated to assess hand function for geriatric population [46, 60]. This scale comprises 18 daily activities questions for the hands. It is completed by the patients in a clinical setting [61].

Australian Canadian Osteoarthritis Hand Index (AUSCAN)

The AUSCAN was developed jointly between Australia and Canada to provide a multicultural assessment of hand function, pain and stiffness in OA. The AUSCAN contains 15 items that capture a combination of common symptoms in HOA and those that occur frequently and are important to symptomatic individuals practically over 45 years. The AUSCAN uses a 48 h time frame and comprises sub-scales of hand pain (5 items), hand stiffness (1 item), and hand function (9 items) [62].

Upper Extremity Function Scale (UEFS)

Pransky et al. developed the Upper Extremity Function Scale (UEFS), an eight-item, self-administered questionnaire, to measure the impacts of upper extremity diseases on function. UEFS is easy to use and can be completed in a self-administered written format in less than

5 minutes [63]. Older individuals have decreased ability to maintain steady submaximal forces, difficulty in determining the slipperiness of objects, an increase in time required to manipulate small objects, and a decrease in finger pinch strength by an average of 14%.

Activities of Daily Living (ADL)

Upper extremity performance (UEP) is tightly associated with a person's functional status because several common ADLs, such as dressing, eating and personal hygiene are mostly upper extremity-related tasks. Notably, the vast majority of women also engage in upper extremity-related IADL tasks (e.g., cooking, housekeeping, and doing the laundry) [64, 65].

Although several UEP measures are widely used in older adults, it is unclear whether any or all of them provide a similar, additive contribution to our determination of functional status. Compared to one measure alone, combining several UEP measures may capture more manifestations of disability, however, it has yet to be determined which, if any, combination of UEP measures is most efficient at detecting functional limitation and disability. UEP components for performing ADLs included upper body strength, flexibility, and dexterity [61].

Disability status is assessed using IADL and ADL scales [66, 67]. The ADLs include aspects of eating, moving from bed to chair, grooming, toilet use, bathing, ambulation, negotiating stairs, dressing, and emptying bowels and bladder. The IADLs include the ability to use the telephone, shop, prepare food, perform housekeeping chores, do laundry, use a mode of transportation, maintain responsibility for own medications, and handle finances. IADL and ADL disabilities were defined as a participant being unable to perform or needing human help with one or more IADL or ADL tasks, respectively.

Although the study of McGuire et al. shows that hand motor function and (I)ADL need not be related, studying the relationship between the two is of clinical relevance, as the level of (I)ADL might be maintained or improved by training hand motor function itself. In healthy aging persons, training for pinch force, hand steadiness and moving small objects has proven successful. Also, the elderly persons have slow and less automated movements, these can be improved too. This is an important finding since many (I)ADL tasks involve hand manipulation, and improvements in these areas could enhance quality of life. That said, not all aspects of hand motor function are easy to train. For example, elderly people have more problems with releasing grip force which is one aspect of the hand motor function that is not easy to exercise. However good news is that the aging process and degree of frailty in older adults are modifiable with the help of appropriate strategies, to allow these individuals to live longer without severe disability [5].

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Hand Function in Common Hand Problems

16

Lynn H. Gerber and Fatma Gülçin Ural

Introduction

Positioning the hand in space and placing it in functional positions is critical for us if we are to interact effectively with our environment. Our hands are our most important tools for survival and fun. Diseases with hand involvement affect its functional status and quality of life.

This chapter presents a discussion of several commonly seen hand impairments that are likely to influence function. Also, evaluations of functions are used for response to the treatment in these disorders. The goal of this chapter is to provide a brief, practical guide to evaluation of some common, non-traumatic, functional hand problems. Additionally, it aims to explain how to evaluate the functional status in these diseases.

It is important to proceed in a systematic way in evaluating these problems, using standardized assessments and considering possible contributions of posture, ergonomics of the work, home and leisure activities. Included in this chapter are syndromes of various etiologies, but overuse is often a common component.

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Included are the following:

- *Carpal tunnel syndrome* is the most common compressive neuropathy of the hand. Its symptoms, often nonspecific, usually include dysesthesias along the median nerve distribution.
- *Trigger finger* is characterized by a snapping or locking sensation and limitation of full flexion of the finger. Often it is the 3rd, 4th, or 5th digit. Occasionally it remains in a fixed flexion position.
- *De Quervain's* tenosynovitis is associated with pain on the radial aspect of the thumb. There is usually pain on palpation or on movement when one is using the thumb for pinching or gripping.
- *Dupuytren's* contracture is the result of hypertrophy of palmar fascia affecting the 5th digit in about 70% of people so affected. It is a clinical diagnosis made with the presence of palpable nodules and cords in the palmar fascia and associated with flexion contracture of the 4th and 5th digit.
- *Chronic regional pain syndrome* is a chronic, neuropathic pain syndrome characterized by autonomic dysfunction and severe pain that may lead to crippling contractures of the limbs. The patient often presents with a cool extremity, color changes (ruddy or bluish), swelling, and allodynia.
- *Focal dystonia*, also called writer's cramp/musician's cramp, is maladaptive response of the brain to repetitive performance of stereotyped

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hand movements. Usually, the individual presents with cramping and pain when they repeat the inciting task. When not used in that fashion, the hand appears normal.

Measurement

A comprehensive hand evaluation, which includes descriptive and quantitative assessment, is essential to understand the impact of impairments on function. The use of standard imaging (x-ray, computed tomographic, magnetic resonance imaging, real-time ultrasound, Doppler ultrasound blood flow) and standardized measurements are essential for proper diagnosis and treatment [1].

Carpal Tunnel Syndrome

Carpal tunnel syndrome (CTS) is one of the most frequently encountered problems and the most common compressive neuropathy in the upper extremity [2]. The median nerve and the flexor tendons pass through a tunnel at the wrist limited by carpal bones and the transverse carpal ligament (Fig. 16.1). Numbness and paresthesias are felt in the distribution of the median nerve (Fig. 16.2). In the United States, 15% of the general population has symptoms consistent with CTS for which they seek medical attention. Symptoms are often nondiagnostic, because those associated with CTS are similar to radiculopathy, wrist arthritis, and tendinopathies. Therefore, electromyographic studies are usually considered necessary for confirmation. Using this as the diagnostic criterion, CTS has a 3% prevalence in women and 2% in men. Prevalence is greatest in women >55 years [3] and in those who are obese, smoke, or have diabetes mellitus [4, 5]. A phenomenon called the "double-crush" syndrome has been reported, which has established the association between cervical spine radiculopathy, thoracic outlet abnormalities, and CTS [6].

The diagnosis of carpal tunnel syndrome is based on history and clinical evaluation. Electromyogram (EMG) is often used for diag-

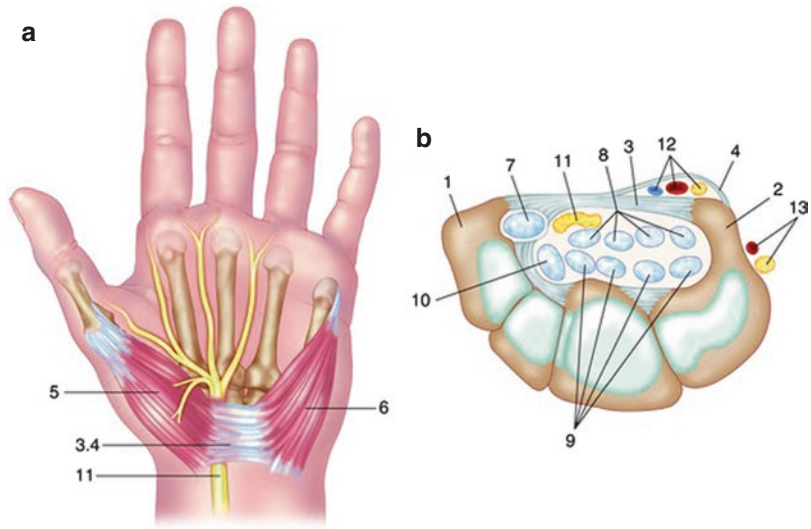

Fig. 16.1 Carpal tunnel syndrome: anatomy of the carpal canal. (**a**) Typical median nerve and hand anatomy at the level of the transverse carpal ligament. (**b**) Carpal tunnel cross-sectional anatomy. *1* Trapezium tubercle, *2* hook of the hamate, *3* transverse carpal ligament, *4* palmar carpal ligament, *5* thenar muscles, *6* hypothenar muscles, *7* flexor carpi radialis tendon, *8* flexor digitorum superficialis tendon, *9* flexor digitorum profundus tendon, *10* flexor pollicis longus tendon, *11* median nerve, *12* ulnar artery, vein, and nerve superficial branches, *13* ulnar artery, vein, and nerve deep branches. (Springer: THUMB_300647_1_En_14_Fig 1_HTML)

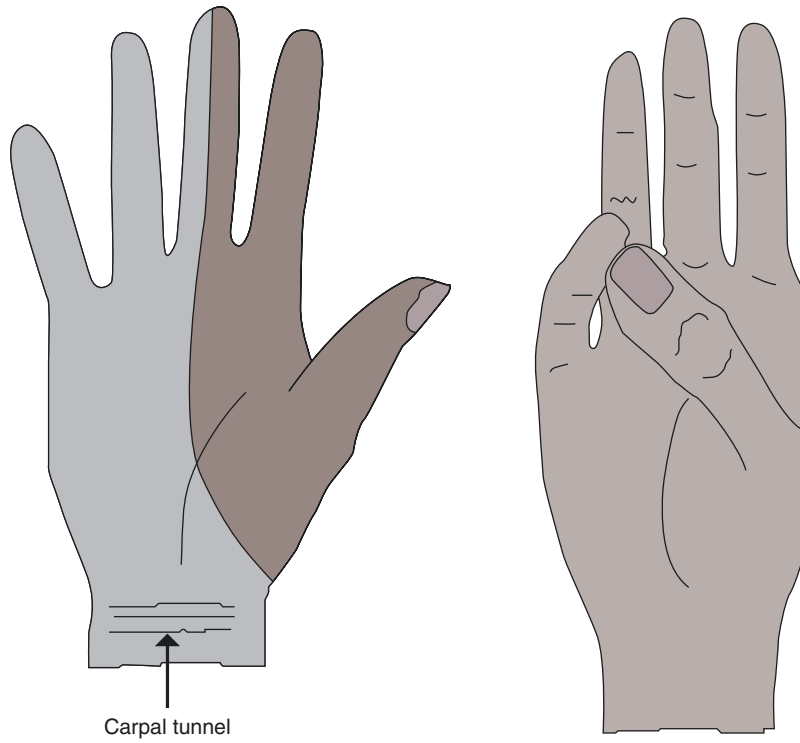

Fig. 16.2 Carpal tunnel syndrome: area of sensation (dark gray in the left picture) and motor function (opposition of the thumb in the right picture) supplied by the median nerve. (Springer: THUMB_978-1-60327-465-_6_Fig 10_HTML)

nostic confirmation of CTS. It can measure the extent of damage and demyelination of the median nerve [7]. In mild cases, there may be an absence of electromyographic and nerve conduction changes. As symptoms progress, sensory distal latency is usually the first abnormal EMG finding. Therefore, the diagnosis of CTS is first established on history and clinical findings and then may be confirmed by EMG evaluation. Recently there have been multiple reports about the usefulness of ultrasound evaluation of the median nerve to diagnose CTS. These studies have shown that there is a change in the cross-sectional area of the median nerve when CTS is present [8–10].

The carpal tunnel is located just distal to the palmar wrist crease. It is surrounded on three sides by the carpal bones, creating a fixed volume of space. The radial wall is bordered by the scaphoid and trapezium and the ulnar by the hamate and dorsally it is bordered by the lunate and capitate. The boney arch is covered by a thick fibrocartilaginous band called the *flexor retinaculum* (or transverse carpal ligament). Tendons of the flexor superficialis (FDS) and flexor profundus (FDP) and pollicis longus (FPL) course through the carpal tunnel [11]. The median nerve travels with these innervating the thenar muscles and providing sensation to the radial three and one half digits. CTS is therefore associated with motor and sensory findings.

Normal pressure within the carpal tunnel is 7–8 mm Hg with the wrist in neutral. Increased pressure of 30 mm Hg can result in symptoms of CTS and 90 mm Hg can be observed with wrist flexion and extension [12, 13]. This pressure increase causes relative ischemia and impaired nerve conduction of the median nerve [14, 15].

The prevalence of CTS increases with pregnancy, inflammatory arthritis, distal wrist fracture, amyloidosis, hypothyroidism, diabetes, acromegaly, and in individuals who use corticosteroids and estrogens. One-third of all cases of carpal tunnel are associated with these medical conditions; diabetes is the most commonly associated diagnosis [16, 17].

Cervical radiculopathy has been thought to potentiate CTS, causing the "double-crush" syndrome. The "double-crush syndrome" is a

condition in which compression of an axon at one location makes it more sensitive to effects of compression at another [18]. For this to be true, one would need to show that there is compression of an axon at a primary location which causes sensitization at another location due to impaired axoplasmic flow [19]. There have been several review articles casting doubt on this, both from the theoretical physiological basis and from physical findings. Mechanical explanations, stemming from muscle imbalance due to positioning and/or postural changes, have been discussed as potential explanations [20, 21]. CTS is frequently associated with specific occupational activities. The repetitive use of tools that vibrate such as drills and equipment used in food processing plants and mills may cause CTS. Continuous compression of the median nerve with the wrist in flexion is also associated with CTS [22]. Debate remains as to the association of CTS and computer keyboard work [23, 24]. There remains considerable debate about whether CTS is a result of repetitive stress without other factors being present [24, 25].

The typical symptoms of CTS are numbness, tingling, pain, burning, or a combination of these [16]. These symptoms occur in the radial three and one half digits: the thumb, index, middle, and half of the ring finger. CTS often causes nocturnal awakening secondary to the hand paresthesias. These nocturnal symptoms are 51–77% sensitive and 27–68% specific for CTS [26]. Gripping, driving, holding vibrating objects, or prolonged pinching, such as holding a book, may result in increased paresthesias. Many patients describe relief of their symptoms with shaking of the hands, a phenomenon called the "flick sign" [27]. With progression, patients may describe an awkward feeling or weakness of the hand and begin dropping objects.

Physical examination usually begins with the exclusion of any cervical, shoulder, or elbow pathology, which may produce similar symptoms. Cervical 6 radiculopathies are often confused with CTS because the sensory symptoms involve the radial aspect of the hand. Strength testing should include wrist flexion-extension, grip, and thumb opposition. Specific CTS provocative tests include Phalen's test, in which the wrist is held in full passive wrist flexion. This position increases pressure within the carpal tunnel and may reproduce paresthesias in individuals with CTS. This test has a wide reported range of sensitivity and specificity (40–80%) [28]. The time to the development of paresthesias should be noted because it can be used to monitor change with treatment. Tinel's test involves tapping the median nerve just proximal to the transverse carpal ligament [29]. Reproduction of the paresthesias into the hand by Tinel's test is 20–60% sensitive and 67–87% specific for CTS [28, 29].

Durkan [30] proposed a test to diagnose CTS and reported that this test is more sensitive and specific for CTS than Tinel's or Phalen's test. To make this test, carpal tunnel compression involves pressure placed with the examiner thumbs or indexes or long fingers over the carpal tunnel. This pressure is maintained for 30 s to 1 min and if positive will reproduce paresthesias.

The function in CTS is commonly assessed by Disabilities of the Arm, Shoulder and Hand (DASH) scale, Boston Questionnaire (BQ), Michigan Hand Outcome Questionnaire (MHQ), and Duruöz Hand Index (DHI). These questionnaires are valid, reliable, and responsive in CTS [31, 32] (Table 16.1). They are used not only assessing for functional conditions but also evaluating for responsive to treatment in patients with CTS.

Table 16.1 The commonly using tools in carpal tunnel syndrome assessment

Maneuvers	Phalen's maneuver (hold wrist in flexion 60 s); carpal tunnel compression, percussion along median nerve (Tinel's sign)
Neurological tests	Two-point discrimination, Semmes-Weinstein filament test (threshold of >2.83 in radial digits)
Electromyography	Fibrillation potentials, sharp waves; sensory latency >3.4 ms; motor latency >4.5 ms compared with unaffected hand
Functional tests	Duruöz Hand Index (DHI); Disabilities of the Arm, Shoulder and Hand (DASH); Boston Questionnaire (BQ); Michigan Hand Outcome Questionnaire (MHQ)

A review of nonsurgical interventions is available for the reader. Their application is clinically accepted, and there is evidence of a moderate therapeutic effect [33]. Treatment of CTS begins with modification of repetitive or awkward activities that precipitate paresthesias. Splinting the wrist in a neutral position at night has been demonstrated to reduce symptoms in 80% of patients [34]. *De Angelis et al.* evaluated the 120 CTS patients, after the 3 months of treatment with both the wrist splint and the hand brace, which improves the BQ scores [35]. Nonsteroidal anti-inflammatory drugs (NSAIDs), diuretics, vitamin B_6, and oral steroids have been tested, but no specific recommendations have been given for their prolonged usage [16]. Therapeutic interventions such as ultrasound, iontophoresis, gentle stretching and strengthening exercises, ice, and carpal tunnel protection principles may be employed. Protection principles stress avoidance of positions or activities that increase pressure within the carpal tunnel. Nerve and tendon gliding exercises have been described and are thought to be useful [36]. Gurcay et al. assessed the 52 CTS patients, and they reported that phonophoresis improves BQ scores and symptoms of disease. The authors recommended the use of wrist splint with phonophoresis for treatment of CTS [37]. Acupuncture and yoga have also been demonstrated to decrease symptoms [38]. Ural et al. compared the efficacy of acupuncture and the wrist splints in CTS by using ultrasonography. They showed that acupuncture treatment ameliorates median nerve morphology, quick DASH, and Duruöz Hand Index more than wrist splint [39].

Corticosteroid injections into the carpal tunnel are recommended if splinting and other conservative measures fail to reduce the symptoms. They have been shown to decrease symptoms in 75% of patients and improve nerve conduction [40]. In a prospective, randomized, single-blind study with corticosteroid injection including 46 CTS patients, both US-guided and blind techniques were found to be effective for improving the functional/symptom condition by using BQ and symptom severity of disease [41]. One study suggests that procaine is as effective as triamcinolone in controlling symptoms [42]. These injections are performed in a sterile fashion with needle placement ulnar to the palmaris longus. The needle is directed dorsally, distally, and radially at a 45-degree angle. In patients with severe CTS, 80% have return of symptoms in 1 year despite appropriate conservative care. Recently, platelet-rich plasma (PRP) injections have been started to use for CTS treatment. PRP is a biologic product obtained from whole blood centrifugation. It includes concentrated platelets and several growth factors that promote wound healing, angiogenesis, and axon regeneration. In a recent study including 60 CTS patients, PRP injection has found to be effective for reducing the pain, BQ scores, and median nerve cross-sectional area 6 months after the treatment [43]. In another study comparing the effects of PRP and corticosteroid injections, it showed that PRP injection is as effective as corticosteroid injection on nerve conduction studies and BQ scores after 6 months of the treatment [44].

If the patient has signs or symptoms of constant numbness, loss of sensation, or thenar muscle atrophy lasting longer than 1 year, serious consideration of surgery is recommended [11]. Surgery has been shown to be an effective intervention for CTS. The techniques, using open carpal tunnel release or endoscopic release, have been reviewed and compared [45]. Data continue to support the safety and effectiveness of mini-incision approach to surgical release [46]. Long-term surgical outcomes have some persistent symptoms, such as pain, inability to perform full wrist extension, and persistent numbness and tingling in some [47]. Postoperative rehabilitation versus home exercises seem to have the same outcomes, except that it has been shown that rehabilitation hastens the time to return to work [48]. Recent studies suggest that adding kinesiotaping may offer added benefit to splinting [49]. There are some differing opinions about the usefulness of neurodynamic techniques for reducing pain and improving function. One study suggests that additional tendon and nerve gliding exercise probably offers no benefits over splinting alone [50] and another, randomized, placebo-controlled trial comparing sham with neurodynamic exercise shows no intergroup differences, but

significant intragroup change over the course of the intervention [51].

A relationship between the severity/duration of disease and selection of therapy was determined and reported in recent studies [52].

Trigger Finger or "Stenosing Tenosynovitis"

The sensation of a finger catching or locking in a fixed position is common. This so-called trigger finger or "stenosing tenosynovitis" is a disorder characterized by snapping of the flexor tendon of the digit (Fig. 16.3). This includes both the profundus and superficialis, acting as pulleys to maintain the position of the tendon [53]. The trigger finger is now thought to be a chronic rather than acute problem and has been described as a disproportion between the sheath and its contents [54]. The most commonly affected area is the distal metacarpal. Sometimes a small nodule can be palpated. On physical examination, one may find a mild flexion deformity of the proximal interphalangeal joint and limitation of full flexion, with the inability to reach the fingertip to the mid-palmar crease. When the condition is chronic, it may progress to a situation in which the finger (often the middle and/or ring finger) becomes fixed in flexion and extension is limited [55]. Pain is not the most frequent presenting symptom.

The pathomechanics include a thickening of the A-1 pulley or flexor tendon owing to sheer or compression forces with inflammatory changes occurring during the acute phase [55, 56]. In chronic conditions, no inflammatory changes are noted, but the tendon is often attenuated [57]. For this reason, the nomenclature of "stenosing tenosynovitis" has lost favor. Chronic conditions result in degenerative changes consistent with fibrocartilaginous proliferation of the A-1 pulley

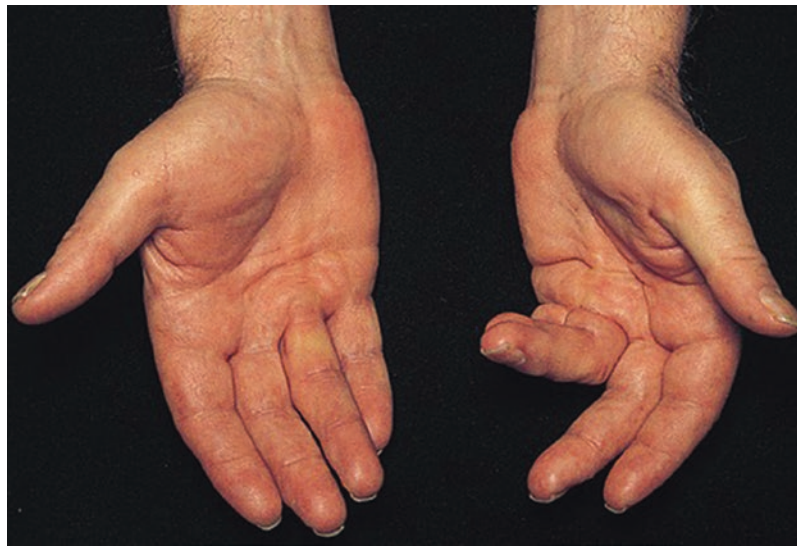

Fig. 16.3 Trigger finger: stenosing tenosynovitis (trigger finger). (**a**) Synovitis of the tendon sheaths can lead to swelling, limitation of motion, and tendon rupture. Stenosing tenosynovitis can lead to "trigger finger," evident in the fourth finger of the left hand. Triggering occurs when the inflamed tenosynovial tissue cannot move through the tendon sheath. Stenosis of the A-1 pulley can be palpated in the palm just proximal to the affected metacarpophalangeal joint. (**b**) Stenosing tenosynovitis. Tenosynovitis of the flexor tendon can lead to the trigger finger syndrome. With tenosynovitis, the digit is blocked in the flexed position (with vertical bar), making extension difficult or even impossible. If the affected tendon is able to pass through the fibrous tendon sheath, a palpable "pop" may be detected. The action may be painful. The tendon may also be blocked in the extended position. Swelling of the tenosynovium proximal to the stenosed annular ligaments may be palpable in the palm as swelling. (Courtesy of Alan T. Bishop, MD. Springer: THUMB_ARHEU04-01-044A)

or tendon. The pathologic thickening results in a disparity of the tendon pulley configuration [53]. This size differentiation causes a mechanical locking of the tendon proximal to the A-1 pulley with finger flexion. Once the tendon is locked in the flexed position, the weaker finger extensors have difficulty overcoming the resistance [58]. When the stuck tendon does release during extension, there is a painful snapping in the region of the MCP joint.

When children have trigger finger, they are usually younger than 6 years [59]. In adults, it is more common in people over 40 years, women, and those with diabetes mellitus and limited joint mobility [60, 61]. The thumb of the dominant hand is most commonly affected, followed by the middle and ring fingers [60]. The symptoms usually consist of a snapping or locking sensation with full flexion of the digit. This sensation is usually painful, but nonpainful conditions have been described. The onset is usually gradual, over several months, but in certain situations can be due to trauma or carpal tunnel release [53]. The symptoms of locking or clicking phenomena are usually worse in the morning and after repetitive gripping or pinching-type activities.

Examination of the finger is usually unremarkable unless reproduction of the locking phenomena can be observed. Most often, a tendon nodule or crepitus can be felt over the palmar aspect of the MCP joint in the region of the A-1 pulley [53]. Grip strength can be diminished secondary to pain. Ligament and neurovascular integrity is normal. No diagnostic tests are confirmatory for this condition. X-rays have not been found to show any abnormality correlated with trigger finger [62]. Serologic testing should be done to check for the presence of underlying conditions such as diabetes mellitus, hypertension, and inflammatory arthritis, which are risk factors for trigger finger.

A trigger finger can lead to disabling pain and may influence work. Symptom control has been reported and ultrasound, iontophoresis, and ice may relieve symptoms [63]. Evans and associates [64] reported 73% success in using a flexion-blocking splint at the MCP for 3 weeks. Their protocol also included limiting activities requiring grasp, active flexion or repetitive stress, and hooked-fish exercises. Colbourn et al. confirmed these findings but required 6 weeks of continuous splint usage [63].

The Froimson Grading System

The Froimson grading system is used to assess clinical severity of trigger finger (TF). According to this classification [65]:

- Grade I, pre-triggering pain, sensitivity on the A1 pulley, history of catching, but nonprovable catching.
- Grade II, provable catching; finger can actively widen.
- Grade III, provable catching requiring passive extension or insufficiency to actively flex.
- Grade IV, provable catching with stable flexion proximal interphalangeal (PIP) joint contracture.

The Quinnell Grading System

The Quinnell grading system is used to estimate clinical seriousness of TF. Classification consists of four parts. According to the classification, fingers are gradated by using range of movement of digit: 0, normal movement; 1, unstable movement; 2, actively amendable locking; 3, passively amendable locking; and 4, fixed deformity of the digit [66].

The function in trigger finger is commonly assessed by Functional Dexterity Test, Purdue Pegboard Test, Hand Dynamometer, and DASH.

Corticosteroid injections have been reported to be somewhat efficacious in the treatment of trigger finger [67, 68]. There have been two small, randomized studies. Newport and associates [69] reported that one to three injections of local anesthetic and cortisone were associated with resolution or improvement in 77% of 338 fingers. Marks et al. [70] reported that 84% of trigger fingers and 92% of trigger thumbs responded to a single injection. This increased to 91% and 97%, respectively, with a second injection. Beneficial

effects with cortisone are superior to those of placebo and last up to 12 months [68]. A European Delphi consensus strategy appointed and defined that use of orthoses (splinting,) corticosteroid injections, also use of orthoses, and surgery are suitable treatment options [71].

Surgical intervention has been advocated if injection therapy does not offer benefit. There has been a plethora of surgical information regarding A-1 pulley releases for the treatment of trigger finger. Thorpe [72] reported that of the 53 operations, 60.4% were completely successful and 11.3% had incomplete resolution with persistence of clicking and pain within the first year after surgery. Long-term outcomes from these procedures are not well documented.

De Quervain's Tenosynovitis

De Quervain's tenosynovitis is an inflammatory process involving the extensor pollicis brevis and abductor pollicis longus tendons on the radial aspect of the wrist. It is characterized by radial-sided wrist pain at the first dorsal compartment (Fig. 16.4). Presenting symptom is usually pain on palpation or on movement, typically pinching or gripping movement involving the thumb. This most commonly affects women between the ages of 35 and 55 years [73, 74], at a tenfold increase compared with men. Repetitive, prolonged unaccustomed posturing of the thumb or non-neutral wrist movements usually provoke symptoms [75]. Waitresses, nurses, garment workers, maids, assembly-line workers, and machine operators are at greater risk for development of this condition [75, 76]. Pathogenetically, the process starts as inflammation within the first dorsal compartment. Not uncommonly, it recurs or fails to fully heal/repair the tendon pathology, leading to thickening of the extensor retinaculum and synovial tendon sheath [77].

The extensor tendons to the fingers and wrist travel through six dorsal compartments of the wrist. The first (most radial) dorsal compartment contains the extensor pollicis brevis and the adductor pollicis longus. These tendons course through an osteofibrous canal to their insertion on the metacarpal and proximal phalanx of the thumb. A significant angulation is present as these tendons traverse over the radial styloid, placing the tendons at risk for repetitive injury [75, 77]. The function of these muscles is to position the thumb in extension and abduction in preparation for gripping and pinching. In these chronic states, inflammation is absent [73, 74]. The thickening results in a mechanical stenosis within the first dorsal compartment, causing impingement of the two tendons [77].

On physical examination, patients usually have tenderness with palpation over the fibro-osseous first dorsal compartment. Pain is commonly elicited with resisted thumb extension and abduction.

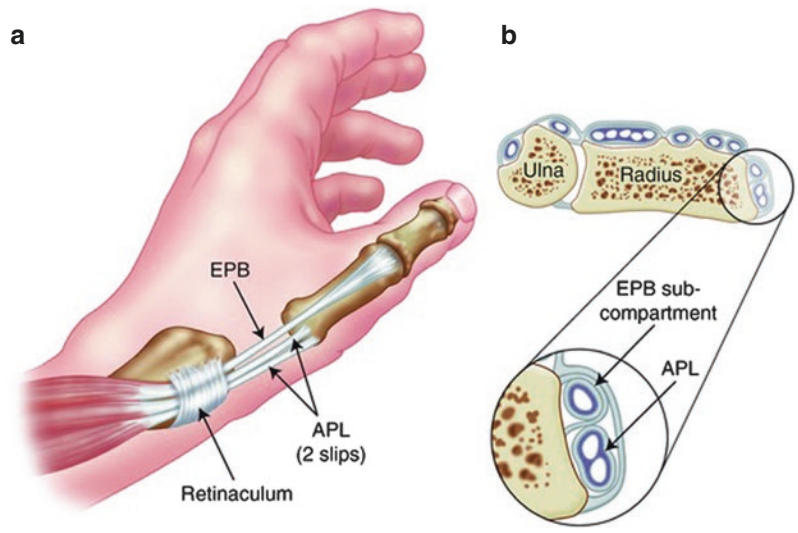

Fig. 16.4 De Quervain's syndrome. (**a**) The first extensor compartment includes the abductor pollicis longus (APL) and extensor pollicis brevis (EPB) tendons. (**b**) The EPB tendon is often located within a separate subcompartment. (Springer: THUMB_300647_1_En_18_Fig 2_HTML)

A positive Finkelstein's test is pathognomonic for de Quervain's tenosynovitis [78]. This test is performed by flexing the thumb into the palm and making a fist around the thumb. The wrist is then passively deviated in the ulnar direction. Increased pain in the region of the radial styloid with this maneuver is considered positive. Pain increases with grasping, adduction of the thumb, or ulnar deviation of the wrist [65]. The symptom complex is usually gradual in onset, but traumatic etiologies have been described [73, 74].

De Quervain's tenosynovitis is a clinical diagnosis. Plain x-rays have not been found to be beneficial. Ultrasound, however, has been reliable in identifying tendon pathology and in guiding treatment [79]. Other conditions with a similar presentation include peripheral neuritis, collagen vascular diseases, amyloid, sprains of the CMC joint, arthritis of the CMC joint, fracture of the distal radius, ganglions of the wrist, acute calcific tendinosis, and aberrant CTS.

The function in de Quervain's tenosynovitis is commonly assessed by *Manual Ability Measure and Michigan Hand Questionnaire*. The Manual Ability Measure (MAM) evaluates sensed manual ability related to hand function with no specified recall term. It has 36-item (MAM-36) and 20-item (MAM-20) types [80]. The Michigan Hand Questionnaire is explained in appendixes.

Non-pharmacological intervention, including education, environmental and ergonomic adaptation are extremely important for treatment and prevention of de Quervain's and its recurrence. Interruption of highly repetitive activities that include pinching or gripping is beneficial [81]. Immobilization of the thumb in a forearm-based thumb spica splint offers protection and rest. Heat modalities, stretching of the first dorsal compartment muscles, and ice may offer relief of symptoms during the acute stage. To date, there has not been an outcome study on the use of modalities and exercise for this condition.

Injection of local steroids has been shown to be of benefit. Anderson and colleagues [82] reported that 81% of individuals undergoing injections for this condition described symptom relief at 6 weeks. At 4-year follow-up, 58% remained asymptomatic, and 33% had complete reoccurrence. If conservative treatment is not effective, surgical release of the first dorsal compartment can be performed [83].

In the literature, NSAIDs, splinting, corticosteroid injections, and surgery were described for therapy of de Quervain's disease. The experts offered that combined therapy is more effective than single therapy for de Quervain's disease [84].

Dupuytren's Disease

Dupuytren's disease (DD) is a process of unknown etiology that leads to shortening and thickening of the palmar fascia and a flexion contracture of the digits (Fig. 16.5). Established risk

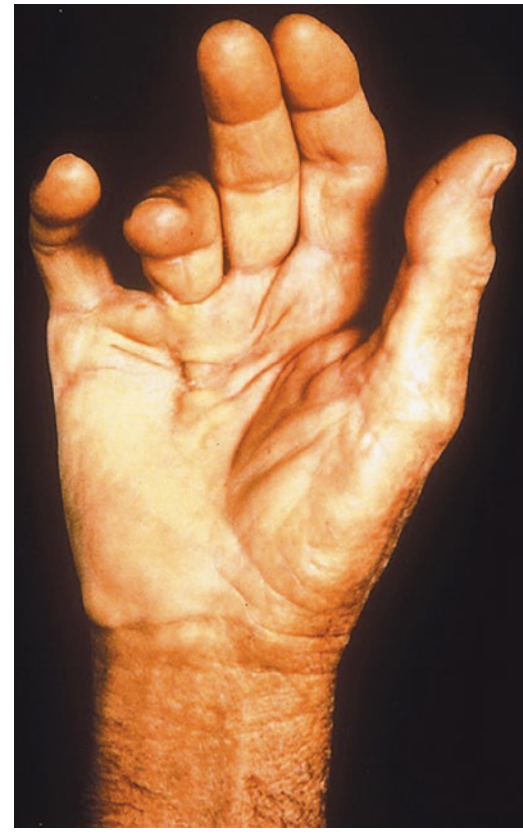

Fig. 16.5 Dupuytren's disease: Dupuytren's contracture involves the palmar fascia and can result in nodules in the hand and a fixed flexion contracture of any of the digits of the hand. As shown in this case involving the ring finger, the central cord proximal to the base of the metacarpophalangeal joint results in flexion contractures of both the metacarpophalangeal joint and the proximal interphalangeal joint. (Springer: THUMB_CORDT01-26-001)

factors include an autosomal dominant inheritance pattern [85, 86], caucasians of northern European origin, male, and older age [87, 88]. Smoking, high levels of alcohol intake, trauma, diabetes, epilepsy, and use of anticonvulsant drugs have all been implicated, with varying levels of evidence [89]. Theories of pathogenesis have included abnormal immune responses or tissue hypoxia secondary to the presence of oxygen-free radicals. The digital contracture is caused by myofibroblasts in the palmar fascia. The mainstay of treatment is surgical release or excision of the affected palmodigital tissue, but symptoms often recur. Nonsurgical correction of DD contractures can be achieved by antifibrotic substances and collagenase *Clostridium histolyticum* (CCH) injection, although the long-term safety and recurrence rate of this procedure requires further assessment [90, 91]. Additional studies report benefit of CCH injection. One, a randomized trial showed improvement in firmness and size of nodule, but not benefit when compared with percutaneous release [92], and the other, a retrospective cohort study identified continued benefit from CCH treatment at last 2 years after completion of treatment [93].

The contracture is a benign hypertrophy of the fascia. The first signs may be the palpation of almost imperceptible nodules in the area of the palmar crease, which progress to thick cords that form along the linear cord-like fascial lines of the palm [94]. The underlying tendons, synovial sheaths, and skin layers are not affected [95].

The pathophysiology of Dupuytren's is not fully understood. The palmar fascia thickening is caused by an abnormal proliferation of fibroblasts [89]. This proliferation is closely correlated with that observed in scar formation and healing. Three stages in the nodule and cord formation have been described. The first stage is proliferation. During this stage, the numbers of myofibroblasts within the palmar fascia spontaneously increase. The second stage is involution, when the myofibroblasts align along the tension lines of the palm and digits. The fascia enlarges owing to contraction of the myofibroblastic activity. In the third phase, the myofibroblasts resolve, leaving contracting collagen, which is perceived as nodules and matures into cords [95, 96]. As the process progresses, these may become somewhat tender. The first finger to be affected, in 70% of those with Dupuytren's is usually the 5th digit. All digits, however, may be affected. Rheumatic diseases, synovitis, and Type 1 diabetes may be associated with similar symptoms [97].

Dupuytren's contracture is a clinical diagnosis made with the presence of palpable nodules and cords in the palmar fascia. It is often a diagnosis of exclusion. The anatomical distribution of the findings usually establishes the diagnosis. Joint deformity, including flexion contractures of the MCP, PIP, and DIP, are usually present in advanced conditions. Transverse or webspace contractures may also occur. These contractures can result in significant functional limitations necessitating treatment.

The staging of Dupuytren's disease is commonly assessed by the measurement of the flexion deformity (by using goniometer) each affected digit (Table 16.2). The measurements were done at metacarpophalangeal (MCP) and proximal and distal interphalangeal joints (PIP and DIP).

The revised Tubiana staging system assesses the severity of Dupuytren's disease. The items of this scoring are the total number of surgical procedures for disease, the number of affected digits, recurrence of disease, the presence of nodules, palmar pits, Garrod's pads, Ledderhose's disease, Peyronie's disease, shape of involvement (bilaterally/unilaterally), and stage of Dupuytren's disease. The high scores are indicated more severe disease [98, 99]. The DASH index is commonly used to assess the functioning in Dupuytren's disease [100].

Table 16.2 Staging of Dupuytren's disease

Stage	Deformity
0	*No lesion*
N	*Palmar nodule without presence of contracture*
1	TFD between 0° and 45°
2	TFD between 46° and 90°
3	TFD between 91°and 135°
4	TFD greater than 135°

TFD total flexion deformity is measured with a goniometer at the MCP, PIP, and DIP joints

There has been minimal effectiveness of interventions, including splinting, radiation, vitamin E, anti-gout medications, physical therapy, and therapeutic ultrasound [90, 101]. Definitive treatment of advanced Dupuytren's is surgical fasciectomy. Advanced Dupuytren's is usually determined based on the performance of a "tabletop test" [102]. In this test, the individual places the palm on a flat surface and attempts to extend the involved finger actively. A positive test is noted if the MCP joint cannot be placed flat against the surface. This usually correlates with a greater than 30-degree fixed flexion contracture of the MCP joint. The goal of surgery is to restore function, not to cure the disease [103]. Despite surgical treatment, this condition can be quite recalcitrant, and reoccurrence rates range from 28% to 80% [104]. The HANDGUIDE study is reported to highlight the importance of the relations between the patient, disease, and surgeon factors to decide the specific surgical technique for treatment [105].

Recently, there has been a great deal of interest in percutaneous or enzymatic fasciotomies as an alternative to surgical fasciectomy. Hurst [90] has demonstrated that by injecting collagenase into the fibrous cords, joint contractures can be improved. They report that 90% enjoyed excellent results at an average of 9-month follow-up. Although no long-term studies have been completed, this procedure does offer promise. Additionally, an 8-year follow-up has recently been reported. While it consists of a relatively small sample size, a relatively high benefit and low risk over the long term was observed to prove long-term follow-up has been reported [106].

Postoperative surgical rehabilitation is extremely important following fasciectomy, with concentration on maintaining skin integrity, restoration of joint range of motion, and overall improvement of function [104].

Complex Regional Pain Syndrome (CRPS)

Reflex sympathetic dystrophy (RSD), causalgia (minor and major), algodystrophy, shoulder-hand syndrome, and Sudeck's atrophy are now considered complex region pain syndrome. The cause of CRPS is not fully understood. One theory, developed from an ischemia model in animals suggests that symptoms are the result of microvascular injury leading to release of inflammatory cytokines [107]. Complex regional pain syndrome (CRPS) is a neuropathic pain syndrome characterized by autonomic dysfunction and severe pain that may lead to crippling contractures of the limbs. Mitchell first described CRPS during the American Civil War when he observed wounded veterans who had burning pain in an injured limb [108]. The term shoulder-hand syndrome described a variant of CRPS in which the entire upper limb was affected.

In 1993, at the meeting of the International Association for the Study of Pain (IASP), a task force proposed a unifying classification for these syndromes [109].

The task force of the IASP proposed two types of regional pain syndromes [110]:

- *Type 1*, formerly known as reflex sympathetic dystrophy (RSD), Sudeck's atrophy, reflex neurovascular dystrophy (RND), or algoneurodystrophy, does not have demonstrable nerve lesions.
- *Type 2*, formerly known as causalgia, has evidence of obvious nerve damage.

The two types share two features in common:

1. There is a history of edema, skin blood flow abnormality, or abnormal sweating in the region of the pain since the inciting event.
2. No other conditions can account for the degree of pain and dysfunction.

The diagnosis of Type 1 CRPS is based on four criteria:

1. The presence of an initiating noxious event or a cause of immobilization.
2. Continuing pain, allodynia (perception of pain from a nonpainful stimulus), or hyperalgesia (an exaggerated sense of pain) disproportionate to the inciting event.

3. Evidence at some time of edema, changes in skin blood flow, or abnormal sudomotor activity in the area of pain.
4. The diagnosis is excluded by the existence of any condition that would otherwise account for the degree of pain and dysfunction.

The diagnosis of Type 2 CRPS is based on three criteria:

1. The presence of continuing pain, allodynia, or hyperalgesia after a nerve injury, not necessarily limited to the distribution of the injured nerve.
2. Evidence at some time of edema, changes in skin blood flow, or abnormal sudomotor activity in the region of pain.
3. The diagnosis is excluded by the existence of any condition that would otherwise account for the degree of pain and dysfunction.

While the mechanisms active in producing the syndrome are not fully understood, recent evidence demonstrates abnormalities of cytokine regulation, with upregulation of the inflammatory cytokines and relative inadequacy of anti-cytokine release. This process, called neuroinflammation, has been identified as a contributor to the pain, swelling, and tissue property changes often seen in the syndrome [111].

Patients who develop motor or/and trophic changes may complain of inability to initiate movement, weakness, tremor, or muscle spasms. Sometimes it is difficult to assess the function because of severe pain. Contractures can occur in late stage disease.

The Assessment Tools for CRPS

Various assessment tools that evaluated pain, skin temperature, and edema are used for evaluating hand functions in CRPS. Numeric rating scale (NRS) is used for pain. In this test, pain is rated by patients, which ranges from 0 (no pain) to 10 (worst pain imaginable). The short-form McGill pain questionnaire (SF-MPQ-2) includes 22 items rated on 10-point metric in 4 items (continuous pain, intermittent pain, predominantly neuropathic pain, and affective descriptors). The Neuropathic Pain Questionnaire (NPQ) includes 12 questions including burning pain, increased pain due to weather changes, and questions such as "How overwhelming is your usual pain." The Neuropathic Pain Scale (NPS) consists of 10 questions rated from 0 to 10 including pain sharpness, heat/cold, dullness, pain intensity, surface/deep pain, and overall unpleasantness. Finally, the Trauma-Related Neuronal Dysfunction (TReND) questionnaire is a self-report consisting of 164 parts in 10 subscales including sensory, trophic, autonomic, motor, and visceral domains [112]. Although the various outcome measurements are used for evaluation of CRPS, there are large gaps in both comprehensiveness and supporting psychometric evidence.

The primary treatment for CRPS requires a combined approach using pharmacological and non-pharmacological agents. One approach has been to use an algorithm for guidance. Bisphosphonates have been studied in multiple controlled trials, based on theoretical benefit of relief of bone pain and bone resorption [113]. These have been only marginally successful. Many current rationales in treatment of CRPS (such as topical agents, antiepileptic drugs, tricyclic antidepressants, and opioids) are used because of their proven efficacy in other pain syndromes. Nerve blockade, sympathetic block, spinal cord and peripheral nerve stimulation, implantable spinal medication pumps, and chemical and surgical sympathectomy, have also been reported, have been shown to provide some relief, but has not been demonstrated to be consistently therapeutic. The use of gabapentin and pregabalin has shown therapeutic benefit in controlling pain [114]. In treating CRPS, one follows the classic order of rehabilitation beginning with pain and edema control, followed by range of motion and then strengthening followed by function. It is important to convey to the patient that immobilization is not an effective treatment for the pain and swelling; in fact, it may be instrumental in the pathogenesis and chronicity of the process [115].

Edema control entails elevation, decongestive massage, and various forms of compressive wrapping or garments. Pain control may be difficult using physical modalities alone. However,

physical modalities should be the first line of defense. Contrast baths, Fluido-Therapy, transcutaneous electrical nerve stimulation (TENS), and desensitization may be used before and after therapy session or exercise. If these are unsuccessful in adequately controlling the pain to the point at which therapy can be progressed, then one may consider further pain-relieving measures. Typical oral medications that may be used are tramadol, gabapentin, amitriptyline, and various α_1-blockers. In about half of all cases, further augmentation of analgesia may be attained by injections such as stellate ganglion blocks. One may also use injections such as intravenous regional blocks, axillary blocks, and cervical epidural injections. These blocks may provide temporary pain relief, enabling the patient to begin more aggressive hand therapy. Once pain is controlled to the level that patients can tolerate therapy, then one may begin exercises [115, 116].

The next goal of CRPS treatment is to restore normal range of motion. Often, the enduring disabilities resulting from CRPS are hand contractures. Gentle active or active-assisted range of motion should begin in a pain-free fashion. Any advancement in therapy should proceed slowly and carefully, keeping in mind that an overly aggressive approach may increase pain and swelling, which would be counterproductive.

When recognized early and treated carefully, CRPS generally runs its course in 6–12 months with complete or nearly complete recovery. About 5% of cases may turn into chronic CRPS with ongoing issues of pain, dysfunction, and disability. These patients may be on long-term pain medications or often are severely disabled by pain, contractures, or both. Reviews of current thinking about the pathophysiology and management or CRPS are available [115–117].

Focal Hand Dystonia

Writer's cramp (Figs. 16.6 and 16.7) and musician's cramp (Fig. 16.8) are both focal dystonias that affect a discreet anatomical area of the hand. Focal hand dystonia is a maladaptive response of the brain to repetitive performance of stereotyped hand movements. However, not all patients have

Fig. 16.6 Writer's cramp: the patient exhibits involuntary extension at the metacarpophalangeal joint of the index finger while writing. (Springer: THUMB_978-1-60327-426-5_52_Figa_HTML)

Fig. 16.7 Writer's cramp mirror movements. (Springer: THUMB_978-1-60327-426-5_53_Figa_HTML)

Fig. 16.8 Musician's cramp: musician's cramp, analogous to writer's cramp, is a focal dystonia of the arm induced with the action of playing a musical instrument. This patient has a pianist's cramp that is manifested when she attempts to perform piano-playing movements on top of the desk. (Springer: THUMB_ACNEU02-09-038)

a strict history of excessive hand use [118]. The focal hand dystonias are characterized by disabling cramps, contractions, or spasms during specific activities [119]. When not so engaged, the hand appears and functions normally. The flexors are more commonly involved than the extensors. Among the flexors, the flexor digitorum superficialis and profundus, the flexor pollicis longus, and the lumbricals may be involved. The extensor pollicis longus, extensor indicis, and digitorum communis may be involved among the extensors. Dystonia may occur sporadically in the population or may be genetically transmitted. The gene for early onset dystonia (DYT1) has been sequenced. Approximately 10% of people with dystonia have a family history of tremor or dystonia [120]. Others report that a higher percentage of those affected have a family history of dystonia [121].

The pathophysiology of dystonia seems to be a loss of inhibitory function. The anatomical locus has been demonstrated at spinal, brainstem, and cortical levels. There seems to be some mild sensory and sensorimotor deficits. The abnormality leads to unwanted muscle spasms. Increasing inhibition may be therapeutic [122].

Newer reports, based on brain imaging technologies and functional MRI, support the view that there is loss of inhibitory control. What is emerging as probably newer information is that this may be due to dysfunction in GABAergic neurotransmission in the cerebellum and sensorimotor cortex. These cerebello-cerebral networks may result in a functional imbalance that may lead to a maladaptive plasticity [123].

The incidence of writer's cramp is reported to be 2.7 per million in Rochester, MN [124]. It tends to affect male young adults. It is usually idiopathic and not a result of overt trauma, although it may follow a traumatic episode. Patients frequently have mirror dystonia, demonstrated by inducing the writer's cramp in the dominant hand even when attempting to write with the non-dominant [120]. Focal dystonias tend to remain focal and do not become generalized dystonias over time.

The pathophysiology of dystonia is not entirely understood. However, there seems to be some evidence for abnormalities in the basal ganglia [120] or problems with cortical organization [107]. Electrodiagnostic studies show a co-contraction of muscle and a loss of alternation of agonist/antagonist muscle contractions. There are prolonged bursts of muscle contractions and overflow contraction seen in those muscles not activated by the motor task [125, 126].

The function in focal hand dystonia is commonly assessed by Burke-Fahn-Marsden Scale, Unified Dystonia Rating Scale (UDRS), and Global Dystonia Scores.

The *Burke-Fahn-Marsden* Scale is the first rating scale evaluated clinometric properties of dystonia. The Burke-Fahn-Marsden Scale (B-F-M) is developed to evaluate dystonia in nine body areas. For each of the body regions, severity ratings between 0 (no dystonia) and 4 (severe dystonia). To better evaluate focal dystonias of the arm, Fahn improved the Arm Dystonia Disability Scale (ADDS) [127]. It details the B-F-M scale in each of the seven specific activities using the arm, one of which is playing a musical instrument.

The Tubiana and Chamagne Scale (TCS) is useful to evaluate the dystonia in musicians, but it isn't specific to the hand. It rated the musical capabilities [128].

The use of botulinum toxin for focal dystonia has been demonstrated to be effective and safe even for chronic application [129]. It has been observed that botulinum toxin is effective for this disorder, but it is not as effective as it is in blepharospasm, suggesting the neural networks are more complex. An excellent review article discusses how these observations have led to assessing the possible treatment options based on a better understanding of the pathophysiology. These treatments include, among others, non-invasive brain interventions, trans cranial direct current stimulation, deep brain stimulation, and repetitive magnetic brain stimulation [130].

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Hand Function in Cancer

17

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There were an estimated 14.1 million new cancer cases around the World in 2012. Approximately 52% of those were male and 48% were female. The four most common cancers occurring worldwide are lung, female breast, bowel, and prostate cancer [1].

With improvement in cancer and increase in survival time, the accompanying problems are increasing. Cancer can produce many different symptoms and impaired quality of life. Upper extremity dysfunction can be seen in the patients with cancer [2–10]. Chemotherapy, radiation therapy, surgery, lymphedema, and direct effects of cancer can cause problems in upper extremities and also in hands. It is important to identify cancer-related hand problems and to focus on these problems in cancer rehabilitation.

Chemotherapy-induced neurotoxicity is a common adverse effect of several commonly used cancer treatments, including methotrexate, platinum derivatives, mitomycin, chlorambucil, doxorubicin, ifosfamide, thalidomide, bortezomib, vinca alkaloids, epothilones, halichondrin B analogs, paclitaxel, and docetaxel. Chemotherapy-related neurotoxicity may involve either peripheral or central nervous systems. Central nervous system involvements are encephalopathy, aseptic or septic meningitis, extrapyramidal syndrome, myelopathy, and seizures. Chemotherapy-induced peripheral neuropathy is the most common neurological complication of cancer therapy. The most common causative agents are taxanes, vinca alkaloids, platinum derivatives, epothilones, proteasome inhibitors, and thalidomide [11]. The most common sensory symptoms and less common motor or autonomic symptoms can be observed. Sensory symptoms are symmetric paresthesia, tingling, numbness, pain, burning, and itching generally in the hands such as "stocking-glove" pattern. These symptoms begin distally in the hand and distribute proximally. Distal weakness and loss of coordination and cramps may also be observed. Severity of symptoms is often related to the dose. These conditions can also cause decrease in joint movements and deformities in hands. Because of these symptoms, the dexterity of the hand decreases. Chemotherapy also impairs concentration and memory and induces generalized fatigue [12, 13].

Radiation therapy can lead to reduced hand function by brachial plexus injury and peripheral nerve damage. Brachial plexopathy involvement usually presents as paresthesia in the fingers, pain reflected from the axilla to the hand fingers, atrophy of hand muscles, progressive muscle weakness, sensory loss in ulnar nerve distribution, and lymphedema. Peripheral nerve damage may occur in patients who receive radiation therapy in the upper extremity. Radiation can damage the surrounding peripheral nerves and also their blood supply and connective tissue. Radiation also causes adverse effects such as pain, fatigue,

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fibrosis, sensitive changes, and cutaneous impairment like radiodermatitis [14].

Hand involvement may result in neurological invasion of primary or metastatic cancers. Neurological tumors, bone marrow tumors, or metastasis caused by breast or lung cancers may cause hand dysfunctions. Spinal cord tumors, brain tumors, and metastatic tumors to spinal cord or brain decrease muscle strength and cause sensory disturbance of the upper extremity. Myeloma compresses the peripheral nerve, nerve roots, and spinal cord by direct tissue compression or by amyloid infiltration.

Nonmelanotic skin carcinoma is the most common malignancy of the hand [15, 16]. Squamous cell carcinoma is 75–90% of all hand malignancies, followed by basal cell carcinoma [17, 18].

Metastasis to the bones is frequent, but metastasis to hand bones is very rare and its incidence is about 0.2% [19]. Distal phalanges, metacarpals, and proximal phalanges are the bones that are frequently held in order. The primary sources of tumors that metastasize to the bones of the hands are lung, kidney, breast, and gastrointestinal tract cancers [20].

Decreased muscle strength due to systemic inflammation, malnutrition, physical inactivity, tumor-derived factor, and adverse effects of therapy is a common problem in cancer patients. The incidence of cancer increases with age, and age-related decline is the other factor of muscle dysfunction in cancer. The studies concluded that patients have reduced muscle strength regardless of cancer stage [21]. Burden et al. [22] reported that patients with early-stage colorectal cancer had diminished hand grip strength which was below 85% of healthy controls. Studies about prostate cancer receiving androgen deprivation therapy (ADT) found that grip strength was diminished and then stabilized over time [9, 23].

Breast Cancer

Breast cancer is the second most common cancer in both sexes but the most common cancer in women. Survival after breast cancer has increased over the past years. Surgical interventions, chemotherapy, and radiation therapy are treatment interventions. The complications of those interventions lead to a decrease in the quality of life of the patients. These are persistent pain and sensory disturbance such as allodynia, hyperalgesia, paresthesia, lymphedema, muscle weakness, and reduced arm function. All of them impair upper extremity functions. The sources of pain are intercostobrachial nerve lesion, myofascial pain syndrome, axillary cord, and neuropathic pain due to chemotherapeutic agents. Furthermore, those patients experience anxiety, depression, and adjustment problems in the social, vocational, and domestic life.

The prevalence rate of upper limb dysfunction was found to be 9–62% of the patients with breast cancer [24–26]. De Groef et al. [24] reported that 19% of the patients had a level of dysfunction unable to work. Type of surgery and treated with adjuvant modalities are identified as risk factors of upper limb dysfunction. Women having mastectomy and axillary lymph node dissection and/or radiation therapy have more upper extremity problems than those having breast conserving surgery and sentinel lymph node dissection [26–29]. The other variables related with upper extremity dysfunction are body mass index, older age, decreased range of motion, and loss of muscle strength [26, 30, 31]. Pain has been reported a risk factor for upper extremity dysfunction [24]. Pain intensity, pain quality and signs of central sensitization, and pain catastrophizing are identified as risk factors in patients undergoing breast cancer surgery more than 1.5 years ago. De Groef et al. [24] also emphasized that signs of central sensitization were the main predictor of upper extremity dysfunction.

Upper limb lymphedema is one of the most frequent impairments in breast cancer. Lymphedema prevalence among patients with breast cancer was 5–30% in a large meta-analysis [32]. Breast cancer-related lymphedema is chronic swelling in the arms and/or hands, trunk, or breast of the patients after treatment interventions. Removal of the axillary lymph nodes is the primary risk factor. This risk is increased when radiation therapy is applied in postoperative period [33]. Lymphedema reduces the quality of life of

patients by impairing upper extremity functionality, causing pain, skin problems, anxiety, and depression. Lymphedema results in loss of sensation, muscular weakness, loss of range of motion in upper extremity, pain, and sense of heaviness in the arm and overall impair upper extremity function. Hand edema negatively affects daily activities and functional mobility. The previous studies reported that hand was affected in 60–70% of the patients with upper extremity lymphedema [6, 34, 35]. A negative correlation was found between the severity of edema and hand function [6]. The studies used standard circumference measurement, volumetric measuring, and figure of eight method. Borthwick et al. [36] reported that figure of eight method is a valid and reliable technique for measuring hand swelling in breast cancer-related lymphedema. Additionally, a strong correlation was found between figure of eight method and circumference measurement technique [6]. Karadibak et al. [6] evaluated the functional ability and kinesthetic sense of hands of women with breast cancer-related lymphedema. Functional severity assessed by modified Kapandji index, kinesthetic sense of hand measured by examining the ability to copy hand position, and daily living skills assessed by 62-item Hand Function Sort decreased significantly with increasing edema severity. Loss of kinesthetic sense of hand due to lymphedema is a problem for performing activities of daily living [37, 38]. Loss of kinesthetic sense was found in 65.3% of patients who had impaired daily activity [6].

Hand function in daily life was assessed by Disability of the Arm, Shoulder, and Hand (DASH) questionnaire and Functional Assessment of Cancer Therapy-Breast plus Arm Mobility (FACTB+4) in the studies about breast cancer [4, 24]. DASH is a self-reported questionnaire measuring upper extremity limb symptoms and ability to perform functional activities in the patients with musculoskeletal disorders. DASH is recommended to assess patient-reported upper extremity function in breast cancer because DASH had most consistent large effect size for construct validity and responsiveness [39]. Women with breast-related lymphedema scored high DASH score than those without lymphedema [4, 10, 40]. A higher score indicates greater activity limitation or more difficulty. Past diagnosis of lymphedema, grip strength, shoulder abduction range of motion, and number of comorbidities contribute to the variance in the DASH score [40]. Some studies also mentioned pain as the most incident comorbidity directly related to worsening of upper extremity function [41, 42]. In some studies, there was a connection between edema volume and DASH, but this finding could not be detected in some studies [40, 43, 44]. The FACTB+4 was developed to evaluate quality of life of the patients with breast cancer and validated for this population. It consists of 36 items: 27 of them are about quality of life; 9 are about specific problems of those with breast cancer; and 4 are about upper body mobility. The total score ranges from 0 to 164 and high scores indicate better quality of life. Recchia et al. [4] found a strong negative correlation between DASH score and FACTB+4 arm subscale and a moderate correlation between DASH and physical domains of FACTB+4. All of these are related physical aspects and symptoms such as pain, edema, reduced range of motion, rigidity, and paresthesia of the arm.

The erroneous belief that the use of the upper extremity can increase edema is one of the reasons of muscle weakness in the upper extremity. Seventy-five percent of patients with lymphedema were instructed to avoid using the affected arm [45]. It has been shown that upper extremity muscle strength is lower in the women with lymphedema than those without lymphedema. Lee et al. [45] found that 36% of the subjects had weakness in the arm with breast-related lymphedema compared to nonaffected arm. Upper extremity strength is commonly measured by assessment of grip strength using hand held dynamometers. Hand grip strength also found to be predictor of upper limb function [24]. Sagen et al. [46] found that there was 11% reduction in grip strength after 2.5 years of axillary lymph node dissection compared to preoperative values. Lee et al. [45] suggested that patients with impaired grip strength in the affected arm had more subjective weakness, fear of using the affected arm, advice to restrict the affected arm,

depressive mood, limited activity, and less upper extremity physical activity.

The causes of sensory disturbances in the upper extremity are nerve damage due to surgery or radiation therapy, neuropathy due to chemotherapy, and lymphedema. Semmes-Weinstein monofilament testing is an inexpensive, easy-to-use, and portable test for assessing tactile sensitivity. It is recommended by several practice guidelines to detect peripheral neuropathy [47, 48]. The women with lymphedema demonstrated reduced sensation.

Hayes et al. [7] identified the influence of selected personal and treatment characteristics on upper body extremity 6 months following treatment for unilateral breast cancer. Objective measures including upper body strength, endurance, flexibility, and hand grip strength and subjective measures including DASH, Functional Assessment of Cancer Treatment, Breast Questionnaire were assessed. Undergoing radiation treatment and hormonal treatment was not generally correlated with worse upper body function, whereas chemotherapy was associated with better objective measurements of upper body function but somewhat worse subjective measurements of upper body function. Radiation therapy was associated with reduced flexibility, while therapy was applied on nondominant side. The authors concluded that those treated on dominant side may use dominant side automatically and incidentally. More extensive lymph node removal and having lymphedema caused deterioration in objective and subjective measurements, such as older age, treatment on the nondominant side, excess of childcare responsibility, low sociocultural level, more lymph node removal, and having lymphedema correlated with upper body functions. The subjective functions decreased when the treatment was administered on dominant side. It is important to evaluate both subjective and objective parameters while considering upper extremity functions after treatment. Extremity dominance should also be taken into account when considering upper extremity function.

In the literature, the studies on hand function in cancer are mostly about breast cancer. There are a very few studies on prostate cancer, squamous cancer, and neck dissection [2, 9, 24, 49, 50]. Prostate cancer is one of the most commonly diagnosed malignancy and third leading cause of death in men [51]. The majority of prostate cancers are hormone dependent, and castration is one of the therapy models in patients with prostate cancer. Androgen deprivation therapy (ADT) is administered to the 50% men with prostate cancer [52]. ADT has several adverse effects including sexual dysfunction, fatigue, anemia, osteoporosis, and diminished muscle strength. Low testosterone levels caused by ADT therapy result in declines in hand grip and pinch strengths and hand dexterity assessed by Grooved Pegboard test in the patients with prostate cancer [9]. Hand grip strength declined at 3 months in ADT users and stabilized over time [23]. Grip strength reflects upper extremity strength as well as mortality risk. The mortality risk increased by 24% at every 5 kg reduction in hand grip strength [53]. Impairment in hand functional status of the men user ADT was also found. Hand functional status assessed by Duruöz Hand Index was correlated with hand grip strength and dexterity [9].

As a conclusion, cancer types, treatment modalities have effects upon hand function. The specialist interested in cancer rehabilitation must have knowledge about involvement area and treatment models such as chemotherapy, radiation therapy, surgery, and lymphatic involvement for evaluating hand dysfunction. It is very important to evaluate and focus on the hand dysfunction in order to improve the quality of life of the patient.

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18 Function Assessment in Metabolic Disorders: Diabetes Mellitus, Hemodialysis, and Gout

Feray Soyupek and Selami Akkuş

Hemodialysis

Musculoskeletal Involvements of the Hand

Musculoskeletal system involvement is frequently observed in patients with chronic renal failure receiving dialysis treatment, which can impair the quality of life. Dialysis-related musculoskeletal abnormalities often present with carpal tunnel syndrome (CTS), destructive artropathy, juxtra-articular bone cysts, or erosions [1]. It was thought that the nonstop accumulation of B2 microglobulin plays a role in the pathogenesis of joint and periarticular involvement. β_2M amyloid deposits usually accumulate in the bones, joint cartilages, synovium, muscles, and ligaments [2]. Musculoskeletal symptoms and signs frequently occur in patients with B2M amyloidosis. The prevalence of musculoskeletal symptoms associated with β_2M amyloidosis increases with longer survival on dialysis treatment [3]. In addition to the duration of hemodialysis (HD), an older age at the initiation of HD is an independent significant risk factor for the development of β_2M amyloidosis [4].

Another possible explanation of hand disability in the patients receiving HD is arteriovenous HD access (AVF) placement. In brachial-based procedures, a decrease in extremity pressures was observed in 60–80% patients [5], but in the previous studies, hemodynamic defects have been reported as a poor predictor of hand disability after AVF [5, 6]. The potential factors explaining hand disability after AVF were ischemia, surgical trauma, uremic polyneuropathy, inflammation, skeletal muscle dysfunction, and blood vessel reactivity [5].

CTS is one of the most frequent complications in patients receiving HD [7]. The prevalence of CTS in patients with chronic renal failure undergoing HD was reported to be 5%, but the incidence of CTS in patients undergoing HD for more than 20 years could be increased by up to 50 percent [8, 9]. Clinical symptoms of CTS are relatively similar to those of idiopathic CTS characterized by paresthesia, tingling, and pain in the median nerve territory of the hand.

Previous studies have shown that CTS has a variety of factors including edema of the flexor retinaculum, associated with superficial vein valvular destruction distal to the fistula, and amyloid deposition in the transverse retinacular ligament [10–12]. CTS symptoms are more common on the side of the longest-running vascular access [13].

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Destructive arthropathy is a common feature of dialysis-associated amyloidosis. Joint involvement is usually symmetric and most commonly affects the shoulder, but other joints including the spine, knee, wrist, and small joints of the hands may also be involved [14]. Destructive spondyloarthropathy is a serious spinal complication of patients on long-term HD. It is characterized by narrowing of the intervertebral discs with erosions and cysts of the adjacent vertebral plates without significant osteophytes and frequently involves craniocervical joint and lower segment of the cervical spine. The disc spaces between the 4th and 5th cervical vertebrae and between the 5th and 6th cervical vertebrae are most frequently involved [15]. Symptoms may occur due to radiculopathy and myelopathy. Spondylolisthesis is common and may be severe, causing compressive myelopathy. Etiology is not fully understood. Amyloidosis, hyperparathyroidism, CPPD, and metabolic bone disease are thought to be etiological factors [16].

β_2M amyloid may deposit along the digital tendons of the hands, causing irreducible contractures of the finger, trigger finger, and tendon rupture. Spontaneous tendon rupture is uncommon in dialysis-associated amyloidosis but has been reported by several authors in extensor and flexor tendon of hand [17–19].

Direct amyloid invasion with replacement of subchondral bone results in the formation of cysts that are often referred to as "intraosseous amyloidomas" [16]. The most common upper extremity "amyloidoma" locations include the distal clavicle, anatomical neck of the humerus, and carpus but are also seen in the cervical spine, glenoid, radius, ulna, metacarpals, and phalanges [9, 20–22]. Bone cysts are usually juxta-articular and surrounded by a thin sclerotic margin. Carpal cysts tend to localize to the radial side and most commonly involve the scaphoid and lunate [23]. The most of the cysts were asymptomatic. Pathologic fracture through amyloidomas has been reported in both the upper and lower extremities [22].

Beside the musculoskeletal abnormalities, hemodynamic and neuropathic problems may impair hand function. The reported hemodynamic complications in the hand include venous hypertension marked by swelling and discoloration and vascular insufficiency from shunting of the blood flow from the hand [24]. Co-existence of muscle weakness and atrophy, areflexia, sensory loss, and graded distribution of neurological deficit in a patient with renal disease suggest the presence of uremic polyneuropathy.

Hand Function Assessment

The musculoskeletal and neurological involvements of HD affect hand function adversely. There are limited studies that have evaluated hand function in patients receiving HD. In a study, the incidence of impaired hand function in patients undergoing HD was found to be 54% [25].

Hand Grip Strength and Pinch Strength tests: In patients with chronic renal failure, receiving HD had diminished hand grip and pinch strengths [26]. Muscle strength was diminished because of neuropathy, myopathy, physical inactivity, tendinopathy, and pain. High values of ultrafiltration may lead to hypotension and a poor general condition, negatively affecting muscle function whenever hand grip strength is performed after the dialysis session [27]. Additionally, muscle wasting is one of the best markers of protein-energy expenditure, reflecting the reduction in the stores of energy and protein in patients with chronic renal insufficiency [28]. Hand grip strength is found to be a predictor of mortality and also an indicator of nutrition status in patients with maintenance dialysis [29, 30]. Handgrip strength is measured with hydraulic hand dynamometer and pinch strength with a standard pinch gauge as outlined by the American Society for Surgery of the Hand. The measurements are performed while the patients are seated with the shoulders adducted, elbows flexed to 90°, and forearms in neutral position [31]. While evaluating the muscle strength, the presence of vascular access and the site of the body must be considered.

Range of Motion: Range of motion of the wrist and digits is assessed with a standard goniometer and a finger goniometer, respectively.

Two-point discrimination test: This test is assessed with esthesiometer. Stimulation of one or two points is applied randomly along the longitudinal axis of the tested digit while the subject's eyes closed. The threshold occurs when the minimum of millimeters of 7 out of 10 responses is true. A two-minute rest period between each trial should be allowed. The subject's thumb and index digit are tested as representative of the median nerve, and the little digit is tested for the ulnar nerve. Both static and moving 2PD are measured. Before the test, the subject is informed about the procedure and asked to make the appropriate response.

Edema is evaluated with a hand volume water displacement tank with a drip spout. The displaced water is collected in a graduated cylinder and measure in the nearest milliliter.

Hand Dexterity and coordination is assessed by Purdue pegboard test. Five subtests comprise the test: right hand (RH), left hand (LH), both hands (BH), right + left + both (R + L + B), and assembly. Performance of the RH and LH subtests requires participants to first use their right hand (dominant) and then left hand (non-dominant) to place as many pins as possible down the respective row within 30 seconds. Each stage of the test is administered three times [32].

Daily Activity tests: In the previous studies Sollerman test, Grip Function test (GFT), Hand Functional Index (HFI), Duruöz's hand index (DHI), and Disability of the Arm, Shoulder, and Hand (DASH) Questionnaire were used for evaluating daily activities [25, 26, 33–38]. Although there are some scales to assess hand function, none of them was developed specifically for hand involvement in patients receiving HD.

The GFT consists of 20 items that incorporate the seven major handgrip types into activities of daily living. Each subject was scored according to the amount of time required to complete the task and the handgrip pattern used. The reliability of this test has previously been examined in patients with hand disorders.

DHI was developed and validated as a self-report questionnaire that can be routinely used to assess the functional disability concerning hand-related activity limitation in patients with RA, osteoarthritis, systemic sclerosis, and stroke and those receiving hemodialysis [26, 37]. It contains 18 items on hand ability in the kitchen, during dressing, while doing personal hygiene, office tasks, and other general items. A higher score indicates greater activity limitation or more difficulty.

Sollerman test uses 20 items comprising activities of daily tasks; 15 items test bilateral hand grip function, and seven of the grips assessed are essential for normal function. Points are assigned to each item on a five-point scale; the final score is the sum of all items. Possible scores range from 0 to 80; subjects with normal hand function should achieve scores of 80 and 78–80 in the dominant and nondominant hands, respectively [36].

HFI consists of the first nine questions of the Keitel Functional Test. It is an observational hand scale which assesses finger and wrist motion, and the total score ranges from 4 to 42.

Despite the knowledge about hand involvements in the patients receiving dialysis, there is limited knowledge about functional assessment of hand involvement [26, 33–37]. Chazot et al. assessed hand function with medicolegal techniques based on sensitivity and amplitude of angulations [35]. Limaye et al. [25] used Sollerman test, hand grip test. The mean Sollerman test score of the patient receiving HD was lower than the normal values [25]. The Sollerman test accurately reflects patient function measured by Health Assessment Questionnaire (HAQ), visual analogue score for function, and grip strength. They concluded that the appropriate hand rehabilitation program targeted at the data obtained from the Sollerman test should be administered to the patient. Tander et al. [34] also found relationship between Sollerman test and age, HAQ, Beck Depression Inventory, and DHI. Duruoz et al. [37] reported that DHI was significantly correlated with HAQ, HFI, Purdue pegboard scores, grip strength, and pinch strengths, while no significant correlation was found with nonfunctional parameters. They concluded that DHI is a practical scale which is efficient in assessing accurately the functional disability of the hand in patients receiving HD.

In a study conducted by Rehluss and colleagues, there were no differences between limb sides over time in digital sensation and dexterity, while grip strength and DASH score decreased in the access-side limb after AVF placement [38].

Diabetes Mellitus

Musculoskeletal Involvements of the Hand

Musculoskeletal complications of diabetes mellitus (DM) may lead to functional disability, which is disrupting quality of life. Complications of DM such as nephropathy, neuropathy, and retinopathy are known very well, but musculoskeletal involvement is less emphasized. Patients with DM may have musculoskeletal syndromes, symptoms which are related to the duration of DM, poor metabolic control, and microvascular complications. The musculoskeletal involvements including tendon, muscle, nerves, soft tissues, and joints are heterogeneous. The musculoskeletal manifestations of the DM in the hand include limited joint mobility (LJM), trigger finger, Dupuytren's disease (DD) (Fig. 18.1), carpal tunnel syndrome (CTS), complex regional pain syndrome type-1, and ulnar neuropathy. The prevalence of hand impairments is reported to be 8–75%, whereas the prevalence was found 0–26% in controls [39, 40]. In a study, 27% of diabetics had no difficulties, 53% of them had minor difficulties, and 20% of them had serious difficulties in hand function [41]. Additionally, a significant correlation has been found between the prevalence of shoulder and hand impairments [39, 42, 43]. Shoulder and hand involvements impact upper extremity functions.

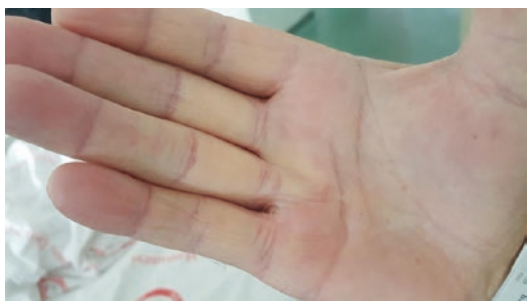

Fig. 18.1 Early stage of Dupuytren contracture in a patient with DM

Limited joint mobility (LJM), also termed diabetic stiff hand syndrome or diabetic cheiroarthropathy, is characterized by skin thickening over the dorsum of the hands. The underlying mechanism of LJM is thought to be accumulation of advanced glycation end-products in collagen [44, 45]. LJM restricts mobility of multiple joints including metacarpophalangeal, proximal, and distal interphalangeal joints and impairs dexterity and grip strength. The prevalence of LJM in DM has been found to be variable, ranging from 8% to 50% [39, 40], whereas the prevalence was 0–26% in the controls [46]. The frequency of LJM correlates with disease duration [47], and it is seen in both types of diabetes. In previous studies, worse glycemic control and the presence of microvascular complications have been reported as risk factors for LJM [46, 48–50]. LJM often affects the fifth finger and spreads radially. LJM is a painless disease, but sometimes paresthesia and pain may be present, which are aggravated by movement of the hands in the early stage. The clinical findings are loss of finger extension and inability of the palms to contact each other which is known as prayer sign. Prayer sign and tabletop test are the clinical tests of LJM. Measuring range of motion of the hand joints by using goniometer is useful screening method [51]. Saugen et al. reported that this method has correlation with prayer sign.

DD is a spontaneously occurring chronic and idiopathic thickening, shortening of the palmar fascia causing flexion contracture of the affected finger. Unlike most cases of LJM, DD may be seen relatively early in the course of the disease, with a 16–60% prevalence [39, 52–55]. The fourth and fifth finger involvement are frequently observed in nondiabetics patients, while the third and fourth finger involvement are more common in diabetic patients [56, 57].

LJM and DD may be seen together in the same patient [39]. Nodule formation along the fascia is early clinic finding and by the time flexion contractures of the fingers were present (Fig. 18.1).

The finger flexion contracture is usually seen at the fourth finger. Top table test is positive, which indicated that the palmar surface of the digits should not contact the table. For screening test, passive range of motion examinations of the digits is useful.

Trigger finger is a frequent complication and characterized by inflammation and narrowing of the A1 pulley, which is causing blockage in flexion. The movement of the finger is generally painful. Palpable nodule in the metacarpophalangeal joint level, popping and locking of the finger during active, and passive finger flexion are the clinical findings. The prevalence is found approximately 20% in the diabetic population [55, 58] and its prevalence is related to duration of diabetes [58].

Hand Function Assessment

There are a wide range of symptoms associated with diabetic hand syndrome such as chronic pain, numbness, stiffness, tingling, reduced strength, abnormal sensory function, and fatigue, which can lead to deficits in the sensoriomotor control and functional performance. Musculoskeletal involvements of the hand impair range of motion of fingers, wrist, muscle strength, sensory input, coordination and dexterity, and hemodynamics. The assessments of these impairments must be considered during the following and planning of treatment. Assessment of hand functions include examinations of dexterity, sensitivity, grip strength, or perception threshold [59].

Hand weakness has been demonstrated in the diabetic population, compared with normal control subjects [60–62]. Reduced grip and pinch strength have been found to be independent of LJM, DD, and trigger finger. Because of described numerous hand complications, functional disability is not amazing. Hand weakness is assessed by dynamometer and pinchmeter. The procedures are mentioned above in hand function assessment of patients undergoing HD section.

Monofilament testing is an inexpensive, easy-to-use, and portable test for assessing the loss of protective sensation, and it is recommended by several practice guidelines to detect peripheral neuropathy [63, 64]. Hand function may deteriorate in cases with diminished protective sensation [43, 65]. Monofilaments, often called Semmes-Weinstein monofilaments, are calibrated, single-fiber nylon threads, identified by values ranging from 1.65 to 6.65 that generate a reproducible buckling stress. The higher the value of the monofilament, the stiffer and more difficult it is to bend. Three monofilaments commonly used to diagnose peripheral neuropathy are the 4.17, 5.07, and 6.10 [66, 67]. The filament is placed on the patient's skin; when there is considerable loss of sensation, the patient will not be able to detect the presence of the filament at buckling. The 5.07/10-g monofilament has been described as the best indicator to determine loss of protective sensation [68]. Despite the frequent use of monofilament testing, Dros et al. [69] do not recommend the sole use of monofilament testing to diagnose peripheral neuropathy.

Moberg Pick-Up Test, Minnesota Rate of Manipulation Test, Purdue Pegboard Test, and Nine-Hole Peg Test were used to assess motor dexterity and coordination of the hand [62, 70, 71]. Impairments in tactile sensory, joint mobility, and muscle strength affect manual dexterity.

Pinch holding up activity test [72] is a tool to determine the characteristics of sensoriomotor control in the hand and involves mobility, strength, sensation, and coordination. Chiu et al. found degradations in sensory and motor functions and sensoriomotor control ability in the hands of diabetics and concluded that PHUA is a sensitive and precise tool that can determine the sensoriomotor function of the hands of diabetic patients.

Measurements with the dynamometer and various scales are used to evaluate hand functions, but there is no specific functional disability scale developed for diabetic hand. DHI was validated for diabetic hand dysfunction and found a practical scale in the assessment of hand dysfunction in diabetic patients [71]. Disability of the Arm, Shoulder, and Hand (DASH) Questionnaire, Hand Cochin Hand Function Scale, and Michigan Hand Outcomes Questionnaire were used to determine the patents' perceptions of functional

hand performance. Several studies reported that DASH scores were worse among the patients with diabetic hands including LJM [48]. In a study, the reliability and validity of Hand Function Disability Scale (HFDS), Michigan Hand Outcomes Questionnaire (MHQ), Dreiser's Functional Hand Index (DFI) for persons with DM were examined and concluded that HFDS and MHQ appear to be reliable and valid measures of hand function in persons with diabetes.

In a study, disability was related to impaired muscle function and carpal tunnel syndrome in the patients with hand syndromes associated with diabetes. Obesity and overall physical functioning influenced hand disability, particularly in women [43]. Redmond et al. reported that functional disability of upper extremity in diabetes could be explained by grip strength, dexterity, and body mass index [43]. Savas et al. [61] reported that functional disability of the hand was related to low hand strength but not to DC, TF, and LJM.

Gout

Gout is a monosodium urate crystal deposit disease and characterized by deposition of the crystals in joints and extra-articular tissues such as tendons, nerves, and kidney. Gout is the most common arthritis in adults with a prevalence of 1–2% (Fig. 18.2) [73]. There is an increase in mortality as well as deterioration of the quality of life and functionality of the patients with gout [74]. The impairment in functionality and quality of life is related to disease itself as well as accompanying metabolic problems. Scire et al. reported that functional and health-related quality of life were also related with activity and severity of disease-related variables including symptom duration, cumulative joint involvement, number of attacks, and presence of tophi [75].

The clinical stages of gout are acute gout arthritis, intercritical gout, and chronic tophaceous gout. Fifty percent of acute arthritis develops its first attack in the first metatarsophalangeal joint. About half of the disease may start in other joints such as the wrist, as well as metacarpophalangeal and interphalangeal joints of the hand (Fig. 18.2). Chronic gout is characterized by the development of tophi in connective tissues. Tophi lead to destructive arthropathy. Tophi present on the fingers and volar surface of the hands in the upper extremity. Tophaceus gout in flexor tendon of the hand is a rare form of tenosynovitis.

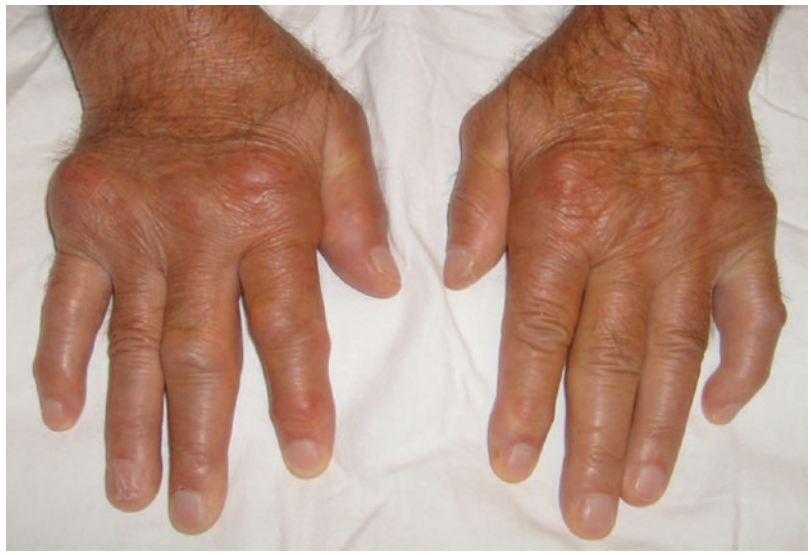

Fig. 18.2 Metacarpophalangeal and proximal interphalangeal involvements in the patient with gout

Hand Function Assessment

Upper extremity involvement has been described especially in the patients have extensive involvements or long history of gout. Functional deficits of the hand caused by gout include decreased joint movement and neurovascular compression. There is limited knowledge about the evaluation of hand function in the patient with gout. This clearly remains an area requiring further work. Dalbeth et al. [76] only investigated the predictors of hand function in gout and demonstrated that tophaceous joint disease is major independent predictors of hand function in patients with gout. Furthermore, others measures of gout disease severity such as disease duration and frequency of gout flares further contribute to hand function. The key predictor of hand function was the number of joints of the hand with overlying gout. Measures of chronic and poorly controlled disease predict hand function [76]. Disease activity such as the duration of the disease and the frequency of gout exacerbations also affect hand function [76]. Tophi can damage joint functions by creating joint damage with synovitis and by limiting joint motion. There is no validated and specific hand functional disability scale developed for gout. Dalbeth et al. [76] administered Sollerman hand function test and Disabilities of Assessment Shoulder and Hand questionnaire (DASH) to determine predictors of hand function in gout.

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Section III

Hand Function with Robotics and Assistive Technology

Hand Function and Assistive Devices

19

Sonja Krupp, Baptist Peltner, and Rainer Zumhasch

Introduction

The diseases described in this book, many others and traumata can lead to deficits in hand function. Assistive devices are all objects that facilitate the completion of tasks depending on the use of our hands as well as those that protect structures of the hand against further deterioration. If we call training recommended to improve hand function a task too, training devices that enable the patient to do self-exercises in the right way to further a positive functional development could be called assistive devices in a broader sense so that the differentiation between both categories melts away. In fact, the term "assistive technology" (AT) is used for devices that augment or replace function (assistive) or serve as a therapeutic tool (rehabilitative) [1].

The decision to prescribe an assistive device depends not only on the momentary state of function but also largely on its prognosis. Of course, a permanent loss of function or even parts of the hand calls for assistive devices that may be needed to compensate.

On the other hand, short-term impairment will seldom be an indication for the usage of medical assistive devices. This is not only due to economic aspects. In fact, consistent immobilization may be the shortest way toward restoration of normal function, whereas assistive devices may lead the patient into temptation to do too much and he might pay for that interruption of the healing process and risk chronification of the underlying pathological condition.

The longer a period with necessity to prevent certain movements of joints may be the greater is the need for assistive devices that allow for partial mobility. Of course, one of the aims is to make the patient as independent of help as possible. Acceptance of deficits that cannot be rectified is a necessary mourning process but the treating physicians and therapists should help their patient to do away with the thought that the impaired hand has become useless. Taking over the role of supporting hand is a good start. Long-term prognosis is strongly influenced by belief in self-efficacy and inclusion of the weaker – that is important not only on a social scale but even concerning our own body members.

Every activity helps a little to reduce loss of muscle mass and the risk of acquiring osteoporosis and contractures. Some patients fancifully invent compensatory techniques that might help other patients too. They can proudly present their ideas to their therapists, giving them a free "train

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the trainer session." This feedback should be cherished and integrated into the treatment regimen, including the improvement of health literacy by helping the patient understand how his actions influence the further clinical development.

Not to forget making an impaired hand take part in as many activities as possible has not only effects on elements of the musculoskeletal system – it influences cerebral areas responsible for coordination of these tasks. This includes processing of sensory data as well as motor control of the affected hand. Neuroplasticity has been underestimated: Already 2 weeks after immobilization of one extremity the corresponding cortex shows regress in the contralateral hemisphere [2]. The same principles used in constraint-induced therapy in a positive way lead to a circulus vitiosus if the disadvantaged hand is neglected and omitting to make optimal use of assistive devices adds to this problem. Every day without usage of physiological patterns of movement weakens their cerebral representation and restoration of what was lost takes many times more, especially in old age.

So wherever assistive devices have the potential to improve long-term prognosis, the attending physician and other therapists should hurry up to find out what fits best according to the individual physical and functional situation and give priority to what activities are the most important in the eyes of the patient. This includes not only basic but also instrumental and advanced activities of daily living. As many patients do not dare to talk about their hobbies but are ready to sacrifice this aspect of quality of life, they should be asked about it explicitly and the need for assistive devices then be discussed.

When it is more a question of comfort than a necessity, there is more time to think over whether the advantages not to use the object under discussion might prevail. It may be enough to learn another method to do things (e.g., lift a kettle or pan with both hands instead of one) or to use nonmedical devices that are easier to handle or clothes that are easier to put on and off. For the same reasons mentioned above adaption to an assistive device and constant use of it has the side effect of unlearning to manage without it. Remaining independent from that device is clearly a plus if it is not paid for by harming vulnerable structures of the hand. As anatomical and functional situation may change in the course of the time reassessment may lead to a different advice concerning aids and some patients with chronic diseases that show fluctuating severity of the symptoms know exactly when to change from one assistive device to the other that offers more support and when both of his little helpers are unnecessary.

The inconvenience to have the device at hand (often literally) in the right moment and the patient's wish not to be stigmatized by being recognized as impaired will normally reduce the wish for a prescription to a senseful level, even if somebody else, e.g., an insurance, takes over all costs – unless the handicapped person got the impression that an open refusal to use the assistive device would make him an unthankful patient in the eyes of his helpers.

Principles of Therapy with Assistive Devices in Diseases with Hand Involvement

Accidental injuries as well as postoperative situations often require a certain degree of immobilization. For the reasons mentioned in the introduction of this chapter, this should be done as sparingly as possible. Assistive devices may be helpful to reduce pain, the period of time certain movements are "forbidden," and the degree of immobilization. Splint supply should allow the largest individual range of movement that can be given without danger to the healing process. This helps the patient to maintain his independence and gives him a better start into reconvalescence by keeping nervous and musculoskeletal system in shape as far as possible.

Assistive devices can be part of a protective strategy to reduce malalignment and progressive deterioration of joint structures. They can be used to reduce muscular compressive forces on the joints, e.g., in connection with strong grip ("internal forces") and forces applied to joints

when objects are handled ("external forces") [3]. For example, in rheumatic diseases when chronic instabilities have developed, every movement that promotes volar luxation of proximal phalanges should be minimized. Exerting powerful pinch grip presses the involved metacarpophalangeal joint into subluxation, so finding a way to operate with less pressure is important, and assistive devices can pave the way. As ulnar shift of extensor tendons and finally the finger itself is triggered by flexion in metacarpophalangeal joints, working with less flexion by using handles with larger diameter or by learning to do something in different position can help to avoid increasing deformation.

For the corresponding articular partners to perform certain movements may mean leaving a bit the comfort zone – no problem for a healthy joint but extra stress on cartilage and other components already affected by a disease. The higher the force used to hold a certain position, the greater the risk to add to the deterioration. Correct application of the laws of the lever leads to the construction of assistive devices that enable patients with high vulnerability of their joints to manage everyday life with a minimum of contraproductive effects. In ideal cases the usage of the device even strengthens especially those muscles that promote physiological position and function.

At the same time a reduction of motion-induced pain can be expected, what is always important for life quality and to hold up motivation to include the affected hand into activities. Highest importance of avoidance of pain induction can be observed in chronic regional pain syndrome (CRPS) where prognosis depends largely on it [4]. But also in all other pathological conditions assistive devices should be taken into consideration as means to reduce pain evoked by activity in order to further mobilization and all this without the negative side effects of analgetic medication. Perception of the patient that an aid is doing him good is the best motivational factor to use it. In desperate cases that should be rare today, joint destruction causes so much pain that immobilization splints are worn permanently – something undesirable but inevitable to reduce pain during function to a bearable level [5].

Many different diseases lead to a loss of muscle strength. Whether a traumatic lesion of the ulnar nerve, a Guillain-Barré syndrome or some other disease is responsible for weakness of hand muscles, patients often benefit from the same kind of assistive device, but it may be necessary to complete the supply by individually shaped instruments.

After stroke paresis and spasticity are different sides of the same coin. Assistive devices that help the patient to accomplish a task without excessive effort reduce spasm at the same time. Where it is possible to make both hands work together, for instance, holding a cup with two handles, this way should be chosen in supply with assistive devices. This stimulates cerebral reorganization through a multi-channel approach as it combines input from the "healthy" side of the body with afferent proprioceptive signals from the paretic hand and adds visual information about the accomplished task, a theory accepted not only by Bobath but in many physiotherapeutic concepts [6].

The influence of surrounding conditions on the effectiveness of assistive devices should not be underestimated. For example, the optimum working height should be chosen when an assistive device is tested. Hand function depends largely on the position of joints more peripheral or especially proximal of the "leading joint." This aspect must be taken into consideration to help patients with chronic paresis to reach the maximum functional restoration possible. In case of paralysis, a splint may bring the affected joint into a position that optimizes the function of the neighboring joints so that they can work with more effectiveness. It is clear to see that such works of art as depicted near the end of this chapter require an individual approach and a lot of creativity and skillfulness on the part of the highly qualified professional that produces them. Splints should never immobilize more joints or limit range of motion to a higher degree than necessary to accomplish the aim of the therapy, e.g., to protect those anatomic structures that need their protection.

"The first step is always the hardest" applies also to the usage of an assistive device that can positively influence the effectiveness of treatment. Many of such objects find a quick way into a drawer that is opened only seldom. So supplying the patient with such a theoretically helpful tool might be in vain without personal training on it, done by a professional. Occupational therapists (ergotherapists) and physiotherapists are not only trained to be these trainers but many physicians need their expertise to make the right decision concerning the most fitting prescription. As the course of education is heterogeneous, difficult cases should best be laid into the hands of specialized hand therapists.

Intense follow-up after the assistive device is handed over maximizes the personal profit that can be drawn from it. The patient's perception of pain versus comfort during the activity that should be facilitated and at rest is of basic concern. It is especially important in all cases where an assistive device is in long-term contact with the body of its owner such as splints. Whereas a forgotten device in a drawer is neither helpful nor harmful, a splint might well cause additional trouble including nerve damage and wounds, especially in patients with sensory deficits and a tendency to develop swelling. Those that work with splints and braces have to know the hot spots of vulnerability. Even less severe undesirable side effects like increase of pain may let any assistive device fall out of favor if there is no quick solution to the problem. In the course of the time, swelling due to inflammation or posttraumatic edema may disappear so that the device needs adjustment.

Whether the provision was successful for the purpose of increased functionality can be evaluated clinically by observing the patient in his activities without and with use of the aid, comparing the two situations. But what can we do additionally as assessment?

Reliable assessment instruments need to be constructed with high standardization to keep objectivity high. Assistive devices are available in so many different types influencing the results of assessment in so many ways that hoping for tests specially designed for patients with such aids is not justified.

Nobody will doubt that pain scales are helpful to get a semiquantitative feedback concerning pain reduction via adding a device as mentioned above. It is also obvious that measuring the range of active and passive motion can be done with and without splints in the neighboring joints. Provided that the assessor precisely documents which result was achieved with and which without assistive device it is not forbidden to make use of questionnaires and performance tests in this situation. So most of the different assessment instruments described in this book can be used if you really know what you are doing. Of course, the achieved score with device must be seen in a different light as cutoffs were calculated just for the situation without aids, but the greater the difference between both results, the more advantageous the assistive device will probably be – supposed the result achieved with it was the better of both rounds. Demonstration of the improvement resulting from usage of the aid can motivate a patient that hesitates skeptically to make better use of his assistive device.

After intensified training at a rehabilitation clinic it is not always easy to retain skills that were restored with support of assistive devices. Only daily practice preserves positive results of therapy. Well-intentioned relatives and friends who take over too much may lead the patient back into passivity and influence the prognosis in a negative way. Potential helpers should know that and have to be included in a successful rehabilitation process.

On the other hand, some patients are overambitious and have to be checked regularly for irritation of joints and tissue due to too intense use of their assistive device. Especially in the initial phase they should be encouraged to avoid overdoing it but keep the needed breaks.

Categorization of Assistive Devices

There are different ways to categorize assistive devices.

According to the need for individual tailoring, we can distinguish between the following:

(a) Assistive devices that need no adjustment to its owner (e.g., anti-slip foil that prevents a plate from being shoved aside accidentally without using one hand to hold it)
(b) Assistive devices that are available in different sizes and shapes according to the patient's measures "pret a porter" for usage without further changes
(c) Assistive devices in an already finished shape that can be fully customized by adding or taking away some material
(d) Assistive devices that are produced on a mainly or entirely individual basis, in general handcrafted

We can categorize based on the field of tasks that need to be performed, for example, assistive devices facilitating intake of food, personal hygiene, dressing/undressing, and fine motor activities like writing, painting, sewing, and so on. In sum assistive devices that have to do with eating and drinking occupy the first place of all devices for different areas of application among rheumatic patients [7] and likely this is true also in connection with most other diseases that lead to deficits in hand function. A multicenter study on patients with rheumatoid arthritis in the Netherlands found that the number one among all assistive devices that had to do mainly with impaired hand function was an electric can opener (in possession of 27% of 240 participants) [8].

Other kinds of categorization are either based on the symptom and functional deficit that needs compensation (assistive devices for patients with tremor, paresis, different joint deformities, or limited range of motion), or they follow the underlying pathological condition (assistive devices for patients with rheumatic diseases, Parkinsonism, stroke, different kinds of peripheral nerve damage, traumas, and so on).

In this chapter, we will present a choice of assistive devices already manufactured and ready to use as well as simple methods to adapt devices to the individual patient, and in the end we will give examples of provisions for patients with complex difficulties that need therapy by experts with considerable handcrafting abilities.

Examples of Assistive Devices

Two people with nearly the same functional state may differ tremendously in their need for assistive devices according to their interests and tasks in private and professional life. On the following pages we present a subjective choice of assistive devices and describe what they can be used for and what symptoms they compensate. The diseases that led to the situation calling for compensation may be different and nevertheless often – but not always – be answered in a similar way. We end with a glimpse into the high art of individual construction of splints and assistive devices.

Slippery surfaces can be a challenge for every hand, so how much more for a hand with sensory or motor disorders. Excessively dry skin as it may occur as result of a neuropathic disease adds to the problem of losing grip on an object that we want to hold in a special position or transfer from one place to the other.

A similar problem can occur in the contact zone between an object we want to handle and its support, e.g., when one hand cannot even serve to prevent a plate from being shoved aside during the time the other hand is cutting food on it. To increase adherence between the object we work on and the area on which it stands, the patient can use a variety of nonslip boards, placemats, and adhesive foils.

Some of these assistive devices can solve both of the problems mentioned: they may be placed under a plate, vessel, or glass to keep it in position (Fig. 19.1a). But they can also be folded and used to get a tight grip on smooth objects like a glass (Fig. 19.1b). This flexible use of the antislip material reduces the number of different assistive devices needed.

Where grip strength is too low to perform a task that needs force and rotation simultaneously (functional force according to Duruöz) [9], assistive devices that increase adhesion and diameter at the same time may help to remain independent. Especially the ability to open bottles without assistance is important to foster drinking enough and thus avoid dehydration when nobody else is around. It could well be necessary to combine the use of an assistive device for opening bottles (Fig. 19.1c), jars

Fig. 19.1 (**a**) Anti-slip mat, (**b**) alternative application, and (**c**) assistive device for opening bottles. (Published with kind permission of © R. Zumhasch 2017. All rights reserved)

(Fig. 19.2a, b), or tins (Fig. 19.2c) with the use of an anti-slip foil by the supporting hand. The better adhesion between the object and its contact surfaces the lesser strength is needed to open it. Using the palm of the hand and involving the arm into the screwing process keeps danger away from the fingers. The tin opener helps to avoid pinch grip with force.

After having managed to prevent the necessary dishes from slipping away the intake of food may still be a problem. Persons with ataxia or tremor and those that can use just one hand to hold their cutlery make the experience that part of their food escapes to the table while they try to divide it into portions and get the morsels onto a spoon or fork. This can be prevented by fixing a little border to the plate (Fig. 19.3a) that serves as a "bump." The user brings the fork or spoon to the edge of the plate and pushes the food onto the cutlery. A similar principle is applied in connection with cutting boards as used for various activities in the kitchen such as spreading bread (Fig. 19.3b).

Fig. 19.2 (**a**) Releasing the vacuum, (**b**) unscrewing the lid, and (**c**) opening a tin. (Published with kind permission of © R. Zumhasch 2017. All rights reserved)

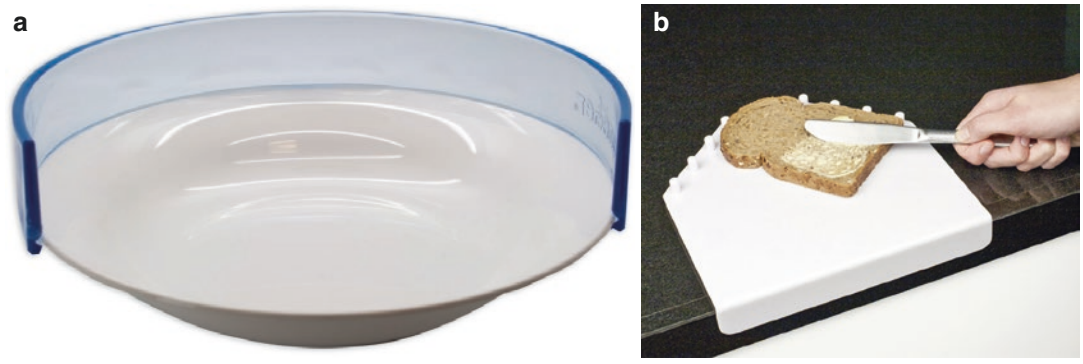

Fig. 19.3 (**a**) Plate with border and (**b**) cutting board with border. (Published with kind permission of © R. Zumhasch 2017. All rights reserved)

Handling cutlery can be much easier with special handles built up according to the anatomic and functional properties of the patient. Indications may be low grip force or spastic. In rheumatic patients, fingers should not exert pressure in a way that promotes hyperextension of the proximal interphalangeal joint. A variety of finished products is available.

Bread and meat knives with handles in angular design allow for a position of the hand and wrist that leads to a better distribution of the needed pressure during the cutting process and protects joints. As usage of such a device involves a larger number of different muscles, it may be the only possibility to cut meat, vegetables, and so on for a patient with reduced strength. The fork in Fig. 19.4a can be curved to the right or left side (depending on the hand that holds it, "to the middle") to make it easier to get food on it. The handle has a grooved structure for better grip. Tiny weight plates can be fixed to it – this helps patients with tremor to hold the fork with less deflections. As attachment a strap band makes it easier to keep the utensil in the hand and prevents unintentional dropping to the ground.

Many patients prefer to get their own cutlery individually adapted to their special needs. Tubes that can be used for that purpose may consist of soft, flexible, but stable closed-cell foam material with water-repellant surface, available in different sizes (Fig. 19.4b with 5, 9, or 17 mm inner diameter). They are cut exactly to the right length and can be slipped on the grip of a great variety of utensils, so that they can be used not only for cutlery (Fig. 19.4c) but also in connection with pencils, toothbrushes, and many other tools. Finding out what diameter of a handle under construction serves best requires detailed examination beforehand. Whether contractures or paresis limit a patient's ability to perform maximal fist closure – the greater the remaining minimum distance between tip of the finger and palm the larger the diameter of the handle should become. If extension of the fingers is (also) a problem like

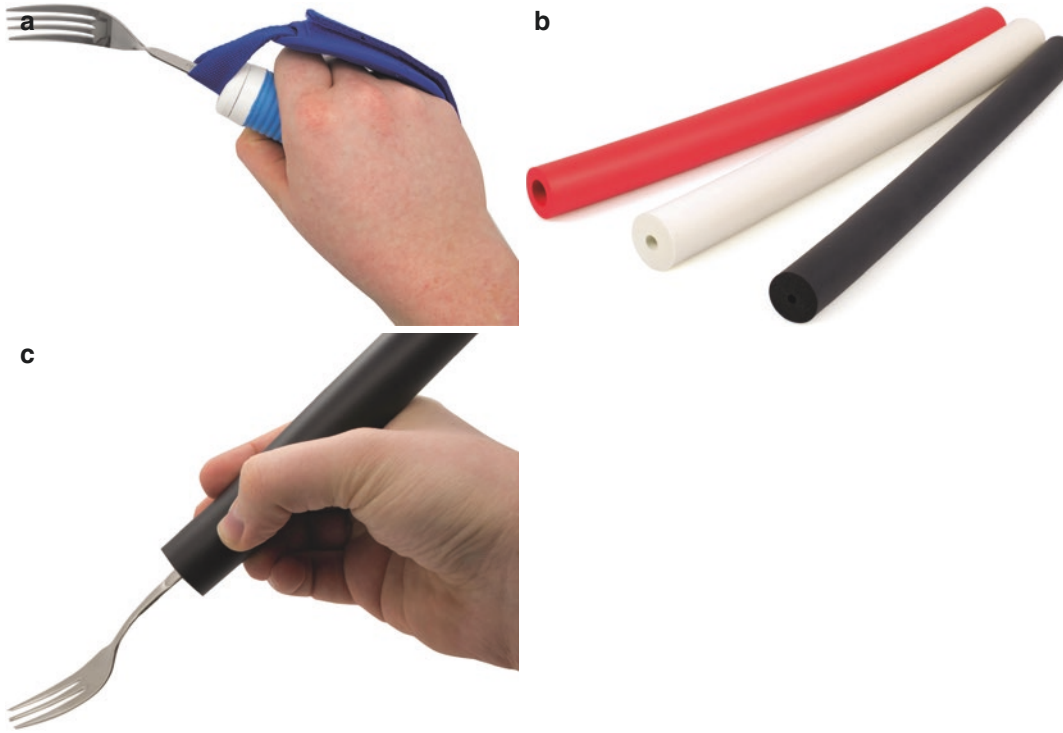

Fig. 19.4 (**a**) Fork with strap band, (**b**) foam tubes, and (**c**) fork with built-up handle. (Published with kind permission of © R. Zumhasch 2017. All rights reserved)

in Dupuytren's contracture, it must be checked what diameter is too large to fit into the more or less open hand.

Patients with even less ability to close the writing hand around a pencil may need an assistive device with larger circumference in the palm center, but a tube-shaped device with too large diameter near the tip of the pencil hinders visual control. In these cases, an egg-shaped device (Fig. 19.5a) can suite better. Figure 19.5b shows an assistive device with three silicone finger molds that facilitate tri-digit pinch. When used on a pencil there is no need for constant active fixation but hand muscles can relax much better. The writing utensil in Fig. 19.5c uses a different approach to the problem of directing the pen. One of the fingers is placed on top of this short pen like a rider on a horse. Radial adduction is not necessary and it need not be the second finger but the third is also good in taking over this task. Each of the demonstrated writing aids or other adaptions may be helpful for patients with action-specific focal dystonia in form of writer's cramps, but this can be verified only by experiment.

Cutting with scissors requires not only closing but also opening, a fact that does not come to mind as long as there is no problem with that function. When active extension of the thumb and radial fingers is the problem (too), scissors that open automatically by means of elastic forces (Fig. 19.6a) can help. Dressing and undressing requires opening and closing zips as well as buttoning. Assistive devices with easy-to-hold grip that fit to nearly all sizes of zips and buttons (Fig. 19.6b) help to manage this without assistance and to avoid overstress of finger joints. Donning aids for stockings should be mentioned here for the same reason.

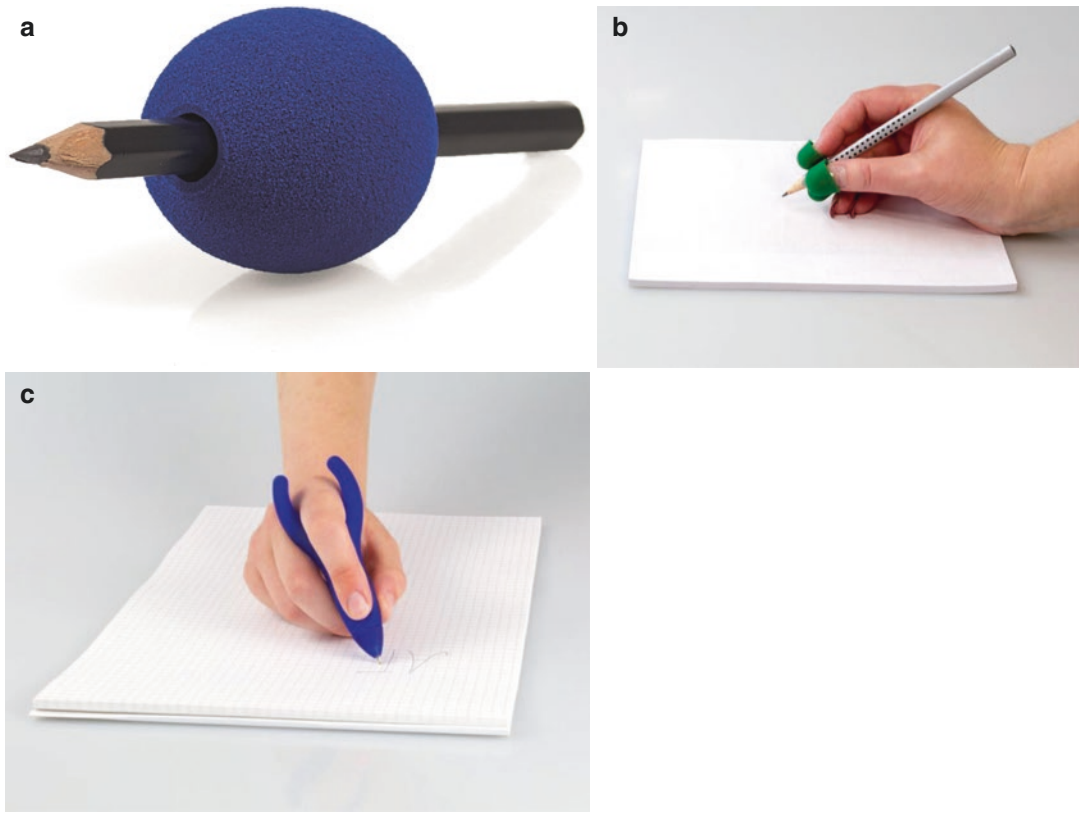

Fig. 19.5 (**a**–**c**) Different devices that assist in writing. (Published with kind permission of © R. Zumhasch 2017. All rights reserved)

Fig. 19.6 (**a**) Self-opening scissors, (**b**) aid for zips and buttons, and (**c**) grip aid. (Published with kind permission of © R. Zumhasch 2017. All rights reserved)

Grip aids open another way to reduce movements that provoke discomfort and to keep up personal independence. The example shown in Fig. 19.6c is 70 cm long, it can carry objects up to 8 cm in diameter with 1 kg weight. It is foldable and it can be used by left handed as well as right handed people.

Lots of action steps are necessary to get toothpaste out of the tube, onto the brush and the cap back into its place. Without any difficulties in hand function, this is done in an instance with both hands working together simultaneously, but ataxia, tremor, or even one hand with reduced dexterity can make the whole procedure much more complicated. A tube squeezer (Fig. 19.7a) (usable not only for toothpaste of course) reduces the complexity of the task – and the risk to let the cap drop to the ground and stumble during the search for it.

In rheumatic and degenerative diseases peripheral functional deficits of the upper extremity often go hand in hand with problems of proximal joints. That is another argument for including a comb with anatomic anti-slip grip and handle extension (Fig. 19.7b) into our list. The comb is bent so that the handle can be held near to the body also when hair on the back of the head needs combing. This reduces strain on shoulder and hand and keeps up independency in this basic activity of daily living.

Functional deficits of the hand are not only a challenge to necessary duties but they can limit

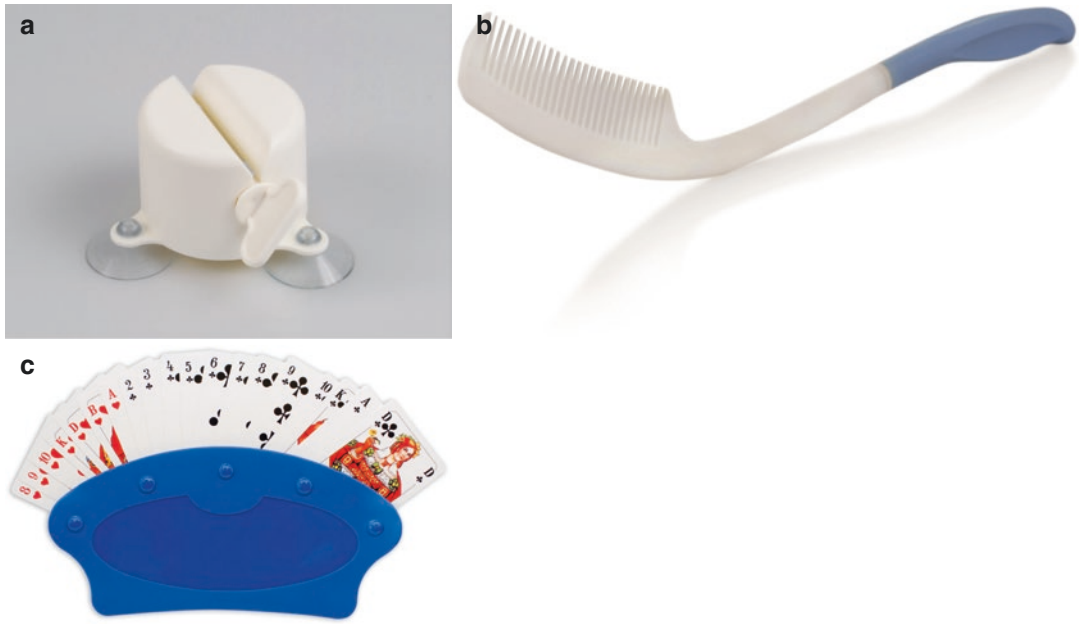

Fig. 19.7 (**a**) Tube squeezer, (**b**) comb with ergonomic grip, and (**c**) playing card holder. (Published with kind permission of © R. Zumhasch 2017. All rights reserved)

a person's possibilities of spending leisure time and taking part in social activities like playing cards. Of course, usage of an assistive device for holding the cards (Fig. 19.7c) is compulsory for patients who can use just one hand. But it is also beneficial, for example, for people with affections of the carpometacarpal joint of the thumb (e.g., rhizarthrosis) as often seen among older ones; otherwise, a nice long game may be paid for with increased pain.

Whereas the choice of assistive devices demonstrated above needed no or few customization after industrial manufacturing, we come now to examples of individual adaptation on a larger scale.

Lateral grip with holding the key between the thumb and the medial side of the index finger is beyond the abilities of this tetraplegic patient. Figure 19.8a and b show an assistive device with T-shaped handle. It was produced using thermoplastic material that allows for exact adaptation to the anatomic conditions of the hand. This offers best grip and allows the patient to manipulate his key accurately.

After replantation of the distal phalanx of the thumb the wound area needs to be protected from any disturbances to the healing process. Figure 19.8c shows the solution the patient and his therapist found to enable handwriting without delay.

The four photos that make up Fig. 19.9 illustrate how important braces and splints are in some cases where one pathological condition fosters the other when no correction of joint displacements is offered. Here thermoplastic adaptation of a preformed lightweight ulnar brace limits hyperextension in the metacarpophalangeal joint and by this also improves functional competence.

The patient in Fig. 19.10 suffers from a lesion of the radial nerve resulting in paresis with drop hand. An individually adapted spine serves not only physiological positioning of the wrist but restores grip function partially so that the patient is able to hold a mug.

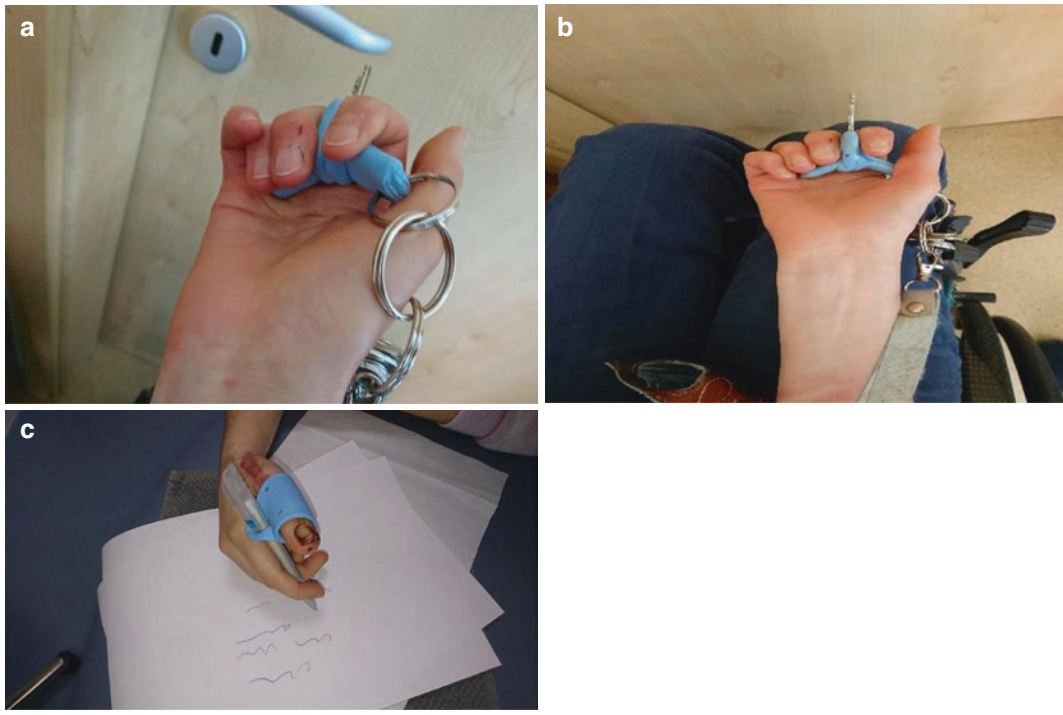

Fig. 19.8 (**a**, **b**) Tetraplegic patient using a T-shaped handle and (**c**) protecting device enabling writing. (Published with kind permission of © B. Peltner 2018. All rights reserved)

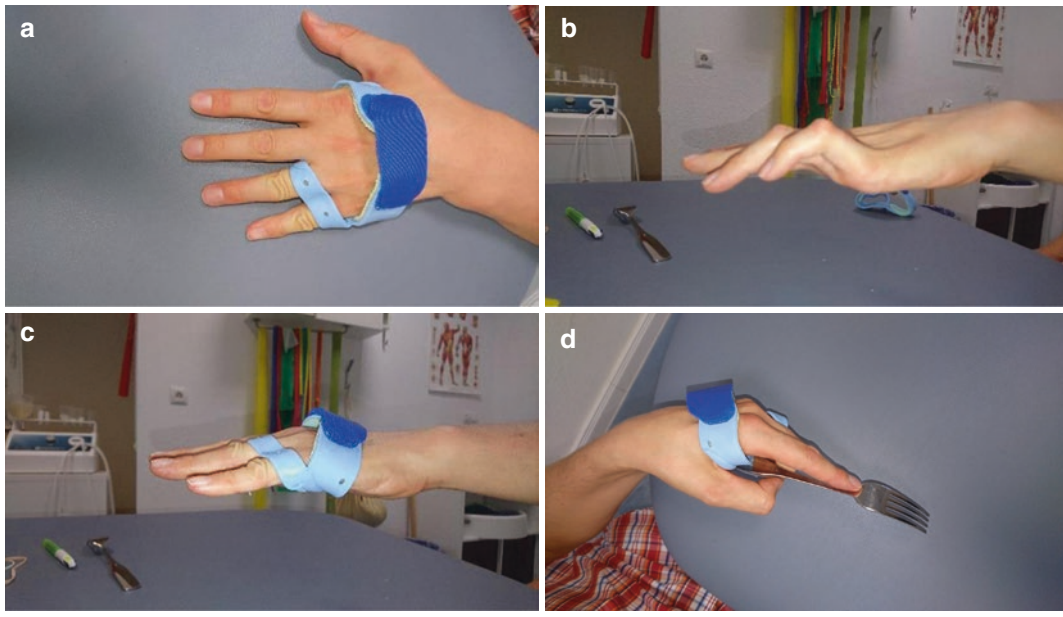

Fig. 19.9 (**a**) Patient with hyperextension in the metacarpophalangeal joints and (**b**–**d**) with ulnar brace. (Published with kind permission of © B. Peltner 2018. All rights reserved)

Fig. 19.10 (**a**) Patient with lesion of the radial nerve and (**b**) with individually adapted spine. (Published with kind permission of © B. Peltner 2018. All rights reserved)

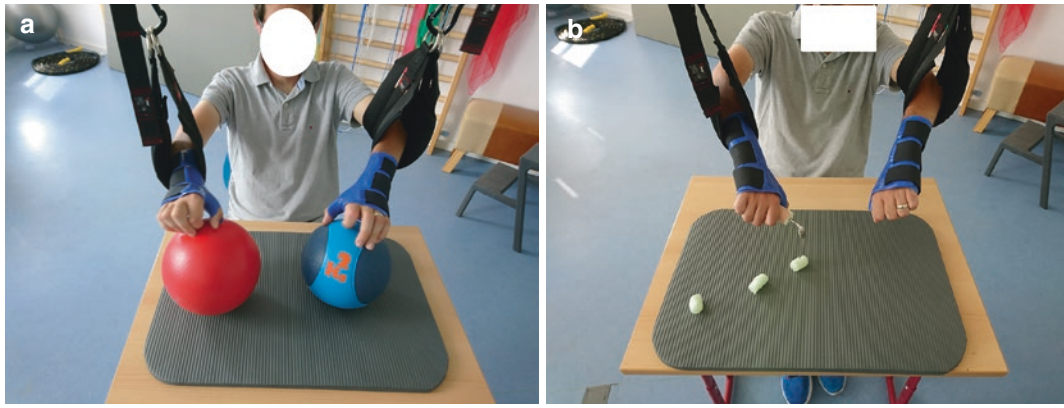

Fig. 19.11 (**a**) Patient with damage of the brachial plexus and (**b**) with silicon ortheses. (Published with kind permission of © B. Peltner 2018. All rights reserved)

The phenomenon that assistive devices can serve distal functionality by ensuring proximal stabilization is demonstrated in Fig. 19.11. Probably damage of the brachial plexus of toxic origin caused bilateral degeneration of the median, radial, and ulnar nerves of this patient in a so-called Help-Arm as training device. Silicon ortheses provide extension of the wrists. In this position flexion of fingers is of much greater functional benefit than with palmar wrist flexion.

Figure 19.12 shows two patients with paresis of the radial nerve. Thermoplastic material that can be molded at a temperature of 70–75 °C was used to construct individual dynamic splints that correct the position of the wrist and offer several anchorage points for slings. The patient in Fig. 19.12a wears a splint that is nearly closed at the dorsal side of the wrist to keep it in physiological position. The other patient (Fig. 19.12b–d) needs more support so that a ventral position was chosen. After stabilizing the intermediate phalanges by means of sling bandages, active flexion in the distal interphalangeal joints can be used functionally. Finding out the optimum tension for sling bandages to assist in extension of the proximal interphalangeal joint without hindering blood and lymph circulation needs a lot of experience. Broad Velcro straps fix the splint without pressure.

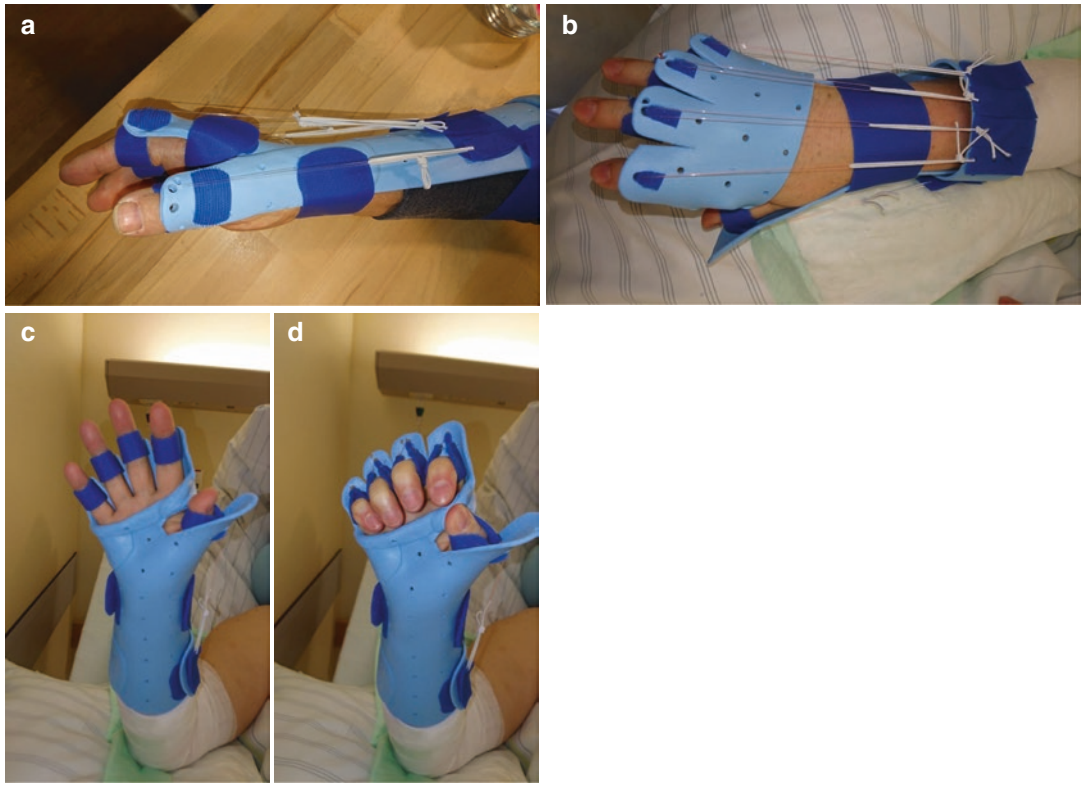

Fig. 19.12 (**a**) Splint dorsal position and (**b**–**d**) splint ventral position of the wrist. (Published with kind permission of © B. Peltner 2018. All rights reserved)

Summary

Assistive devices that protect joint structures, help compensate functional deficits, and reduce pain should be taken into consideration early as the various negative effects of immobilization and/or nonuse grow quickly. Some devices just have to be chosen correctly without need for further adaptation, some can easily be adapted and some must be built by experts to be of help. Training the patient to make optimum use of his aid is the necessary step after getting the device – otherwise the aim is not reached. Feedback given by users and therapists should motivate inventors and constructors of assistive devices to improve their products and develop more according to our changing requirements.

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20 Sports and Recreational Adaptations for Amputee Hand

Yaşar Tatar

Individuals with disabilities benefit greatly when they participate in sports and community recreation settings. Amputation may negatively influence the psychological and physical well-being, mobility, and social life of individuals. Participation in team sports and recreation may provide physical, psychologic, and emotional benefits for the amputee [1]. The improvements in technology, services, and communications in the last decades are creating many new lifestyle opportunities for amputees. Improved lives and lifestyles pertaining to this expansion provide additional free time for sports and recreational activities. Despite the fact that sports and recreation provide physical, psychologic, and emotional benefits for the amputee, scientific data concerning the efficiency, reliability, and functionality for the sport prostheses or prosthetic adaptations are scarce [2]. This chapter aims to illustrate a comprehensive look at sports and recreational adaptations for amputee hand.

There are crucial factors that should be taken into account for amputee sports activities. As a result of amputation or limb deformity, body surface will decrease, and heat regulation will be disturbed; sweating will increase in order to cool the remaining body parts. Consequently, it is quite important to choose appropriate clothes. Ambient temperature, stump, and socket hygiene are also important. Prosthetic use increases the energy expenditure and sweating; therefore, it leads to bacterial and fungal growth in the socket. The athlete should be observed and adequate fluid supplementation given throughout the training periods, including preparation and posttraining [3]. In the early years, when silicone elastomers were used, this problem was more common. Currently, this problem has been partially overcome by making new-generation air permeable silicone elastomers and specially designed production for stump dimensions. Despite the technological developments and light-weight products, amputees' mobility has decreased, and the energy consumption has increased due to the necessity to make compensatory movements [4]. Due to their easy fatigability, amputees are unwilling to participate in exercise; thus weight gain takes place related to inactive life [5]. Abrasions, pressure sores, blisters, and redness are particularly common in unsuitable socket use [3, 6, 7]. Arthritis can also be seen in quite early times of prosthetic use as a result of mechanical failure [3, 6].

Exercising strengthens the stump, increases blood circulation, prevents muscle atrophy, and improves body alignment, posture, and walking [6]. Muscle strengthening and endurance studies should include the development of all parts of the limb, and balance should be ensured [5]. Proper

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posture has an indispensable importance. In patients with upper extremity amputations, injuries in the cervical and even thoracic vertebrae are common due to imbalanced and inadequate movement during training and competitions. An imbalance in body weight occurs because there is less weight on the side of the amputation, and this imbalance may cause the spine to curve in the direction of the amputation. Therefore, in unilateral upper limb amputees, scoliosis is inevitably seen because of the imbalance [7].

Due to the lack of options in strength and endurance training, cardiovascular fitness of bilateral amputees is particularly poorer than their age-matched peers, [5, 8]. In a study which compared traumatic amputees with healthy sedentary people, physical condition levels of amputees were found lower than sedentary people [8]. Recommended aerobic activities are swimming and ergometric studies. According to studies, exercise also increases muscle strength, stamina, and locomotor performance and reduces cardiovascular risk factors as well as local contributions on the amputated side. As a result of resistance training, max VO2 and strength were improved [9].

The demands for adaptation of sports and recreation in upper extremity prostheses began to increase toward the late 1970s. The increase in the willingness of disabled people to sports has led to an increase in the demands of upper extremity amputees to suppliers. The upper extremity also has disadvantages compared to the lower extremity with regard to the use of prosthetic and adaptive equipment due to the small amount of soft tissue, high number of bone protrusions, and inability to work under load. Scientific studies on the efficiency of prosthesis and adaptations used in sports and exercise are very few and insufficient. Current studies mostly focus on lower extremity prostheses. Basically, there are no scientific evidence in areas such as biomechanical compliance and performance evaluations of these equipment; thus users prefer product according to their personal experience and manufacturer information. In particular, scientific data on range of motion and propulsion of elastic energy storage are needed.

Strengthening and flexibility studies in those with limitation of movement will ensure that physical fitness is at the most appropriate level. Range of motion is an essential basis for all activities. The frailty or lack of motion control will lead to the development of inappropriate motor skill patterns. Bilateral upper extremity amputees will be successful in activities that use lower limbs. Brockport Physical Fitness Test is the most suitable test for assessing musculoskeletal functions (flexibility, muscle strength, endurance), body composition, and aerobic functionality in persons with disabilities [10].

The evaluation of the prosthesis by specialized teams will ensure that possible simple problems are solved and functionality is increased. Basically, it is expected that the person will be able to wear the prosthesis independently and it is important that the terminal device can be opened and closed in the appropriate positions and can capture objects with different sizes. In particular, it is important that unilateral and transradial prosthesis can support self-care activities. It is further expected that most amputees improve fine motor skills in bimanual tasks and return to work life. Although sports and exercise activities can be assessed partially by testing the skills that needed in daily life, they will not be able to meet the needs of exercise. It is not possible to evaluate the hand which is used in the activities performed with motor skills and the hand that will be used in an exercise under heavy load in the same test. The evaluation will also vary depending on the amputation level. Prosthetic hand that may be functional in the transradial amputee who wants to play billiards may be inadequate in the transfemoral amputee. Although various tests are used to evaluate the prosthesis and its functionality during daily activities, more tests are needed to evaluate the functionality of prosthesis and adaptive equipment during sports and exercise. The function speed is the most commonly used parameter in these tests. Some tests evaluate functions such as grabbing and releasing objects of various shapes and sizes while there are also tests where the use of the prosthesis in different planes is evaluated. These are important elements of prosthetic skills but also insufficient to

evaluate the functional use of prosthesis. Among these tests, UNB test (The University of New Brunswick Test of Prosthetic Function) which measures skill and spontaneity of prosthetic use consists of activities that a child is confronted with in his daily life [11]. The PUFI (Prosthetic Upper extremity Functional Index) test was also developed to evaluate efficiency of prosthetic use during the child's daily life [12]. Evaluates and compares functions with and without prosthesis. Upper extremity functional index (UEFI) evaluates the functional disability of the upper extremities with daily living questions [13].

The fact that medical rehabilitation periods are often difficult and tedious has brought forth a search for alternatives. Especially in children with physical disabilities, this approach has been compulsory in order to ensure the sustainability of rehabilitation. Participation in exercise and sport activities often results from the desire to maintain the activity of the person in the routine prior to amputation. These activities will also provide an opportunity for socialization as well as physical and psychological contribution to amputee. Upper extremity is composed of complex structures in terms of functionality, and prosthetic technology has a low level of contribution to the upper limb. Thus, exercise and sports preferences of the upper extremity amputees are predominantly in favor of lower extremity usage required activities [14]. Since upper extremity amputation will also disrupt body balance, sports and exercises that involved the upper extremity are necessary in order to maintain symmetry of the body and prevent muscle atrophy. Aiding equipment/devices make it possible for upper extremity amputees to participate in a variety of sports activities. In today's world, technologies are blended within almost all aspects of sports, even in swimming, where it virtually seems that no technology is involved. Participation in sports and performance enhancing can only be realized with the application and improvement of new technology. Handicapped athletes are the pioneer in the quest to the betterment of the technology by allowing the devices to be tried on them first. Nowadays, the needs of amputees to resume social life while sports and recreational activities becoming crucial parts of their individual experience by using customer tailored prostheses, is the driving force for manufactureres to diversify their appropriate products. The latest technologies improved with the intention to remove the shortcomings of the previously designed ones have proved to be much better in terms of weight and functionality [15].

In sports conducted by the handicapped what matters most is the customized and activity-specific equipment as well as the environmental technology. According to the International Classification of Functioning, Disability and Health (ICF) standards, there are three categories outlined in terms of functionality of the equipment in question: (a) personal equipment, (b) activity-specific equipment, and (c) environmental technology. Personalized equipment is aimed at developing either the bodily functions or structure, or both, of the amputee through main elements such as prosthesis, wheelchair, hearing-aid, memory board, glasses, etc. Consistency of the materials can change in a wide range from little arrangements (extending strips, changing material type) to complex designs that required customization (custom-made mono-ski) or advanced technology adaptations (personalized tennis racket rack). These changes are considered valuable if they provide optimal functionality. This includes multifactorial assessments, including also the time and energy spent besides costs to provide them [16]. There are many factors that need to be considered when playing sports or recreation modifications that require basic and advanced technology. Most important factor is their effectivity [16]. First of all, applications for low-tech modifications such as linking racket to the hand do not provide exactly the same function; however, it is always feasible, cost-effective, easily reachable, and allowing the participation of a large number of people. Participation in many sports activities can be achieved with such simple arrangements. Advanced technological modifications are more suitable for professional athletes. In these groups of patients, besides adaptation principles, internationally valid official competition limits will also determine the product to be used.

Equipment designed in order to enhance performance at a specific sports or activity, for example to enable a paraplegic person to go mountain climbing, is called activity-specific equipment. The technology applied to change the facility or vicinity including changing rooms, the showers, placing necessary warning signs where the sports in question is played is called environmental technology [14]. No matter what the type of the equipment is, the main point is to adapt the equipment totally to the handicapped athlete in terms of both effective usage and maximum safety. Taking into consideration the handicapped athletes' body and the physical motor development in constant exchange with his/her body, the environmental protection must focus on enabling the handicapped athletes to conduct the movements freely [17].

Adapting activities can be held in order to create equal grounds for the handicapped to participate in sports activities. The goal is the provision of quality recreation programs and environments for all members of the community, including people with disabilities. The principles for adapting activities in recreation programs and settings were classified as follows [18, 19]:

- *Principle#1 Adapt only when it is necessary:* After receiving feedback from participants such as the things participants can and cannot do, the process of adaptation may be initiated by starting from the simplest one. Adaptation cannot be against the rules and the law. Adaptation is inevitable to lead the subject to success.
- *Principle#2 Adaptation is individual-based*: Make sure that the adaptations, which are considered and designed for an activity, are in fact relevant to a particular participant. In general, participants of recreational activities purchase modified or specialized equipment (e.g., beeping balls for blinds) or hire additional staff assuming the needs of prospective participants with disabilities.
- *Principle#3 Adaptations must be regarded as transitional:* Adaptation can be reassessed in line with emerging new needs after participation is established. Adaptations are considered as transitional until the person can learn the skills and behaviors to participate in the standard or typical way. Some modifications can be necessary. However, with the current technological advancements, preventing people with disabilities dependent on these adaptations, and thereby further limiting future options and opportunities for these people to enjoy these activities is no longer in question.
- *Principle#4 Adapt for congruence:* Adaptation must be harmonious (should not spoil the compliance). In addition to commonly applied adaptations, healthy partners may not regard the adaptations which affect others positively as acceptable. Adaptations or modifications are aimed to make sense for both the person using them and also to others observing their use. Unique or extraordinary adaptations and modifications can have unforeseen effects of further inclusion and acceptance of the person with a disability. The adaptations in question may appear too strange or, more importantly to youngsters, unfair. As a matter of fact, they help bolster stereotypes about disability and underscore how different "these people" are.
- *Principle#5 Adaptations must be accessible:* The adaptive equipment must be designed to be utilized at a number of activities and, at the same time, have to be within reach of others. Some other very expensive and special equipment should be taken into account in terms of their contribution. Adaptive equipment, materials, and support may vary according to a peculiar recreational environment. If the purchased materials and services are not specialized then it may be considered that the participants using these adaptations are deprived of any chances to use them in a variety of settings.

Moreover, a number of companies sell a specialized equipment especially to be marketed to the disability community. Unfortunately, because of the specialization in types of material as well as the target customer, these products are relatively expensive and difficult to obtain. The average person may not be able to purchase these products.

Aerospace materials, such as carbon fiber and titanium, are now commonly incorporated into high-performance prosthetic limbs [14]. As prostheses improve, amputee function improves. Such improved function is often accompanied by increased desire to participate in additional activities and/or further improvements in performance, especially with respect to athletics and recreation. As such, there have been continued developments regarding task-specific prostheses and adaptive equipment.

It is also important that the person gains from the equipment and whether the disability will be affected by the equipment [16]. Orthotics, prosthesis, or accessory equipment can prevent performing real motor functions [20]**.** Inappropriate prosthesis can lead to soft tissue damage [16].

First of all, the first step in providing a prosthetic or adaptive solution is understanding the biomechanics involved in performing a particular sport. Bilateral hand function (volar hand surface control) is needed rather than traditional opposed thumb (three chuck pinch) prehension for certain sports, such as basketball, volleyball, and soccer while multiple degrees of freedom in the torso and arms efficient energy transfer is crucial for sports, such as baseball and golf. Safety is another factor that should be considered while performing sports by amputee. To avoid the user and other players from injury, covering prosthesis by a stretchable, soft-padded cover or neoprene wetsuit material is a solution that may overcome safety problems.

The absence of the limb will cause problems in terms of balance and leverage, especially when performing resistance activities. If the socket can distribute loads equally, prosthesis use will be possible [19]**.** Amputees use effective prosthesis in many activities; however, they prefer to perform some activities without prosthesis. The prostheses that they use are not intended to cause harm to others and not to give much advantage to their competitors [3]**.** Prosthesis and aiding equipment applications in upper extremity amputations are utilized more commonly in recreational activities than they are used in competitive sports. The performance of the athlete with an amputated upper extremity depends on the tailored design of the prosthesis for the athlete in question. Each element, e.g., socket design, material used, adjustments, and all parts, affects the performance of the athlete. The other crucial factor is the physical condition of the amputee. No matter how well the prosthesis is designed, the physical condition cannot make up the shortcomings of a limited ROM or insufficient power. At the beginning of the sports prosthesis, the capacity and needs of the amputee should be understood very well [18]. Although some main factors, e.g., the length of the stump, constitute the backbone of the socket design, the type of sport plays a crucial role in determining the socket model. In transradial amputees, it is preferable to provide the suspension through the triceps cuff which is connected to the skin or similar flexible equipment during the exercise and sport. This cuff which is expected to restrict the ROM will also reduce the problems that may arise from the mobilization of the socket on the stump. The applications of roll-on silicon elastomers and especially shuttle-lock systems provide advantages for both fixing the socket position and load bearing [18]. However, it is necessary to use the prosthesis as externally powered with the help of an external harness in sports applications, because of utilizing myoelectric and electromechanical arms for the terminal end to function. Especially during activities that require lifting great weights (weightlifting) externally powered designs are a necessity. The correct reciprocal transfer of the load between the body and the socket will result in efficient use. Therefore, the use of external harness is a requirement in terms of providing biofeedback.

Proper alignment of the prosthesis will have a positive impact on performance, especially in hitting the target sports such as archery. Prostheses which have improper alignment can cause inappropriate pressures and injuries in sports that perform with loading such as weightlifting. If the load that came to the socket is not properly equilibrate, it may cause overloading of the anatomical suspension regions and osseous prominences, abnormal opening of the joints and injury. It is essential to increase the socket resistance to provide the load balance; however, socket thickness and weight

should not increase under these improvements. Using carbon fibers as a material has changed the behavior of prosthetic sockets under the load in a positive way. Additionally, liner systems such as silicon and copolymers decrease pressures over extremities especially in activities that perform with heavy loads besides their benefits to ease suspensions.

The design of the terminal device plays an important role because in all applications the main focus and function is on the grabbing/holding. These bettered suspension systems in question, and strong, lightweight materials provide an opportunity for the use of terminal devices (i.e., accessories that are specifically designed to accomplish particular activities). As a terminal device, hook is frequently used. Participation demands for different activities have made it possible to special designed hands for activities. Occasionally, the special equipment for activity that is not in the form of a hand is used as a terminal device. The developments in polymer technology have provided variety in this regard. Wrist connection units are also specially designed for activity. It is preferred that the wrist units allow the terminal device to be easily dismounted if necessary. The wrist connection unit may be preferred as fixed type, or the adjustable friction featured.

A prosthesis which is used for cycling must be light and used in different positions during riding. Therefore, specialized cycling prostheses are needed for cycling competitions. In case of above-elbow amputation level, attaching an elbow unit to the prosthetic device that can be locked at different angles or can be left unlocked, allowing the cyclist to assume various elbow positions during a race will be helpful.

As the amputation goes proximally, more complex structures are needed because of increasing number of amputated joints. If amputated limb side is the person's dominant hand, this status can change the designs. Upper extremity amputees can use prosthetic or adaptive equipment in sports in which upper extremity usage is required such as golf, swimming, cycling, basketball, baseball, gymnastic, and billiard (Figs. 20.1, 20.2, 20.3, 20.4, 20.5, and 20.6). However, the use of adaptive equipment is not allowed in some international competition sports such as swimming.

Even unilateral upper limb amputees can play golf without a prosthetic adaptation; he/she may face decreased control and speed. When using prosthetics in golf, the golf club can be attached directly to the prosthesis at the distal end of the socket by using a special adaptor.

Sport activities that require catching a ball will bring additional problems to the amputee.

Fig. 20.1 Upper extremities amputated athlete with apparatus for grasping golf club. (www.trsprosthetics.com COLORADO USA)

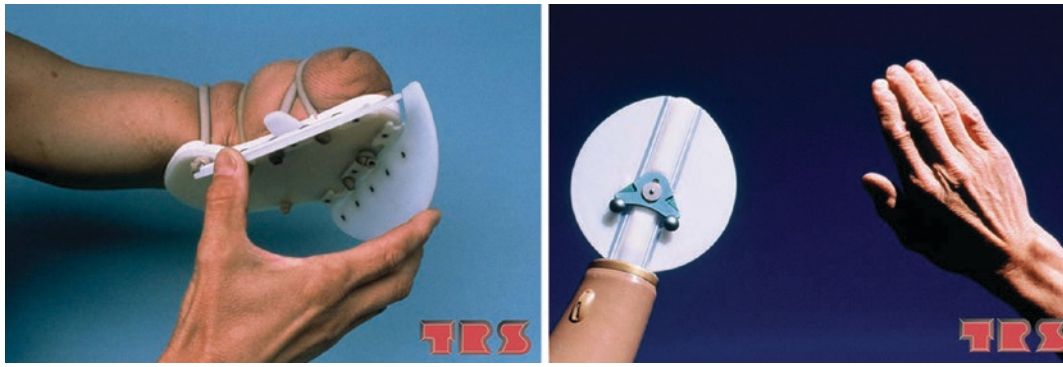

Fig. 20.2 Specially designed swim hands. (www.trsprosthetics.com COLORADO USA)

Fig. 20.3 Hand models designed especially for basketball. (www.trsprosthetics.com COLORADO USA)

Amputee may be able to do this using a prosthetic hand, as well as capture it with the sound hand. In any case, the forearm must be able to supine for the capture function. This may not be possible in short transradial amputees. Mesh-like structured materials can be used to catch the ball in different sports (baseball glove) or elastic material, large spherical surfaces can be used at the terminal ends (basketball) (Fig. 20.3). This is the only way in which imitating the volar face of the hand for tasks that require grabbing with both hands was possible. Although there are some advantages

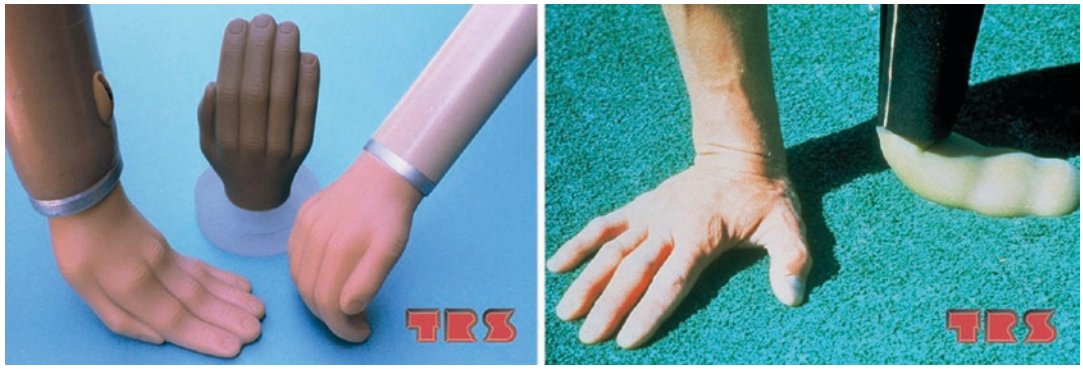

Fig. 20.4 Hand models designed especially for gymnastic. (www.trsprosthetics.com COLORADO USA)

Fig. 20.5 Hand models designed especially for bike/motorbike. (www.trsprosthetics.com COLORADO USA)

Fig. 20.6 Hand model designed especially for billiard. (www.trsprosthetics.com COLORADO USA)

of having the hands placed with a small flexion angle in most prostheses, this nonanatomic angulation would be a problem in sports that require full extension.

The transfer of energy should be balanced between ternary of arm-prosthesis-club and controlled when playing golf. Conventional wrist components and terminal devices do not have capability for this balance distribution. Golf sport requires designs that can biomechanically imitate wrist-forearm smooth swing movements and its energy transfer (Fig. 20.1).

Volar face of the hand must be used for pushing while swimming. Although the flipper-like structures are suitable in the stroke phase function, they adversely affect the recovery phase because of their resistance creation. In order to overcome this, it is possible to convert the hand to the friction-reducing anatomical position in the recovery phase; however, the wing-like terminal ends closure in the recovery phase may be preferred (Fig. 20.2). Fixing the flipper-like structures used in swimming to

the forearm is possible with waterproof socket models, as well as simple solutions are also possible. Although amputees prefer swimming without prosthesis, its usage is also beneficial for rehabilitative purposes. Some sports such as canoeing and kayaking require a wide range of motion. It may not always be possible for the prosthetic hand to perform the repositioning to adapt to new positions without contact with the shovel.

The most successful approach focuses on activity-specific prosthetic attachments designed to imitate the biomechanics of the human hand and arm in that particular activity. This has paved the way for the development of products which enable many amputees to perform both recreationally and competitively with their two-handed rivals. Sports activities shall lead us to further advancement of prosthetic science, by bringing about prosthetic revision and innovation in order to meet the emerging needs for new conditions or requirements [14].

The start of utilizing energy-saving elastomers both as terminal end and as wrist interconnection element has been a turning point for upper extremity prosthesis. Sufficient and satisfying solutions could be put forth especially for activities requiring sharp gripping and control of a racket/club, e.g., in golf, baseball, etc. The reason why wrist attachments have been developed was to solve the challenges for the need to have a firm grip on the club when maintaining a flexible wrist. The wrist attachments in question are made of an elastomer shaft that leads from the prosthetic arm to a gripping tubular component that matches the diameter of the club. The other hand of the amputee wraps around this grip as it would wrap around the opposite thumb to create a full hold. The function of the elastomer shaft is to allow the arms to synchronize throughout the swing [17].

With all things said and taken into consideration, high-tech products may not always provide more satisfying results than those products with less complicated systems. Cost-effective but functional products are used more commonly and received better by the amputees. The best qualities of the high-tech products that draw attention are being lighter and more reliable. The first users set the standards and draw a horizon for the path to take in the future [21].

The main problem in the participation of people with disabilities in sportive activities is the competition of equitable people with similar disabilities. For this purpose, the classification practices working on equality in the game have been produced. In the early years of these sports, the most important problem arose from the lack of classification systems and this situation resulted in the disadvantage of those with advanced disabilities. In the process, the three basic classification systems were tried and the functional classification system came to the forefront from these systems with different advantages. This classification is considered valid by most federations.

Medical Classification The aim of this classification is to race those who have a similar kind of disability, regardless of the severity [22]. It was based on spinal colon lesions, but the content of the medical classification system was expanded as a result of increasing prominence of other disabled groups, especially amputee athletes with wheelchair sports. In medical classification, the expert who has medical degree makes a classification based on the anatomical structure. This classification is considered to be more objective; however, it should be kept in mind that the anatomical difference which is taken as a basis may not always be enough to reflect the sporting performance of the person, and also there will be many features that will differ from each other while a number of characteristics are even common.

Classification by Sportive Performance In this classification, the criterias such as the best performance of the athlete in previous periods, the best time he has made are taken as a basis. But it was abandoned due to loss of relevance.

Functional Classification It is the classification based on the function that the person can do without considering the type of disability

[22]. The system was edited by Horst Strohkendl and tested in wheelchair basketball for the first time in the Paralympics. This system, which is developed upon the disadvantages of anatomical classification, is based on whether the individual can show the desired skills alone or in the group. System is classified players according to the basic movements or functions that required for activity regardless of athletes' experience, education, or skills. The classifier must know the performing characteristics of that sport, and an expert on disability must attend the event as an observer. The disadvantage of this method is that athletes who are malevolent can mislead experts. Because of the functional difference between beginners and experienced athletes may be a problem to assess accurately in this classification system. Therefore, the player is kept under observation in the first years. This classification is considered valid by most federations after Paralympics in 1992 [6].

One of the most important problems of disabled sports is who can participate in these sports. In other words, what should be the limit of the person's disability so that he can compete in this category of sports? In this regard, concept of the minimal disability has been developed and every international federation has declared what is the minimum disability required for their field. The basis of the ISOD (International Sports Federation of the Disabled) classification that used for amputees depends on acquired or dysmelia-like amputations. For extremities, complete or nearly complete amputation of the wrist or ankle is considered as a minimal disability. Actually, another factor that determine minimal disability is sportive activity that made by amputee. For instance, upper extremity functions are more important for volleyball players than football players. The classification system that used in this group is different from the patients who have spinal canal lesions or amputations, it is based on anatomical and pathological findings. In these group, muscle strength and joint mobility in the lower and upper extremities, shortness in one of the lower extremities, disability in the back or trunk, and status of dysmelia are exactly evaluated and then placed to most suitable ISOD category.

The system used in the classification of amputee sports is as follows:

- A1: Bilateral above the knee lower limb amputations
- A2: Unilateral above the knee lower limb amputations
- A3: Bilateral below the knee lower limb amputations
- A4: Unilateral below the knee lower limb amputations
- A5: Bilateral above the elbow upper limb amputations
- A6: Unilateral above the elbow upper limb amputations
- A7: Bilateral below the elbow upper limb amputations
- A8: Unilateral below the elbow upper limb amputations
- A9: Combination of amputations of the upper and lower limbs

Specialized sport prostheses could potentially improve athletic performance of professional athletes or amputees who participate in competitive sports. Close collaboration with a sport coach and prosthetic technician is crucial to achieve the most suitable prosthesis that is fitted to individual needs and capabilities. Thence, a prosthesis can be modified and adapted to target specific individual needs related to its athletic and physiological characteristics. Future studies should focus on the improving technical characteristics and performance of sport prostheses and prosthetic adaptations for sports.

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The Functional Capacity of the Humanlike Robotic Hands

21

Zhe Xu

Introduction

Human hands can perform many dexterous grasping and manipulation tasks. Hand dexterity is the ability to precisely control movements and forces using all the hand's degrees of freedom (DOFs) to perform a variety of tasks. Examples include the ability to play musical instruments, use chopsticks, gesture, and perform daily tasks such as cooking and writing. Currently, we are far from replicating human hand dexterity in robotic hands.

A number of robotic hands have been designed to meet a variety of goals. Most existing robotic hands meet specific task requirements using state-of-the-art technology; they were not designed as a tool for scientific investigation. For example, since prosthetic hands must be comfortably fitted to humans, they must be made of lightweight materials. In contrast, weight is not a constraint for industrial grippers, which must conform to a specific object's shape to assure a stable and guaranteed uniform grasp. Two types of robotic hands will be discussed in this section. First, we will describe prosthetic hands, which are designed for comfort, lightweight, and ease of control while accommodating societal norms of size and hand appearance. Design goals for these prostheses often emphasize their functional needs. Second, we will examine dexterous hands, which work in unstructured environments for applications such as space exploration and personal assistance. These hands often mimic the human hand form, degrees of freedom, and motion patterns. Neither type of robotic hand currently exhibits the robust manipulation abilities of the human hand.

High levels of dexterity are achieved in the human hand due to a combination of hand biomechanics (hardware) and neural controls (software). The benefits of investigating anthropomorphic robotic hands have been widely acknowledged. However, it is also widely accepted that the cost of time and funding on developing a research-oriented, custom-designed anthropomorphic robotic hand is often prohibitive. The control of a robotic hand can be affected by many factors, such as the finger length, the range of motion (ROM) of the joints, the weight of the robotic hand, or transmission types. Many researchers had to shape their control goals due to the limits of commercially available anthropomorphic robotic hands as even the slightest modification on those off-the-shelf robotic hands could easily result in months of waiting.

For those researchers focusing on the hardware aspects of anthropomorphic robotic hands, it is also challenging to modify the design or improve the functionality of an existing system in a short period of time. This is because each of the design iterations needs to go through the validation of physical tests before any useful

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information can be collected for planning any improvement. Therefore simulation as a promising tool to help evaluate the performance of robotic hands has been adopted to speed up the design process [1].

Many anthropomorphic robotic hands were designed to be cable-driven [2–12]. This approach has several appealing advantages. On the one hand, it is intuitive to mimic the muscle-tendon mechanism of the human hand with cables and wires; on the other hand, a carefully designed cable-driven system is back-drivable, backlash-free, lightweight, and flexible for the robotic hand to choose between being fully actuated and being underactuated depending on the needs of different applications. So far numerous efforts have been put into the development of anthropomorphic robotic hands with cable-driven system. Tremendous progresses have been made, yet the ability of most of the existing robotic hands to perform human-level manipulation tasks remains limited.

In the following sections, we first review related work from aspects of prosthetic and robotic hands, respectively, in section "Related Work," and then explain the importance of adopting human hand taxonomy in anthropomorphic robotic hand research in section "Human Hand Taxonomy." After this, we detail the design and prototyping process of a low-cost 20-DOF anthropomorphic robotic hand in section "Development of a Low-Cost Humanlike Robotic Hand via 3D-Printing," and experimentally evaluate its performance in section "Performance Evaluation of the Robotic Hand." At the end, we conclude the chapter and discuss potential future work in section "Conclusion."

Related Work

The development of advanced prosthetic hands heavily relies on the lessons we learned from investigating anthropomorphic robotic hands. To position our proposed anthropomorphic hand in relation to other prosthetic/robotic hands, we now review representative robotic hands that were designed over the past three decades (see Table 21.1).

Prosthetic Hands

The most frequently used prosthetic hand, a hook-and-cable device designed over a century [23] ago, has only one body-powered degree of freedom. A cable is connected to another part of the body to open/close the hook. Hospitals and insurance companies often provide amputees with these prosthetics at little or no cost. Other prosthetic hands emphasize aesthetics but lack a single degree of freedom [35]. Sophisticated prosthetic hands have one degree of freedom that can be controlled by electromyographic (EMG) signals from the stump [14–16].

The most recent research has focused on developing more functional hands [5, 21, 23, 26]. For example, the i-limb prosthetic hand contains more than 1 DOF and is widely used by amputees. Its popularity shows that amputees desire to have more functional robotic appendages even though they lack the control of human hands. Another critical factor for improving control fidelity is sensory feedback capabilities. Liberating Technologies and i-Limb Hand employ vibration-based sensory feedback that indicates when fingers are experiencing a load [15, 21].

An ideal prosthetic hand would be one that allows natural control through "thoughts" of moving the fingers. Recent studies enable monkeys to control the 3D movement of a robotic arm to achieve self-feeding tasks [36, 37]. Over 30 human arm/hand amputees have received nerve reinnervation surgery to rewire the peripheral nerves that used to go into the hand/arm to the chest muscle instead [38]. The signals amplified by the natural muscle can then be tapped into with surface EMG for prosthetic arm/hand control.

Dexterous/Anthropomorphic Hands

The need for robust and dexterous robotic hands extends to applications such as space exploration and personal assistance. Space exploration entails constant repair of the space station and exposure to environments often dangerous for humans and therefore benefits from robotic help. Personal

Table 21.1 Representative robotic/prosthetic hands

Robotic/prosthetic hands	# identical fingers	# joints/DOF (Total DOFs)[a]	Range of motion	Speed of motion	Activation/transmission method	Types of grasps/manipulation
Hosmer hook [13]	2 split hooks	1/1 (1 DOF)	<human hand	<human hand	Body-powered	Splitting hook pinch
Utah Arm/Liberating/ OttoBock [14–16]	2	T-1/1, I-1/0, M-1/0 (1 DOF)	<human hand	<human hand	EMG signal driven, DC motor, cable	Three- finger pinch
USC/Belgrade [17]	4	T-3/2, I-3/0.5, M-3/0.5, R-3/0.5, P-3/0.5 (4 DOFs)	<human hand	<human hand	DC motor, cable, linkage	Grasp: power & fingertip
Harvard SDM [18]	4	4 2/1 (1 DOF)	>human hand	<human hand	DC motor, cable, elastic joints	Enveloping grasp
Gatech Dusty [19]	1	2/1 (1 DOF)	<human hand	–	DC motor, cable, spring hinge joints	Nonprehensile grasp
Barrett [20]	3	T(Right)-2/1.5, T(Left)-2/1.5, I-2/1 (4 DOFs)	>human hand	≈1.2 human hand	DC motor, worm drives integrated with cable drive and breakaway clutch	Grasp: power & fingertip
i-Limb/Bebonic [21, 22]	4	T-3/1, I-2/1, M-2/1, R-2/1, P-2/1 (5 DOFs)	<human hand	≈human hand	DC motors, gear transmission/lead screw	Grip: key, hook, power & precision; grasp: spherical & palmar
Southampton [23]	4	T-2/2, I-3/1, M-3/1, R-3/1, P-3/1 (6 DOFs)	<human hand	≈0.22 human hand	DC motor, worm-wheel, lead screw	Power grasp, lateral pinch
Cyber [5]	5	T-4/2, I-3/1, M-3/1, R-3/1, P-3/1 (6 DOFs)	≈0.22 human Hand	≈0.38 human hand	Geared DC motor, lead screw, cable, extensor spring	Lateral pinch; grasp: cylindrical, spherical & tripod
Univ. of Tokyo Hand [24]	3	T(R)-3/3, I-2/2, T(L)-3/3 (8 DOFs)	>human hand	=15 human hand	DC motor, harmonic and bevel gear transmission	Grasp: power & fingertip dynamic manipulation
Stanford/JPL [25]	3	T-3/3, I-3/3, M-3/3 (9 DOFs)	>human hand	–	DC motor, cable	Fingertip grasp
DARPA hand [26]	4	T-3/3, I-3/2, M-3/2, R-3/2, P-3/2 (11 DOFs)	<human hand	<human hand	DC motor, cable, gear transmission	Grasp: hook & power
Robonaut [6]	4	T-5/3, I-4/3, M-4/3, R-3/3, P-3/1 (11 DOFs)	≈ human hand	<human hand	DC motor, flex shaft, lead	Grasp: power & fingertip
Naist [27]	4	T-4/3, I-4/3, M-4/3, R-4/3 (12 DOFs)	≈ human hand	≈ human hand	Screw, cable geared DC motor, bevel gears	Lateral pinch power grasp

(continued)

Table 21.1 (continued)

Robotic/prosthetic hands	# identical fingers	# joints/DOF (Total DOFs)[a]	Range of motion	Speed of motion	Activation/transmission method	Types of grasps/manipulation
DLR II [28]	4	T-4/4, I-4/3, M-4/3, R-4/3 (13 DOFs)	>human hand	=3 human hand	DC motor, belt, harmonic drive, bevel gears	Grasp: power & fingertip lateral pinch
Utah/MIT [29]	4	T-4/4, I-4/4, M-4/4, R-4/4 (16 DOFs)	<human hand	≈ 1.82 human hand	Pneumatic actuator, cable	Fingertip grasp/manipulation
Gifu III [30]	4	T-4/4, I-4/3, M-4/3, R-4/3, P-4/3 (16 DOFs)	≈ human hand	≈1.35 human hand	DC motor, gear transmission, linkage mechanism	Power grasp
UB III [7]	4	T-3/4, I-4/4, M-4/3, R-4/2, P-4/3 (16 DOFs)	<human hand	≈ 0.51 human hand	DC motor, cable, helical spring	Grasp: power & fingertip
Shadow [31]	4	T-5/5, I-4/3, M-4/3, R-4/3, P-4/3 (17 DOFs)	≈ human hand	≈ 0.5 human hand	Air muscle, cable, spring	Grasp: fingertip & power
Keio [8]	4	T-4/4, I-4/4, M-4/4, R-4/4, P-4/4 (20 DOFs)	≈ human hand	≈ 2 human hand	Ultrasonic motors, elastic elements, cable	Grasp: power & fingertip lateral pinch
Vanderbilt Univ. [32]	0 (all unique digits)	T-4/2, I-3/1, M-3/1, R & P-3/1 (5 DOFs)	≈ human hand	≈ human hand	DC motors, gear transmission, cable	Lateral pinch; grasp: fingertip, palmar, cylindrical, spherical & tripod
MPL/JHU Hand [33]	0 (all unique digits)	T-4/4, I-4/2, M-4/2, R-4/2, P-4/2 (12 DOFs)	≈ human hand	≈ human hand	DC motors, three-stage planetary/ cycloidal gear transmission	Lateral pinch; grasp: fingertip, palmar, spherical & tripod/manipulation
ACT Hand [10]	0 (all unique digits)	T-5/5, I-4/4, M-4/4 (13 DOFs)	≈ human hand	≈ human hand	DC motor, cable, and spring	Grasp: power & lateral pinch; palmar
Pisa/IIT SoftHand [34]	4	T-3/1, 4 4/1 (2 DOFs)	≈ human hand	≈ human hand	DC motors, cable	Grasp: power, fingertip grasp/ manipulation,
Highly Biomimetic Hand [12]	0 (all unique digits)	T-5/2, I-4/2, M-4/2, R & P-4/1, palm-1 (8 DOFs)	≈ human hand	≈ human hand	DC motor, cable, and spring	Lateral pinch; grasp: power, spherical, tripod, palmar & fingertip grasp/ manipulation

[a]For counting total active DOFs, T, I, M, R, and P denote thumb, index, middle, ring, and pinky (little) finger, respectively

assistants, such as a robotic arm on a wheelchair or a domestic robot, will soon fetch objects in the house for people with disabilities [19].

Most hand/prosthetics assume a human hand shape because it is so versatile (see Fig. 21.1). Several important features have been achieved in these anthropomorphic hands, including high degrees of modularity [28], built-in actuators [8, 27, 28, 30], low weights [7, 8, 30], extra palm DOFs [6, 31] and high-speed finger motion [8, 28–30], and 3D-printing with low cost [11, 39].

It is difficult to design a useful, versatile, and robust anthropomorphic robotic hand. When building one, decisions must be made about the number of fingers, joints, DOFs, range of motion, speed, etc. These decisions are constrained by space and weight considerations. Sophisticated controllers must then be able to handle the hand to produce dexterous movements. Most anthropomorphic hands do not demonstrate human levels of dexterity and dynamics even as a preprogrammed sequence. It is likely that hardware specifications, selected before the hand is built, make it difficult to implement dexterous behavior and that it is inherently difficult to control high DOF systems in a meaningful way. There is also a lack of understanding about how humans realize dexterity both biomechanically and neurologically.

A current trend is to build simpler hands with only a few actuators, augmented by smart mechanisms and passive compliance. For example, BarrettHand [44], one of the most widely used robotic hands in research, attempts to produce robust grasps while providing some versatility [20]. Harvard SDM hand [18] and Gatech

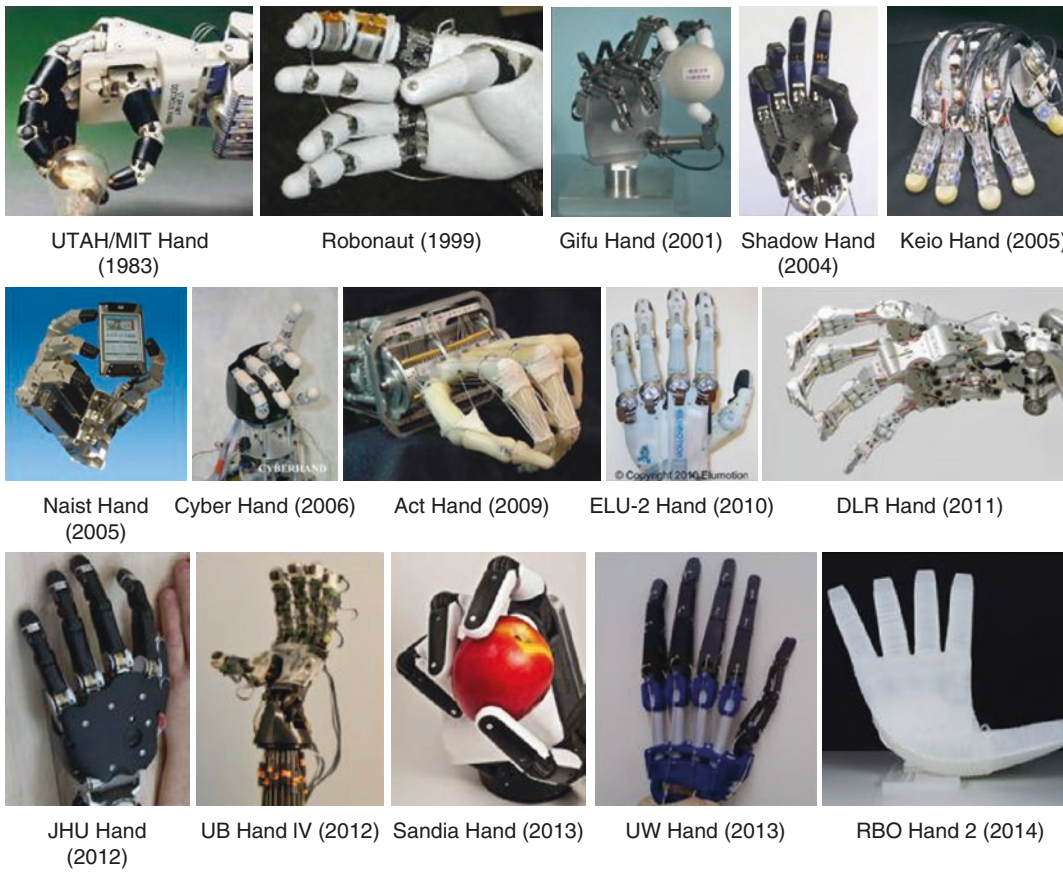

Fig. 21.1 The representative, anthropomorphic robotic hand systems developed in the past [5, 6, 8, 10, 11, 27, 29–31, 33, 39–43]

Dusty manipulator [19] have only 1 DOF but can grasp a wide range of objects. RBO Hand 2 is made of low-cost compliant materials, and can be pneumatically actuated [43]. The underactuation in these hands reduces their overall size, weight, and complexity of usage. Their mechanical structures and joint compliance allow for grasping objects of different size and shape in unstructured environments without sophisticated controls. However, the ability of these hands to execute human-level manipulation tasks remains limited.

Human Hand Taxonomy

The dimensionality of the grasp/manipulation space of the human hand could be very large. Based on individual differences in compliance, biomechanics, kinematics, and neuromuscular control strategies, numerous hand postures could be chosen for picking up the same object. Therefore it is impractical to design a universal anthropomorphic robotic hand that can duplicate all the possible hand functions. In fact, it has been found that our human hands also use a small number of key synergies in most of grasps [45]. Hand synergy allows a group of different hand muscles to be evoked at the same time and demonstrates biological couplings resulted from the formation of branching tendons as shown in Fig. 21.2.

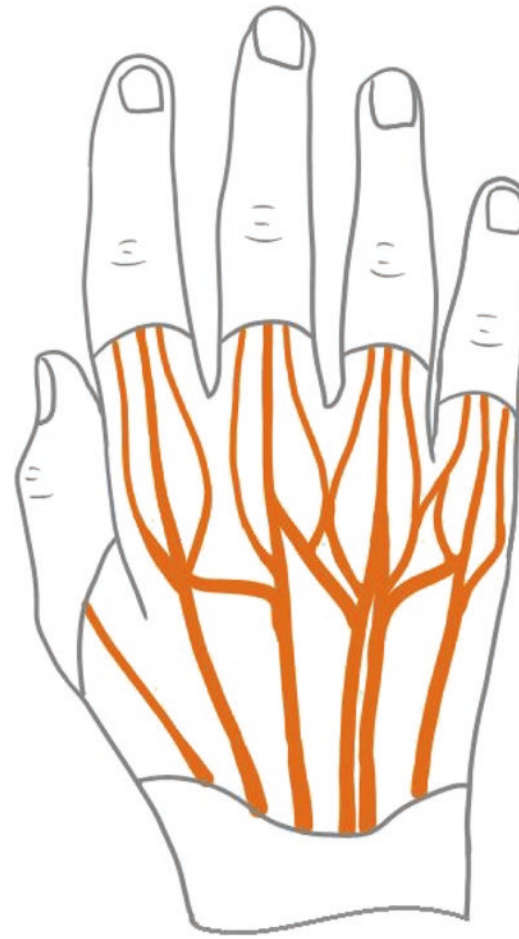

Fig. 21.2 Branching tendons of the human hand (dorsal side)

Thus, before designing and prototyping any anthropomorphic robotic hand, it is crucial to thoroughly understand the human hand anatomy, investigate the taxonomy of the human grasp types, and make sure to take into consideration those environmental constraints that may result in a desirable simplification of the design. In this way, a reasonable set of design goals could be cost-effectively achieved without sacrificing the dexterity of the resulting robotic hand.

As shown in Fig. 21.3, by taking advantage of the important human hand biomechanics, 15 grasp types can be achieved by the highly biomimetic robotic hand we developed in the past [12]. These representative postures are similar to the ones summarized by Cutkosky [46] as the basis for all the common human grasps. In addition, it is interesting to note that as the weight and size of the object getting smaller, the grasping sites are gradually moving from the palm to the fingertips. This suggests the type of objects as an environmental factor can also affect the functional capacity of the robotic hand during its design process. Regarding the common household objects, Kemp's group statistically generated a list of 43 items (see Fig. 21.4) prioritized by 8 amyotrophic lateral sclerosis (ALS) patients for robotic retrieval [47]. This list could be used

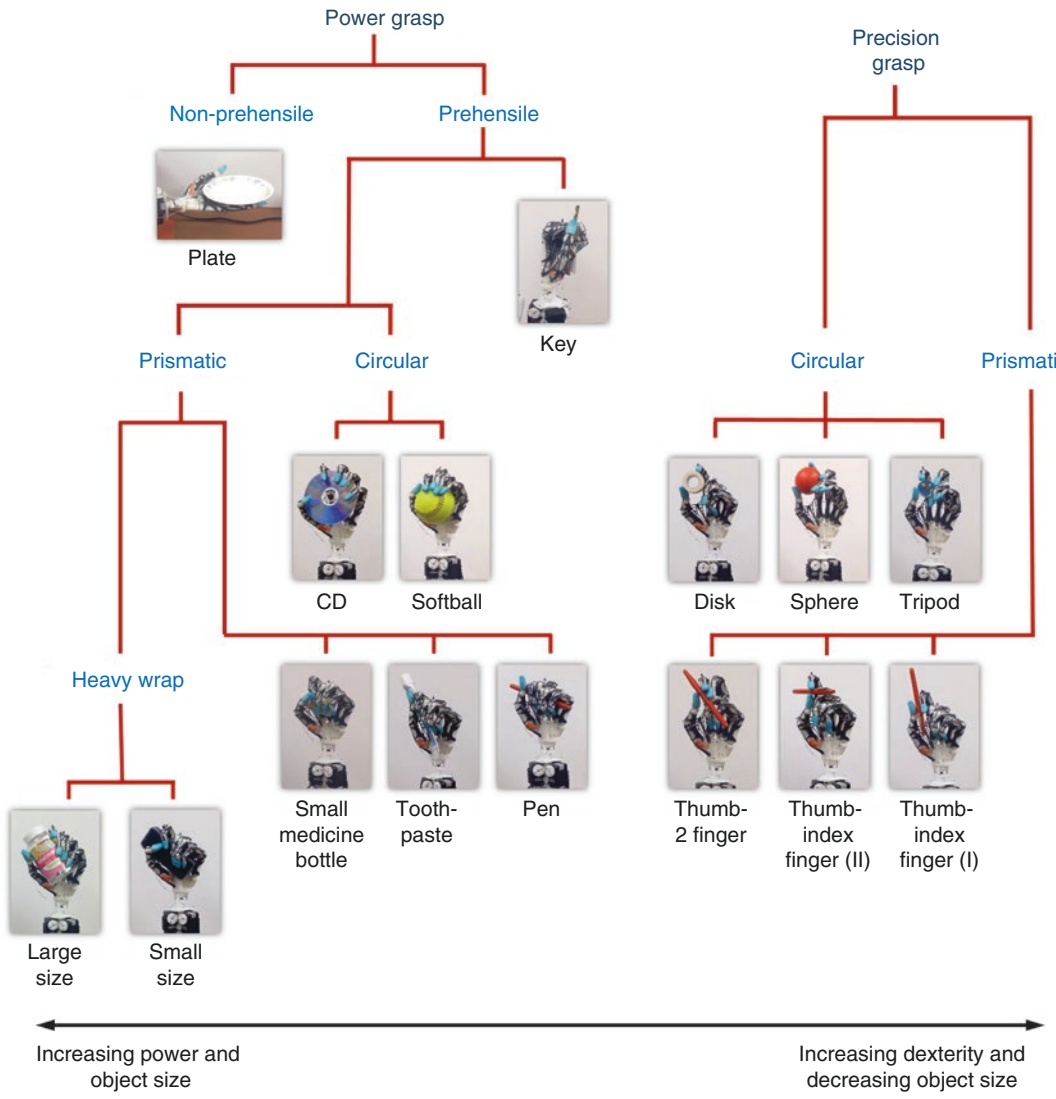

Fig. 21.3 Human hand taxonomy achieved by the Highly Biomimetic Hand [12]

as a reference for answering the question of what types of grasps are most important for people with impaired manipulation ability. Surprisingly, most of the objects from the list could be picked up by using only four basic grasps as shown in Fig. 21.5. That means the dimension of the human hand grasping space can be greatly reduced when the environment is bounded by the common household settings. Similar results were also observed when we later conducted object grasping experiments with the Highly Biomimetic Hand as shown in Fig. 21.19 in Appendix.

Thus, from a practical point of view, useful humanlike robotic hands can be designed to be good at performing a subset of grasp/manipulation tasks that are regarded as essential functions under certain circumstances, such as in health care, space exploration, and prosthetics applications. For different applications, various subsets of the robotic hand motions can also be pro-

Rank	Object Class	Image	Rating Mean	Rating Stdev.	Weight (grams)	Max size (cm)	Rank	Object Class	Image	Rating Mean	Rating Stdev.	Weight (grams)	Max size (cm)
1	TV Remote		6.64	0.57	90	18	22	Credit Card		4.96	2.37	5	8.5
2	Medicine Pill		6.36	1.55	1	2.2	24	Medicine Box		4.88	1.88	25	10
3	Cordless Phone		6.28	1.31	117	15	24	Bill		4.88	2.26	1	13.5
4	Prescription Bottle		6.08	1.31	25	7	26	Straw		4.80	2.22	1	20
4	Fork		6.08	1.12	39	18	26	Magazine		4.80	2.02	206	27.5
6	Glasses		6.00	1.53	23	14	28	Plastic container		4.72	2.16	49	13
7	Toothbrush		5.96	1.81	15	19	29	Newspaper		4.60	2.16	247	31
8	Spoon		5.92	1.19	38	17	29	Non-disposable bottle		4.60	2.00	709	20
9	Cell Phone		5.88	1.69	76	9	31	Pants		4.53	2.47	539	100
10	Toothpaste		5.72	1.84	160	20	31	Shirts		4.53	2.47	229	66
10	Book		5.72	1.46	532	24	33	Wallet		4.48	2.33	116	100
10	Hand Towel		5.72	1.46	65	58	34	Small Pillow		4.44	2.08	240	38
13	Mail		5.60	1.98	22	24	35	Socks		4.40	2.08	41	23
14	Cup / Mug		5.56	1.76	267	12	36	Hairbrush		4.36	2.46	100	24
15	Soap		5.44	2.08	116	9.5	37	Can		4.32	2.08	350	6.4
16	Disposable bottle		5.40	1.66	500	13	38	Coin		4.16	2.51	6	2.5
17	Shoe		5.36	1.98	372	30	39	Walking Cane		3.76	2.47	1140	94
17	Dish Bowl		5.36	1.66	154	13	40	Wrist Watch		3.52	2.35	86	10
19	Keys		5.28	2.28	24	8.5	41	Scissors		3.40	2.33	25	14
20	Dish Plate		5.24	1.85	182	18	42	Purse / Handbag		2.84	2.29	380	24
21	Pen / Penicil		5.04	2.13	3	14	43	Lighter		2.04	1.99	91	6
22	Table Knife		4.96	1.95	76	24							

Fig. 21.4 Prioritized list of household objects from [47]

grammed. For example, a task-oriented robotic hand can be mounted on a wheelchair and pre-programmed with functions crucial to a senior who needs assistance to hold a key to unlock a door or pick up a single pill from the floor. The challenges of developing such robotic hands lie in three major design requirements. Firstly, the mechanical design of the robotic hand needs to be modular and customizable so that researchers focusing on different aspects of the robotic hand project can all use the same platform and collectively contribute to its development. And

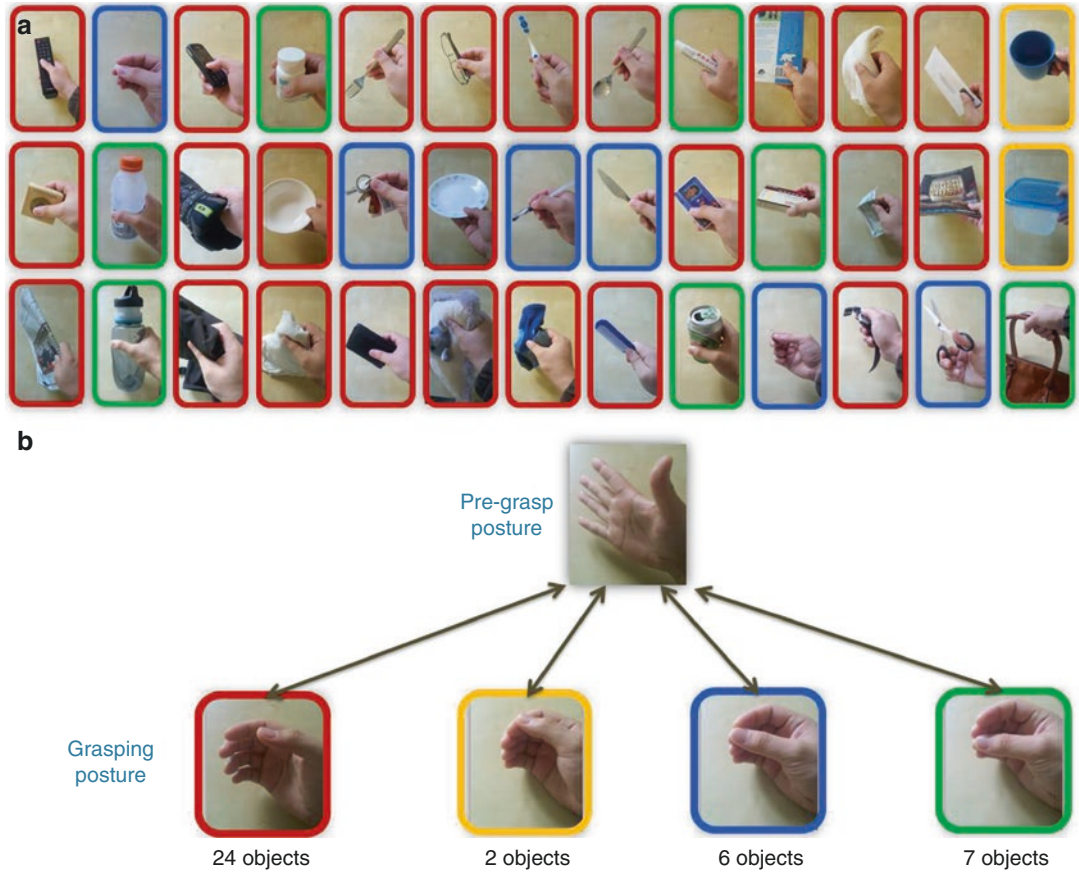

Fig. 21.5 The classification process of four basic grasp postures. (**a**) Pictures of the human hand grasping 39 objects from the prioritized list [47]. (**b**) Four basic grasping postures are observed based on the relative positions between the thumb and fingers

even if small changes are needed in some cases, the cost of modification is independent and manageable. Secondly, the designs of the actuation system and tactile sensing should all be simultaneously considered as important components when a humanlike robotic hand is developed so that the resulting system can possess all the necessary features for researchers to avoid reinventing the wheel and concentrate on their important scientific investigations. Last but not least, while possessing comparable functionality with other advanced commercially available robotic hands, the cost of a humanlike robotic hand system needs to be dramatically reduced to allow easy access for researchers, students, and even hobbyists exploring new ideas at affordable price. In the following sections, we are going to systematically describe how a 20-DOF humanlike robotic hand can be developed to fulfill the above three requirements from a roboticist's point of view.

Development of a Low-Cost Humanlike Robotic Hand via 3D-Printing

The benefits of investigating anthropomorphic robotic hands have been widely acknowledged, and some of them have been effectively demonstrated, such as the anatomically correct testbed (ACT) hand designed for understanding the human hand [10], lightweight prosthetic hands with improved functionalities [21, 23], and many other anthropomorphic robotic hands developed for investigating dexterous manipulation [2–8, 27, 30, 48].

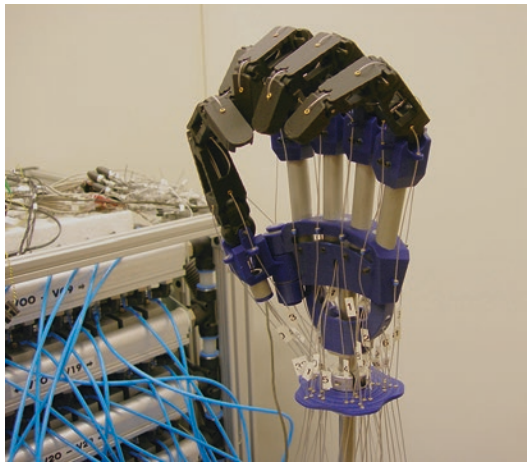

Fig. 21.6 The 3D-printed 20-DOF anthropomorphic robotic hand

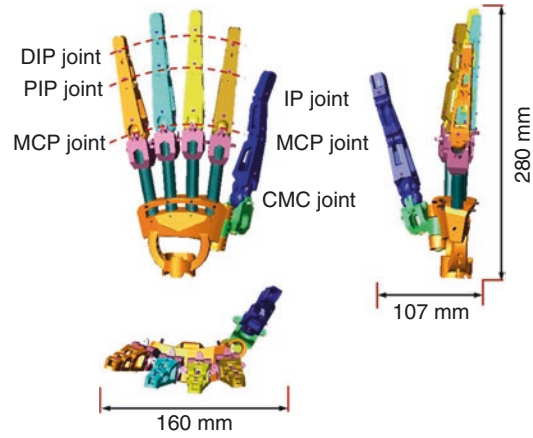

Fig. 21.7 3D model of the anthropomorphic robotic hand

However, it is also commonly accepted that the cost of time and funding spent on developing a research-oriented, custom-designed anthropomorphic robotic hand is often prohibitive. The control of a robotic hand can be affected by many factors, such as the finger length, the range of motion (ROM) of the joints, the weight of the robotic hand, or transmission types. Many researchers had to shape their control goals based on the limits of commercially available anthropomorphic robotic hands because even the slightest modification on those off-the-shelf robotic hands could easily result in months of waiting.

In the following subsections, the innovative design methods of the 20-DOF robotic hand (see Fig. 21.6) are detailed, and then the tactile sensing and actuation system are described; at the end, the performance of the robotic hand system is experimentally evaluated.

Mechanical Design of the 3D-Printed Robotic Hand

Although the anatomy of the human hand provides detailed sources of static models, such as joint structure, tendons routing, and layered skin, how to organically incorporate state-of-the-art engineering advances into a fully functional robotic hand system is what we want to achieve in this project. This section describes the mechanical design and prototyping process of our robotic hand.

As shown in Fig. 21.7, our proposed robotic hand is composed of four articulated fingers and one opposable thumb. The size of our robotic hand matches that of the ACT Hand [10] whose biomechanical properties were extracted from a laser-scan model of a human left hand.

There are three joints in each finger of the human hand: namely, the metacarpophalangeal (MCP), proximal interphalangeal (PIP), and distal interphalangeal (DIP). Each DIP and PIP joint possesses one DOF. The MCP joint has two DOFs: one to achieve flexion-extension and another to realize abduction-adduction finger motion. The three joints of the thumb are the carpometacarpal (CMC), metacarpophalangeal (MCP), and interphalangeal (IP) joints. Its IP and MCP joints were designed to possess one DOF in the flexion-extension direction, respectively. In contrast with other fingers' MCP joints, the CMC joint of the thumb has two DOFs with two non-intersecting, orthogonal axes [10]. Table 21.2 lists the ROM of our proposed robotic hand.

One of the major barriers that prevent researchers from adding new functions to any existing robotic hands is the daunting amount of work involved in redeveloping the complicated mechatronic systems. However this challenge can be sidestepped by taking advantage of rapid prototyping technologies. As shown in Fig. 21.8, each segment of the finger is 3D-printed by the

Table 21.2 The joint ROM of the anthropomorphic robotic hand

Finger	Joint	Minimum	Maximum
Index	MCP	20° extension	90° flexion
Middle		30° abduction	30° adduction
Ring	PIP	0° extension	90° flexion
Little	DIP	0° extension	90° flexion
Thumb	CMC	40° extension	90° flexion
		40° abduction	40° adduction
	MCP	0° extension	80° flexion
	IP	20° extension	90° flexion

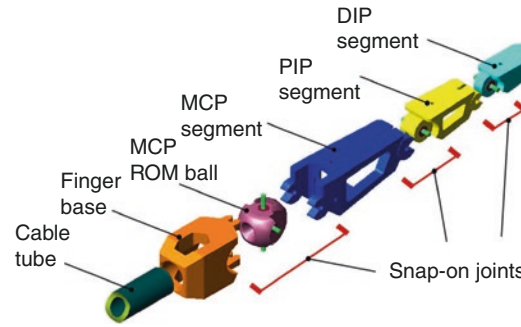

Fig. 21.8 Components of each finger unit

Fig. 21.9 Two examples of assembling a Snap-On joint. Top row: assembling a DIP hinge joint. Bottom row: assembling a MCP ROM-ball on to the finger base

Dimension BST 768 (Stratasys Corp., Eden Prairie, MN). The resolution of the 3D-printed parts is 0.025 mm, and it takes only 1 hour to print all the components of an entire finger. Additionally the strength of the ABS plastic is sufficient to resist the induced stress of cables.

One of the important factors we believe that makes LEGO toy popular is because it allows players to inspiringly prototype their design ideas via a number of interlocking plastic bricks within a short period time. Following the same principle, our proposed robotic hand was designed to be modular and adaptable. The joint connection between two finger segments was formed by one "LEGO-style" Snap-On joint. As shown in Fig. 21.8, there are three Snap-On joints in one finger. The interlocking mechanism of the Snap-On joint is composed of a 3D-printed C-shaped clip on one side of the joint and a steel shaft passing through the center of the other side of the joint. After snapping into the clip, the steel shaft can be secured by the friction engagement, and a Snap-On joint is thus formed (as shown in Fig. 21.9).

The ROM of a joint is limited by the mechanical constraints between adjacent finger segments in extreme postures and can be modified in CAD model without affecting other sites of the part. For instance, by snapping on a new MCP ROM-ball with different mechanical constraints, the ROM of abduction/adduction can vary from 20 ° to 40 ° easily.

In addition to simplifying the robotic hand design, the Snap-On mechanism can also help to ease the burden on assembly: by replacing a set of finger segments with shorter ones, a smaller hand will be reformed in minutes.

Adaptable Tendon Routing

The tendon routing plays an important role in control of anthropomorphic robotic hands. As shown Fig. 21.10a, our proposed robotic hand uses four pairs of antagonistic tendons to control each of its 4-DOF fingers. The tendons are made of 0.46 mm Spectra® fiber (AlliedSignal, Morristown, NJ). The fiber was chosen because of its strength (200 N breaking strength), high stiffness, flexibility, and its ability to slide smoothly through the cable tube. Compared to other types of transmission, such as linkages, gears, and belts, choosing cable-driven system enables the anthropomorphic robotic hand to quickly switch between being fully actuated and being underactuated with little modification as shown in Fig. 21.10. This in return broadens the application of the anthropomorphic robotic hand ranging from dexterous manipulation research to practical prosthetics.

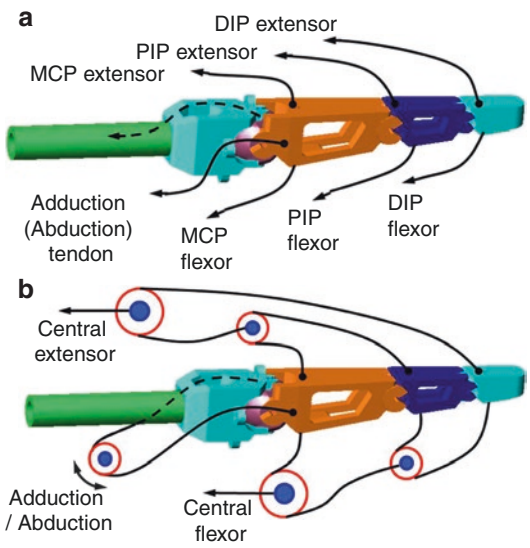

Fig. 21.10 Schematic drawing of two possible cable routing types. (**a**) A fully actuated 4-DOF finger with four pairs of antagonistic cables (Note: cables connected to the DIP and PIP finger segments route through the center of the cable tubes in the real robotic hand; for better illustration, their routings are drawn explicitly). (**b**) A 3-DOF underactuated finger with pulley systems

Although changing the tendon routing is a good way to explore the potentials of an anthropomorphic robotic hand, it is also the most time-consuming process during the assembly (e.g., 90% of the total time in our case). How to efficiently optimize the cable routing and paths so that each of the finger joints can be controlled properly plays an important role in our proposed robotic hand design.

Before rushing to prototype/modify the robotic hand, The MuJoCo modeling software [49] provided us a unique platform to evaluate our design ideas. For instance, the STL files generated for the 3D printer can be directly loaded into the software for detecting mechanical conflicts. Details about the modeling process can be found in [11].

Tactile Sensing of the Robotic Hand

The tactile sensing field of the hand is composed of 16 independent skin pads, each of which consists of three layers as shown in Fig. 21.11. From the skin's surface (top) to the skeleton (bottom), they are Velcro embedded in artificial skin (silicone rubber), a tactile sensing element (sensel), and a 3D-printed frame.

The layer of artificial skin is made of silicone rubber (PlatSil® 71 Series RTV, Polytek Development Corp., Easton, PA) with high shear strength. Its shape is cast by a set of 3D-printed molds (see Fig. 21.12) which forms a tapered shape resembling the pad of the human's fingertip. The fingerprint on its contacting surface can be custom designed to possess different surface textures which will affect its sensing performance. The hydrophobic property of the silicone rubber provides the artificial skin with beneficial properties such as easy-to-clean, water- and oil-resistant, and anti-smudge coatings, but this also prohibits the silicone from sticking to any adhesive. This poses a big challenge when bonding it with neighboring layers. This problem has been innovatively solved by making the most of Velcro as follows: Before the silicone rubber becomes fully cured, a slice of Velcro (loop side) is embedded into

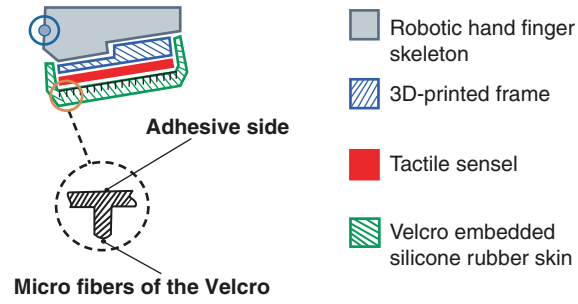

Fig. 21.11 Schematic drawing of the artificial skin's multi-layered structure (Note: differently colored regions are not in proportion to the real distributions of those layers)

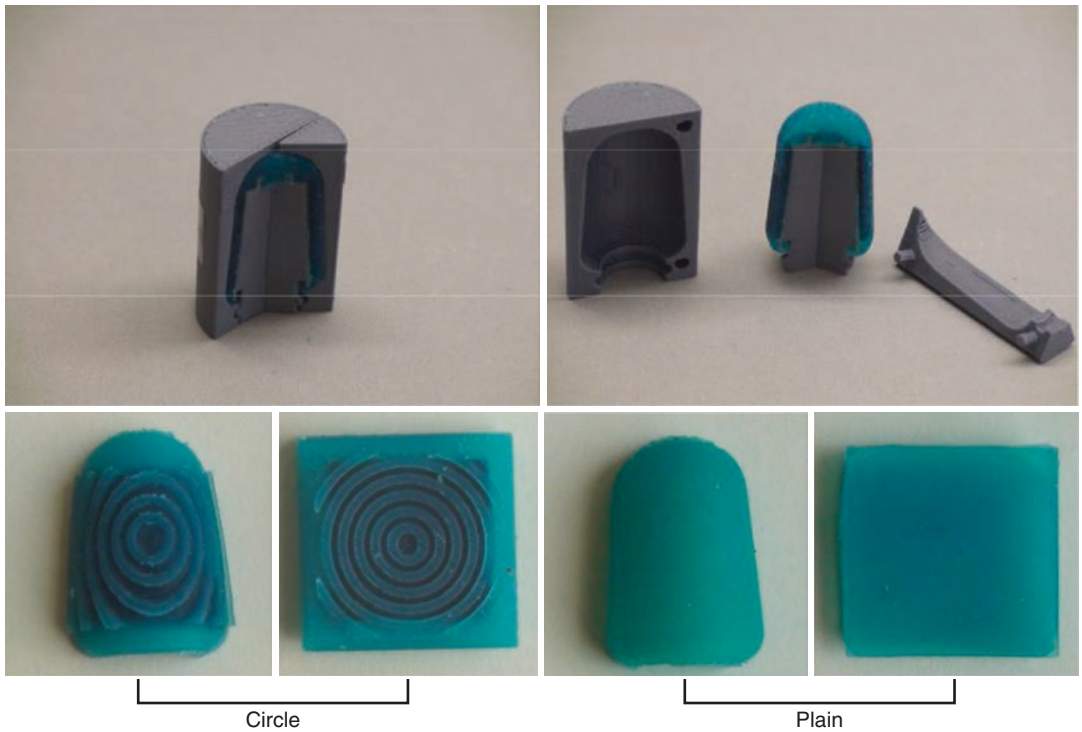

Fig. 21.12 The prototyping process of the artificial skin. Top row: Components of the molds used for prototyping the fingertip's skin. Bottom row: Skin pads with different textures on two types of skin shapes

the skeletal side of the skin layer. After the curing process, the Velcro is securely bonded due to the strong interaction between a large number of microfibers and their surrounding silicone rubber. The whole skin layer can then be easily adhered to the sensel through the adhesive surface of the Velcro. The total thickness of this top most layer through to the Velcro is about 2 mm. To achieve optimal performance (and durability) of the silicone rubber a vacuum chamber is used to remove any air bubbles from the silicone mixture before curing.

The second layer is formed by a 4×4 (20×20 mm in dimension) sensel array from an off-the-shelf five finger Grip™ system (Tekscan Inc., South Boston, MA) for identifying the location and magnitude of pressure points on the hand (see Fig. 21.13). The Grip™ system made in this way has paper-thin flexibility (0.1 mm in thickness). After binding with the Velcro's adhesive surface, the sensor layer is carefully wrapped onto the 3D-printed frame and attached with an adhesive (3 M 77 spray adhesive). The sensel is more strongly bound to the printed frame than the

Velcro; the bonding on either side of the sensel prevents slippage.

The third layer is a 3D-printed frame and works as a skeletal component of the whole structure, and determines the basic shape and contour of the artificial skin. Its outer surface is bonded with the tactile sensel, while its other side is structurally coupled with the finger's skeleton via the opening on each segment of the fingers. The resulted skin pad can be easily put on and off making maintenance of the artificial skin possible—worn silicone rubber can easily be snapped off and replaced with a new one. Because the Velcro's bonding with the sensel is weaker than the sensel's bond to the frame the sensel remains attached to the frame during replacement.

This skin design can potentially improve manipulation performance by providing tactile sensing and more reliable grasping forces, and its performance will be evaluated in the section "The Performance of the Tactile Sensing."

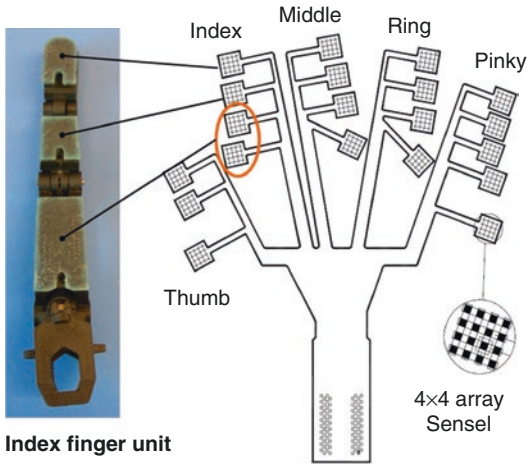

Fig. 21.13 The configuration of the tactile sensor used as the second layer of the artificial skin

Actuation System

As shown in Fig. 21.14, the actuation system consists of two major components: pneumatic control unit and robotic hand's actuation unit.

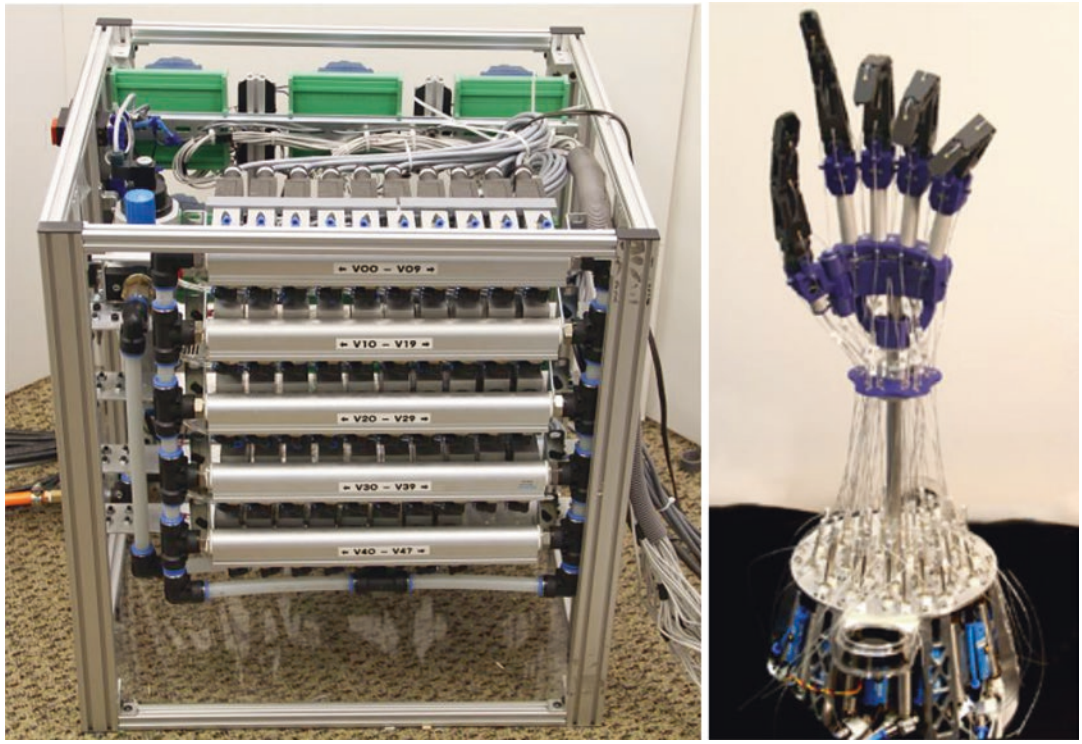

Fig. 21.14 The actuation system of the robotic hand. Left: the pneumatic control unit. Right: The fully assembled robotic hand actuation unit

The actuation unit contains 36 of the M9 Airpel cylinders (Airpot Corp., CT) for finger tendons, and four of the M16 Airpel cylinders for wrist tendons (also used for finger actuation in this work). Double-acting cylinders were selected for complete control over the actuation force in both directions (although this feature is not yet utilized). The fully assembled actuation unit forms the base of the hand and weighs 660 g. It can sustain about 75 N from each air cylinder with a safety factor of three. When attached to a robot arm, most of this mass is near the base (elbow), thus won't cause mechanical conflicts during manipulation tasks.

In addition to the tactile sensing and actuation system, we also developed an optimized three-axis fingertip sensor (see Fig. 21.20), which can be easily modified and integrated into the design of our proposed robotic hand. Due to the page limit, interested reader can find detailed specifications about the pneumatic actuators [50] and fingertip sensor [51] from our previous work.

Performance Evaluation of the Robotic Hand

In this section, we conducted a series of experiments to test the performance of the tactile sensing, compliance, and speed of our proposed robotic hand. Preliminary results are reported.

The Performance of the Tactile Sensing

As show in in Fig. 21.15, we designed an experiment to simulate a pinch where small contact

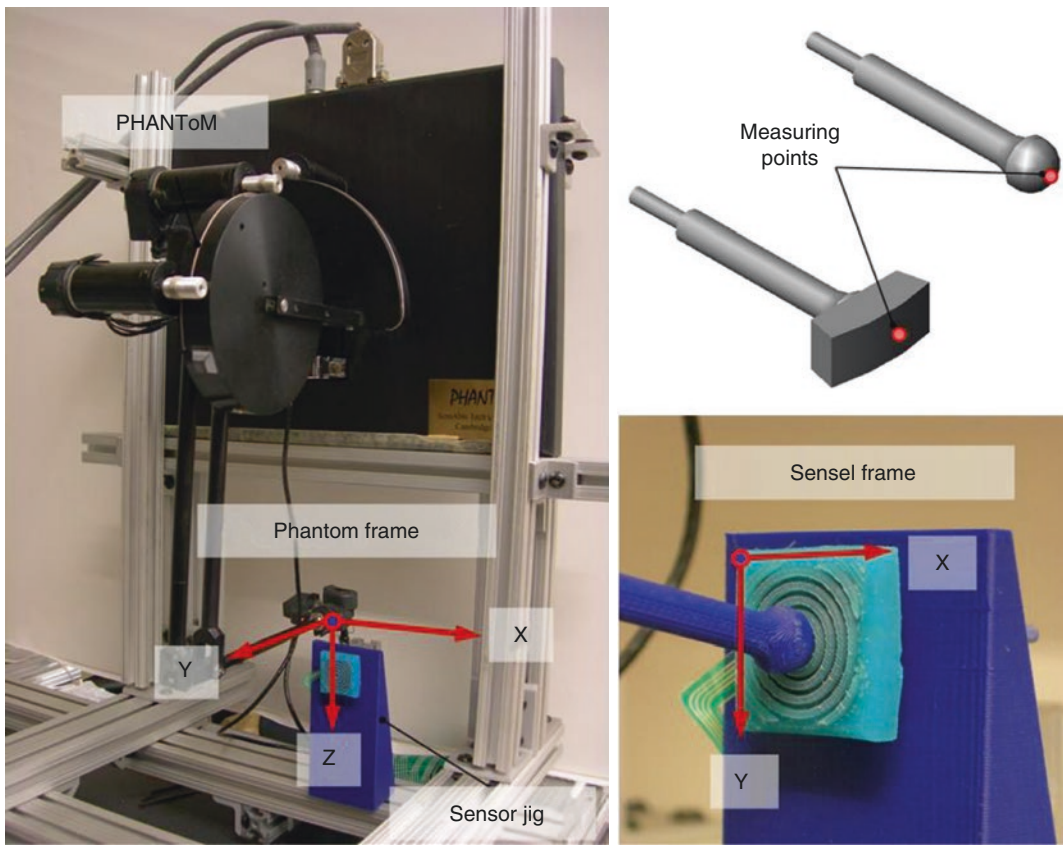

Fig. 21.15 Experimental setup for testing the skin pad. Left: The Phantom robot's coordination system. Top right: Two different shapes of the probes: the sphere (10 mm in diameter) and the curved surface (47 mm in radius). Bottom right: Initial test position. (Note: the difference between the Phantom and sensel frames)

areas are often limited to the fingertips. For this physical simulation, we used a 3-DOF Phantom Premium 1.5A (SensAble Technologies, Inc., Wilmington, MA), with a special end effector (the probe, 10 mm in diameter), to replicate an object impinging on the skin's surface. This mimics the situation of holding an object between the thumb and index fingertips, where the thumb force is produced by the Phantom robot and the object is the probe.

The length of the probe was decided in such a way that the center of the contacting point on the probe (as labeled by red round dots in Fig. 21.15) could match the acting point of the Phantom's end effector. The size of the spherical probe (10 mm in diameter) was chosen based on a contacting surface test: A piece of planar glass was used to push against the human fingertip firmly, through the transparent glass the average diameter of the deformed area on the fingertip was then used as the diameter of spherical probe.

At the beginning of each trial, the probe was manually placed onto the spot close to the center of the skin pad fixed onto the sensor jig. And then the displacement, velocity, and forces of the probe at the contacting point were recorded at 1000 Hz. The average sampling rate of the force sensor used in this work is 20 Hz. Once the probe was positioned properly, 3.5 N of normal force in Y-direction and a 1 N of tangential force in Z-direction (both in the Phantom frame) were simultaneously commanded onto the surface of the skin pad through the probe. While keeping the tangential force consistent, the normal force was controlled to gradually decrease with a constant rate of 0.3 N/s. Each trial ended at the moment when the probe eventually slipped off from the skin pad.

Raw data from the sensel were used to estimate the displacement of pressure center along vertical direction by using the following equation:

$$D_{\text{centroid}} = \frac{\sum f_i y_i}{\sum f_i} \tag{21.1}$$

The force reading from the sensel at the center of pressure, with respect to the sensel frame is calculated as

$$F_{\text{centroid}} = \frac{\sum f_i y_i}{\sum y_i} \tag{21.2}$$

Figure 21.16 shows the results from testing an assembled hexahedral skin pad (with circled texture) with the 10 mm spherical probe. The shaded areas in Fig. 21.16a, c represent initial probe adjustment before trial onset. The contacting forces were measured by the tactile sensel embedded inside the skin pad (see Fig. 21.16a). Onset of each trial is defined by the peak of the sensel's force. The calculated and actual displacements of the pressure center are compared in Fig. 21.16c. It is clear that the estimated center of pressure agrees quite well with the recorded data. And the trend of slip could also be observed.

The Force Behaviors and Speed of the Robotic Hand

In order to investigate the characteristics of the force and compliance of the actuation system, we conducted experiments using a Shadow hand in a previous work [50]. In this work, we conducted the same experiments on our proposed robotic hand and compare its performance with the Shadow hand in Table 21.3. An external force of 2 g at the index fingertip was enough to flex the MCP joint thus confirming the exceptional compliance of our fully actuated robotic hand. During the test of the maximum fingertip forces, all the index fingers of the two robotic hands were commanded to be fully extended, the moment arm of our proposed robotic hand is 13 mm (104 mm finger length) compared to Shadow hand's 10 mm

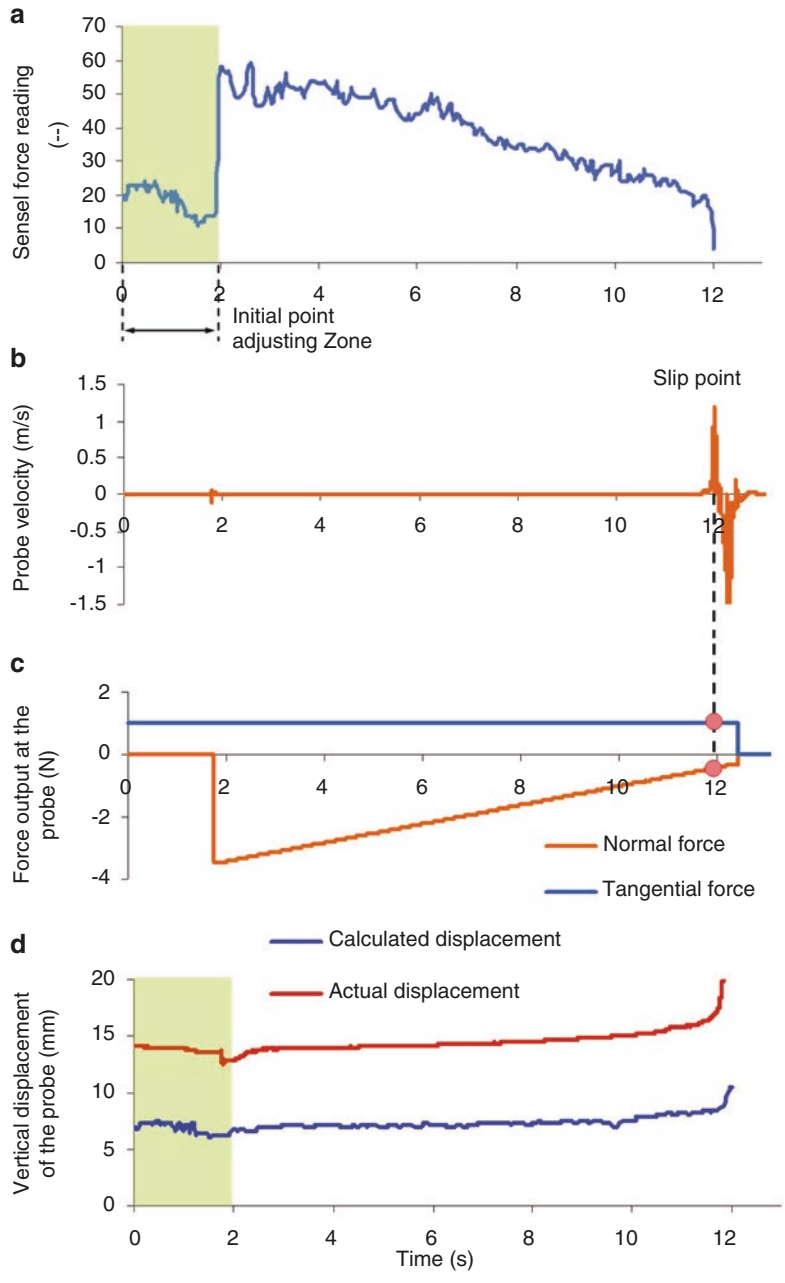

Fig. 21.16 The detection of contact forces using a fully assembled skin pad. (**a**) Force reading from the sensel. (**b**) The probe velocity measured from the Phantom's end effector. (**c**) The output of normal and tangential forces from the Phantom robot. Comparison of the calculated (in sensel frame, along Y-axis) and measured (in Phantom frame, along Z-axis) displacement of the probe along vertical direction

moment arm (96 mm finger length), but produced over doubled forces in both flexion and extension directions.

The actuation system we developed was mainly prepared for the tendon-driven hands and performing dexterous hand manipulation experiments. Any dexterous hand manipulation demands agility and responsiveness from its actuation hardware. The speed capabilities of our robotic hand were evaluated using a simple

open loop bang-bang control strategy over the index finger. The goal was to achieve full stroke movements (joint limit to joint limit) at maximum frequency. Control switching frequency was gradually increased until the finger started making incomplete strokes, i.e., reversed before hitting the joint limits. Using this simple strategy, a frequency of about 3 Hz was achieved for a full finger motion (from fully extended to fully flexed for all the three joints) as shown in Figs. 21.17 and 21.18.

Table 21.3 Comparison of characteristic force behaviors

Specifications on force behaviors	Our proposed robotic hand	The Shadow hand
Minimum actuation force at fingertip to move MCP joint (vertical actuator, at atm pressure)	0.020 N (2.0 g weight)	0.039 N (4.0 g weight)
Minimum actuation force at fingertip to move MCP joint (vertical actuator, at min slack correction pressure)	0.078 N (8.0 g weight)	0.059 N (6.0 g weight)
Maximum flexion force at index fingertip	6.91 N (705 g weight)	2.94 N (300 g weight)
Maximum extension force at index fingertip	6.86 N (700 g weight)	4.31 N (439 g weight)

The Cost of the Robotic Hand

The cost of our proposed robotic hand itself is very low—approximately $100 for all materials. Of course this does not include the tactile sensing ($300) and actuation system. However, a Shadow Hand robot with similar mechanical capabilities and also without actuation costs around $60,000. Thus the proposed design offers a dramatic reduction in cost, as well as time required to manufacture and test a modified version of the system when needed.

A notable advantage of having an inexpensive hand (and instead investing in the actuation system) is that only the hand will typically interact with the environment. Thus any damage is likely to occur in parts that are inexpensive to replace. The modular design of the robotic hand and its tactile sensing can further reduce the cost as well.

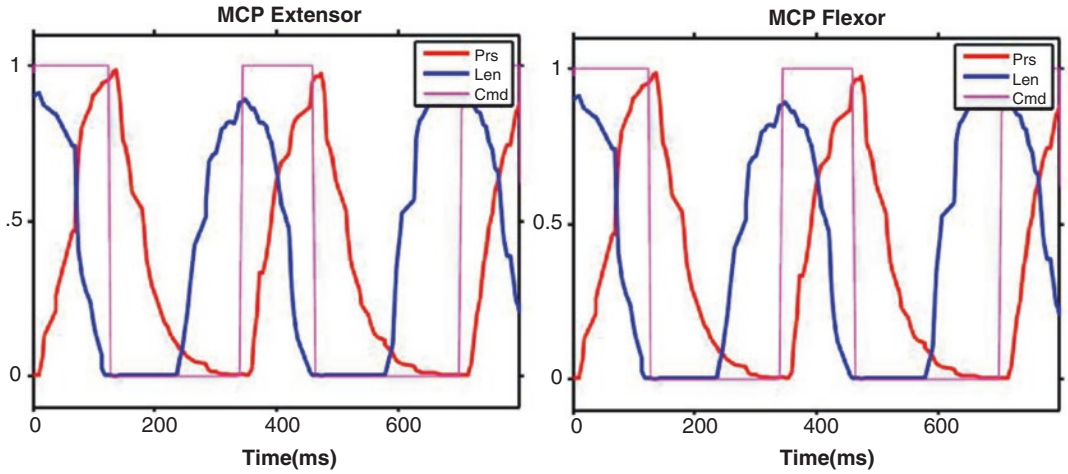

Fig. 21.17 Full finger motion at 3 Hz. Left/right: response of the valve pressure (prs) and length sensor (len) of the MCP extensor/flexor with respect to the command signal

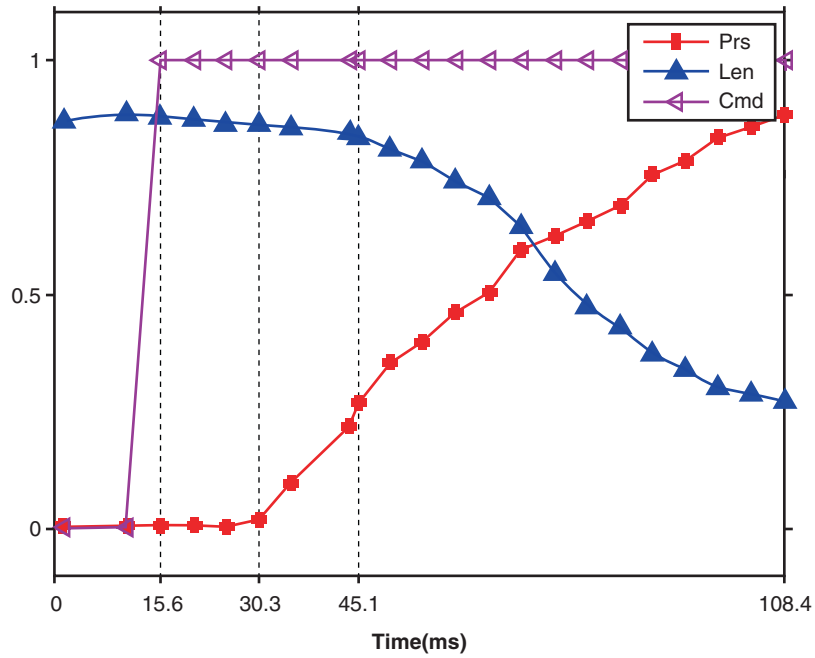

Fig. 21.18 Time stamps. From left to right: T1, event trigger, command written to the pneumatic value; T2, pressure wave arrival; T3, index finger MCP movement detected

Conclusion

After surveying the existing prosthetic and anthropomorphic robotic hands, in section "Development of a Low-Cost Humanlike Robotic Hand via 3D-Printing," we have described the method of designing and modeling of a 20-DOF anthropomorphic robotic hand. Our proposed robotic hand has 31 components, and can be manufactured in 24 hours. Important parameters such as finger length, DOF, and ROM of the robotic hand can all be individually changed with little effort or modification. For evaluating design ideas and speeding up our design cycle, we used our custom modeling software to establish the kinematic model of the robotic hand.

In addition to the mechanical structure of the robotic hand, tactile perception is a very important but complex system composed of several different receptors in layers of our skin. Inspired by this multi-layered structure, we developed the artificial skin pads. Different from the highly biomimetic design we adopted previously, the resulting design of the artificial skin is not to fully replicate the human-level tactile sensing, but more toward equipping the anthropomorphic robotic hand with a general force sensing system that is compatible to our existing design.

Experimental results on tactile sensing, force behaviors and actuation speed suggested that our robotic hand has comparable performance to the Shadow Hand robot, but requires only a fraction of the latter's cost. Our proposed robotic hand has the potential to become an important tool for helping prosthetic/robotic hand researchers to cost-effectively and efficiently investigate different control methods.

In order to further improve the functionality of our proposed anthropomorphic robotic hand, we believe that future efforts toward the following directions will be worth investigating:

- Our current version of the robotic hand does not include a design of the wrist. It will be interesting to add a 2-DOF wrist in order to fully explore the dexterity of our anthropomorphic robotic hand. Meanwhile, the modification could be challenging since all the flexor/extensor tendons will route through an articulated wrist joint.

- In terms of testing different control strategies to realize autonomous manipulation, we would like to first model the entire robotic hand system in MuJoCo environment [49], and then investigate the feasibility of using optimal control method to perform dexterous manipulation tasks.
- Although the detailed kinematic model can help us estimate the joint angle change during different grasping and manipulation tasks, it would be great if small joint angle sensors can also be implemented in the future version of the robotic hand.

Acknowledgments This work was supported by the US National Science Foundation and the National Institutes of Health. The author would like to thank Dr. Emanuel Todorov for his generous support and valuable discussions, thank Dr. Christopher Allan at the Harborview Medical Center for his help on guiding the cadaver hand dissection, and thank Dr. Yoky Matsuoka for her initial support and guidance on the investigation of the ACT Hand.

Appendix

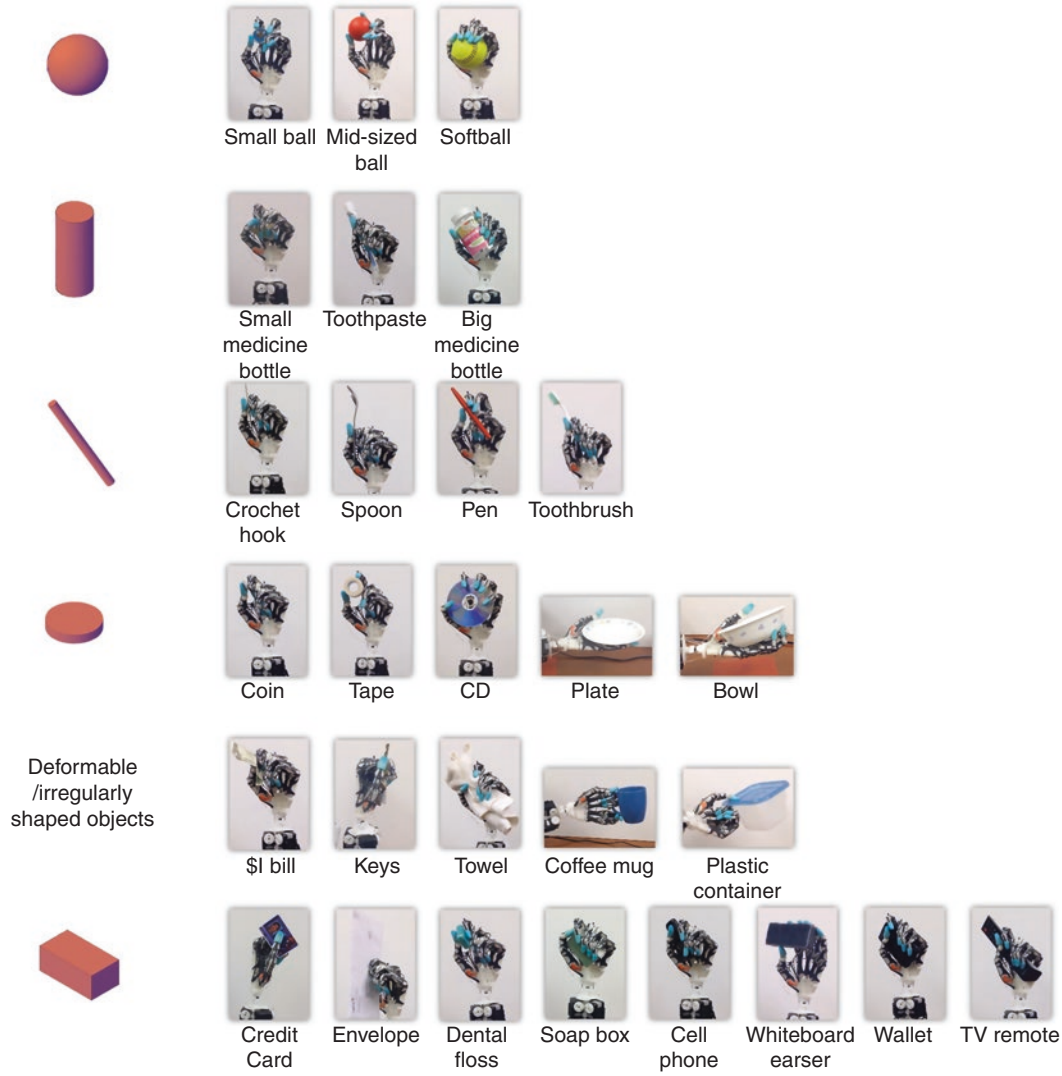

Fig. 21.19 The classification of the objects that can be grasped by the Highly Biomimetic Hand [52]

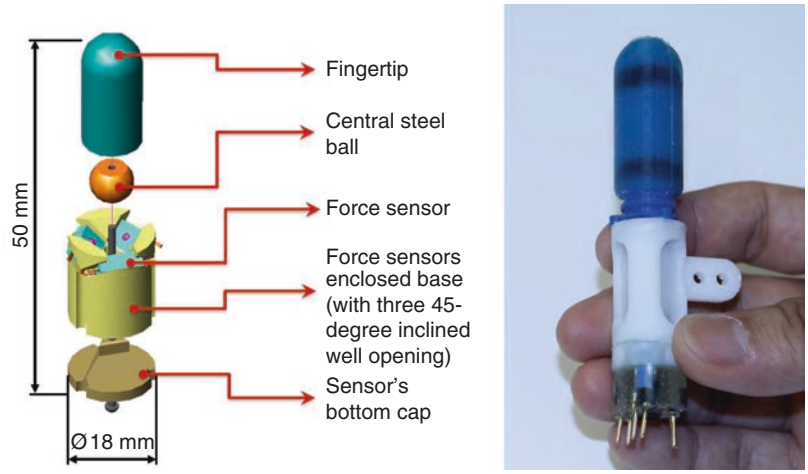

Fig. 21.20 The 3D CAD model and picture of the fingertip sensor [51]

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Section IV

Hand Function and Imaging Outcomes

Hand Function and Imaging Outcomes

22

Atulya A. Deodhar and Özge Keniş Coşkun

In arthritic conditions affecting hands, imaging tools used for diagnosis, monitoring disease activity, as well as for predicting hand function need to be sensitive, reproducible, and easily available. Conventional radiography (X-ray) has been the gold standard for imaging hands in patients with rheumatoid arthritis (RA), even though it is unable to detect changes in the soft tissues such as synovitis, and is also insensitive for the early stages of bone damage. Dual-energy X-ray absorptiometry and digital X-ray radiogrammetry are two techniques that assess changes in hand bone density and have been used with modest success to monitor disease progression in RA. Modern imaging techniques such as ultrasonography (US) and magnetic resonance imaging (MRI) allow direct visualization of soft tissue and bone in the hand with a much better sensitivity and precision, and have been progressively used to assess early changes in inflammatory arthritides in the era of early aggressive treatment. This chapter will review the key aspects of these various imaging modalities with the focus on hand functional outcome.

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Conventional Radiography (X-Rays)

Conventional radiography (simple X-rays) has long been considered the gold standard for the diagnosis and monitoring of various arthritides affecting hands. Simple X-rays can depict juxtaarticular as well as generalized osteoporosis, joint space narrowing (indicative of cartilage thinning), bone damage with cysts, erosions, osteolysis, and also joint subluxations, malalignment, and ankylosis [1, 2]. The universal popularity of X-rays is due to their low cost, easy availability and hence familiarity, as well as fairly good reproducibility. Several validated and standardized measurement scales for inflammatory arthritides are available, making X-rays the method of choice for monitoring disease progression in clinical trials [3]. However, there are several disadvantages of X-rays such as exposure to ionizing radiation, inability to assess soft tissue changes and even early bone damage, and the two-dimensional imaging of a three-dimensional pathology [4, 5].

X-ray assessments for various arthritides in clinical trials include measurements of joint space narrowing and bone erosions in hands, wrists and feet to measure structural joint damage [6]. Two validated scoring methods of radiological damage are available – the Larsen method and the Sharp method – but their use is limited to clinical trials alone [7, 8] since they are too time-consuming, tedious, and not reproducible in untrained hands. The Sharp method was later

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modified by van der Heijde and also by Genant, which improved its sensitivity to change, but did not reduce the time-consuming aspect [9, 10]. For routine clinical practice, the less time-consuming "Simple Erosion Narrowing Score" – simply counting joints with bone erosions plus joints with joint space narrowing – may be more suitable [11].

The clinical relevance of structural joint damage as seen on X-ray is due to its close relationship with future functional outcome. Since X-ray depicts the time-integrated cumulative joint damage, X-ray scores significantly correlate with functional status and explain approximately 25% of the disability over the long term [12]. In a patient with RA, early bone erosions on plain X-ray of hands and feet, as well as serial radiographs showing progression in erosions, predict an aggressive course of the disease with poor long-term functional outcome [13, 14]. In early, undifferentiated arthritis, presence of X-ray erosions increases the risk of developing persistent arthritis [15].

It is important to remember a few caveats for this "gold standard." In early disease, X-ray scores do not correlate with functional outcome as measured by the Health Assessment Questionnaire (HAQ) score, though in established disease (disease duration >8 years) the radiographic damage does correlate modestly with functional outcome in populations of patients. However, in an individual, the relationship between joint damage as seen on X-ray may not predict the functional outcome that well. Also, radiographic erosions are only present in a minority of patients with early RA, with a prevalence of 8–40% at 6 months [16], and X-rays overall are not effective in identifying future "non-progressors," i.e., patients that will not have increasing structural joint damage [17].

Digital X-Ray Radiogrammetry

Digital X-ray radiogrammetry (DXR), a computer-aided technique for the measurement of cortical bone mineral density (BMD) of metacarpal bones using digitized hand X-rays, has been used to assess RA progression and hand function. DXR determines BMD (in gm/cm2), cortical thickness (in cm), metacarpal bone width (in cm), MCI (an index based on the mean cortical thickness normalized for the mean outer bone diameter of the metacarpal bones), and porosity index (correction factor of DXR-BMD) [18] (Fig. 22.1).

The early radiogrammetry technique for the measurement of BMD used ordinary hand radiographs for measuring the total width and the medullary width at the midpoint of the second metacarpal bone of the non-dominant hand [19] (Fig. 22.2). The ratio of cortical thickness to total bone width (the metacarpal index) was used to calculate the BMD. The poor reproducibility of the operator-dependent identification of the endosteal margins at the mid-shaft location made the radiogrammetric measurements inaccurate and less reliable [19]. Despite being inexpensive, radiogrammetry never became popular and was rarely used in clinical practice. Apart from the problems of reproducibility, another reason could be that the dual-energy X-ray absorptiometry (DXA) for measuring bone density at the hip and spine had already been widely available, was easy to order, and has much better reproducibility. Semi- and fully automated computerized radiogrammetry techniques developed later reduced the operator dependency of the old technique and improved the reproducibility of cortical bone BMD measurements [20–22]. The intra-radiograph reproducibility (defined as the BMD data variability seen by repeated measurements of the same individual at a set time point) is reported to be between 0.05% and 0.33%, while the inter-radiograph reproducibility is reported to be 0.26–1.54% [23]. Pfeil et al. published the results of their newly developed version of BoneXpert as a newer version of DXR. It can also measure the metacarpal index in adults. In their study 45 out of 49 hand radiographs of the patients with RA and with different stages of radiographic destruction were automatically accepted by the self-validation process of the BoneXpert technique [24].

Magnus et al. have shown that the development of RA can be predicted with hand bone loss measured by DXR in patients with arthralgia. They included 108 patient who had arthral-

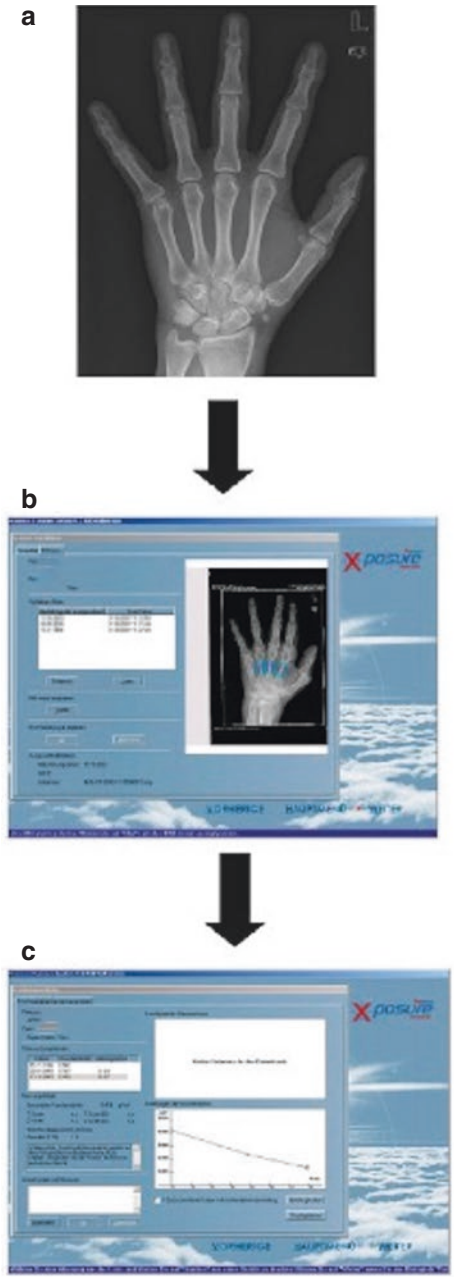

Fig. 22.1 Hand bone density measurement by digital X-ray radiogrammetry (DXR). (**a**) Radiographs are scanned in digital X-ray radiogrammetry (DXR) system. (**b**) Screen view of DXR with the marked region of interest positioned at the metacarpal diaphysis II–IV (see Fig. 22.5 for a close up). (**c**) Screen view of the scanning protocol. The coefficient of variation (CV) of DXR measurements in the hands of premenopausal women was 0.68% and the CV in the postmenopausal women was 0.61%. (Image from Pfeil et al. [30])

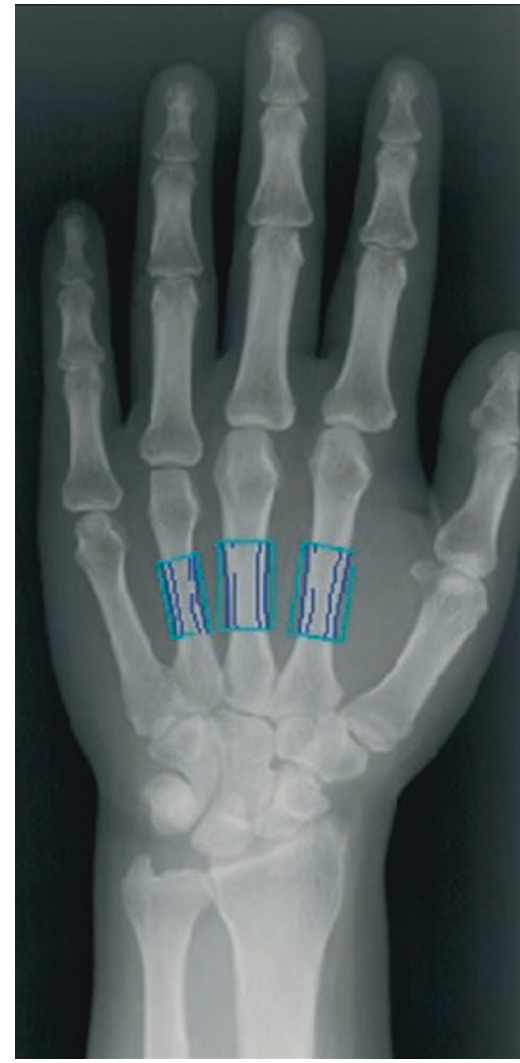

Fig. 22.2 Digital X-ray radiogrammetry. A scanned and processed hand radiograph with the three regions of interests (close up of "B" from Fig. 22.1). The digitized image is subjected to a number of image processing algorithms where the three regions of interests (ROIs) around the narrowest part of the second, third, and fourth metacarpal joints are automatically identified. (Image from Pfeil et al. [30])

gia for <1 year and were at risk of progressing to RA according to their rheumatologists. These patients were named as patients with clinically suspect arthralgia (CSA). Hand bone loss in CSA patients was associated with arthritis development (adjusted for age hazard ratio (HR) = 6.1, 95% confidence interval (CI) 1.7 to 21.4) and

was most frequently estimated in the months before clinical arthritis development [25]. A recent study by Szentpetery et al. have compared the bone loss between the patients with RA and psoriatic arthritis (PsA) and shown that bone loss continues in RA while the periarticular bone density does not change in patients with PsA after the initiation of treatment. The results hint that very different pathomechanisms are involved in these diseases and also show that DXR can be used as a tool to help us enlighten various aspects of pathogenesis in RA [26].

In a 10-year longitudinal study on 136 patients with RA, patients with hand BMD loss at 1 year as measured by DXR had a higher median increase in vdH Sharp score compared to patients without loss at 5 years ($p = 0.001$) and 10 years ($p = 0.002$) [27]. The linear regression model adjusting for age, gender, baseline C-reactive protein (CRP), anticyclic citrullinated peptide (CCP), IgM rheumatoid factor (RF) and radiographic damage showed that absolute hand DXR-BMD loss at 1 year was an independent predictor of radiographic outcome at 5 years ($p < 0.01$) and 10 years ($p = 0.02$). The odds ratio (95% CI) for radiographic progression was 3.5 at both 5 and 10 years among patients with hand BMD loss. The authors concluded that hand bone loss in RA precedes radiographic joint damage and quantitative measurements using DXR may be used as a tool for assessment of bone involvement in RA [27]. In another study hand cortical BMD measurements by DXR were found to be predictive of erosive manifestations in RA [28]. The reduction of DXR-BMD after 1 year was very specific and sensitive (63%) in predicting erosions after a 4-year observation period in patients with RA [29].

Function is the most important outcome measure from RA patients' point of view and structural damage as measured by radiographic progression is a surrogate marker of hand function and future disability. Few studies have directly measured the relationship between DXR bone loss and hand function in RA patients. It is argued that as DXR-BMD predicts future radiographic progression – a surrogate marker of future function – it could also predict the loss of hand function [30]. Two separate studies have shown a significant negative correlation between DXR-BMD and the Health Assessment Questionnaire (HAQ) score (for women, $R = -0.22$; men, $R = -0.35$) [28, 31]. Increased mortality in RA compared to age and sex matched general population is well recognized [32]. The association between mortality and DXR-BMD in RA patients was evaluated in a retrospective analysis of 108 patients over a 30-year period. The baseline X-rays were used in the assessment of hand BMD using the DXR technology. The DXR-BMD, along with Steinbrocker functional class III or IV, the physician's global assessment, and ESR were significant predictors of mortality [33].

In the recent years Rezaei et al. have published their results form the SWEFOT trial investigating hand bone loss measured by DXR in 159 patients with early RA receiving different treatment regimens. They also investigated if DXR change rates during the first 12 months correlate with radiological damage after 24 months. They have shown that patients who respond to MTX therapy have less bone loss when compared to the patients who did not. They have also documented that patients with hand bone loss during the 12 months had greater risk of radiographic progression after 24 months. They have used HAQ as a functional measurement. At baseline, MTX responding patients HAQ scores were significantly better than the patients who received triple DMARD therapy or MTX + TNF inhibitor combination therapy. At 3 months follow-up visit, MTX responding patients still had better HAQ scores. The correlation of HAQ with BMD was not presented in the results of the study [34].

Ornjberg et al. have established the age and sex-adjusted DXR data for Denmark and compared the results with 350 RA patients in 2016 [35]. They showed that hand bone loss varies greatly with age and sex. In men, their model estimated an increasing hand bone loss ratio per year from 35 years of age onwards reaching a maximum at the age of 85. In women, an annual increase in bone mineral density until 35 years of age was estimated, followed by a continuous hand bone loss that is accelerated between 55 and 70 years. In patients with RA, this study shows that hand bone loss is unsurprisingly increased, but it normalizes in 38 of the total 135 patients in the cohort after the initiation of TNF inhibitors.

They have investigated hand function with HAQ as a predictive measure and found no correlations with hand bone loss. The same study group has published their results from the OPERA trial very recently. In this study, they have followed-up 180 treatment-naïve patients with RA for 2 years. They have given MTX to all 180 patients while adding placebo or adalimumab 40 mg subcutaneously every other week. At the patient visits, triamcinolone was injected in the swollen joints. When these patients were followed up for their hand bone loss, it was documented that irrespective of adalimumab treatment, disease activity during treatment was significantly associated with 1- year hand bone loss. They have also shown that baseline HAQ scores are predictive of higher hand bone loss in the first year [36].

Dual-Energy X-Ray Absorptiometry (DXA) of the Hand

As noted above, the early clinical manifestations of RA are seen mainly in the small joints of hands and feet [37] and the structural damage measured by radiographic scores incorporating joint space narrowing and erosions is known to correlate with the ultimate functional loss [7, 38]. Even though juxtaarticular osteoporosis in hands, as seen on plain radiographs, is the earliest radiographic sign before joint space narrowing and erosions become evident [2], the periarticular osteoporosis is rarely measured objectively apart from the DXR technique described above. Dual-energy X-ray absorptiometry (DXA) is the gold standard of measuring bone density at spine and the hip and is readily available around the world.

Deodhar et al. described and validated an objective and reproducible technique (CV = 2.3%) to measure hand bone mineral content (BMC) using DXA to monitor progression of RA in early stages [39]. They decided to use bone mineral content (BMC) rather than bone mineral density (BMD) since the density calculation is dependent on the area of the part scanned (Fig. 22.3).

A cross-sectional study by Peel et al. using hand bone densitometry in 70 post-menopausal women with corticosteroid-treated established RA and 20 patients with early disease demonstrated a significant correlation between hand BMD and that of other sites such as the hip and spine [40]. Patients with established RA had a lower BMD in the hands relative to other sites such as femur and lumbar spine when compared

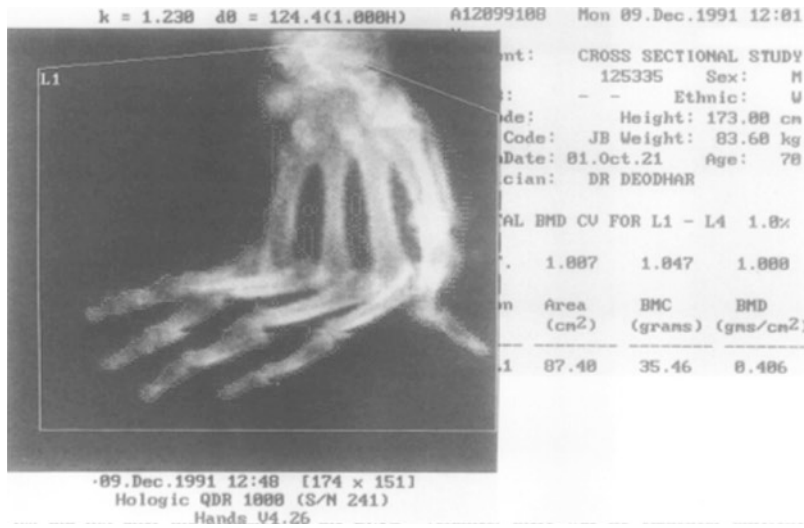

Fig. 22.3 Hand bone densitometry by DXA in a patient with severe hand deformities due to rheumatoid arthritis. Patients with RA have lower hand BMC compared to age and sex matched controls. Since the hand area can change due to progressive hand deformities, bone mineral content (BMC) rather than bone mineral density (BMD), which depends upon the area) should be followed. BMC is independent of the surface area. (Image from Deodhar et al. [39])

with age-matched controls. The authors concluded that in early RA, bone loss is more rapid from hand, a site that is directly involved in the disease process compared to spine and hip, sites that are not directly involved.

In a study of 202 unselected patients with early RA, Devlin and colleagues demonstrated loss of hand BMD even prior to the onset of systemic disease and before lumbar BMD loss [41]. This group confirmed the correlation between high CRP and loss of hand BMD, a relationship previously reported between markers of inflammation and bone loss at other sites (femur and lumbar spine) [41]. Another prospective longitudinal study from Deodhar's group measured hand bone mineral content in 82 RA patients with a disease duration of less than 2 years [42]. They showed hand BMC continued to worsen despite an improvement in overall disease activity and confirmed that bone loss was maximal in early disease, correlating positively with measures of disease activity and inversely with disease duration.

A 5-year longitudinal study of hand bone mineral content from the same group reported that the significant bone loss continued during the first 3 years of disease onset despite effective control of the disease activity within the first year [43]. Persistent disease control led to stabilization of the bone mass after 3 years. In this study, patients losing more than 3% of the hand bone mineral content within the first 6 months had a significantly worse functional outcome at 5 years (Fig. 22.4). This is the only study to use a functional index designed specifically for hands rather than using HAQ, which measures overall functional outcome. The hand function index used in this study was the Duruoz hand index (DHI) described elsewhere in this book [44]. This demonstrated for the first time the importance of early bone loss in hands as a predictor of long-term functional outcome [43]. A study by Gough et al. measuring BMD in spine and hip in RA patients was able to establish that controlling disease activity (measured by suppression of CRP level) resulted in a stabilization of the bone loss in axial skeleton [45]. In 2013 Dogu et al.

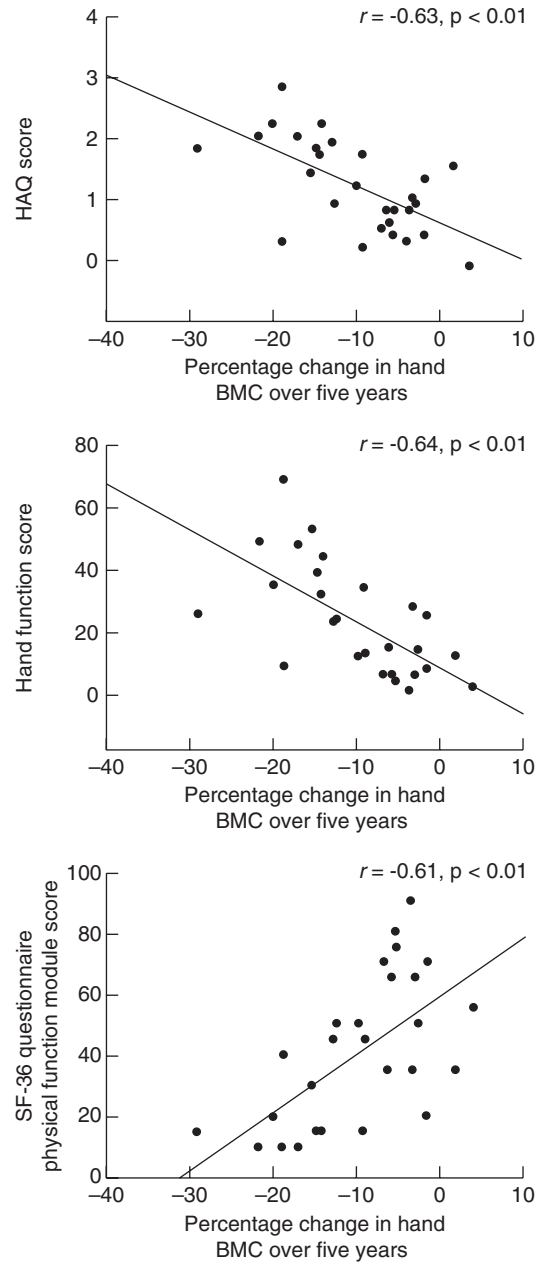

Fig. 22.4 Correlations between cumulative loss of hand BMC over 5 years and other measures of outcome in patients with early RA. The percent change in hand BMC over 5 years correlated with HAQ score, Duruoz hand function index, and inversely with physical function as measured by SF-36. Change in hand BMC was found to be a prognostic marker since a loss of >1.17 grams in the first 6 months predicted bad hand functional outcome at 5 years with an odds ratio of 6.9. (Figure taken from Deodhar et al. [43])

have investigated in 83 females with RA if hand bone mineral density can be an effective outcome measurement of hand function and if there is a relationship between X-rays, hand BMD and function. They have used Duruoz hand index as the functional measurement. The results did not show a significant correlation between BMD and Duruoz Hand Index. However, grip strength is affected negatively from bone loss in patients with RA [46].

The new strategy on treating RA early and aggressively has been accompanied by the recognition that this approach is best employed in patients with a high probability of rapidly progressive disease [47, 48]. Its rational use requires validated prognostic indicators that predict the outcome in an individual patient in the early stages of the disease. The hand bone densitometry data described above indicate that hand BMC measurements may be useful from the early stages of the disease for selecting patients at risk of future disability for more aggressive treatment and for monitoring the response to therapy [49].

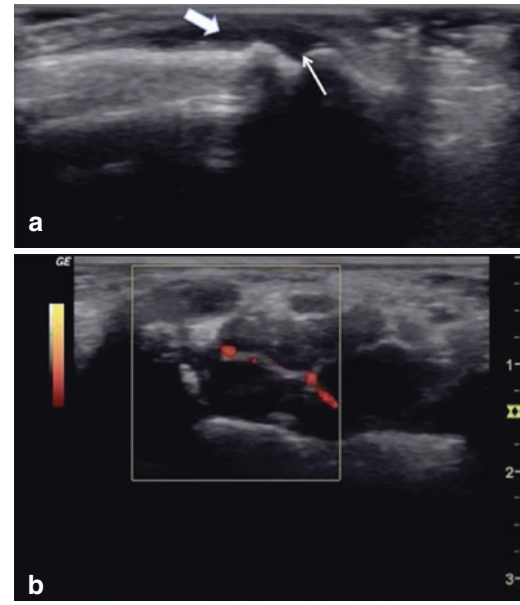

Fig. 22.5 Ultrasonographic findings in a patient with rheumatoid arthritis. (**a**) Edema around the proximal interphalangeal joint. Arrow: joint space. Block arrow: tissue edema. (**b**) Increased Doppler activity around the wrist

Musculoskeletal Ultrasonography

Compared to DXR and DXA that assess hand bone density alone, musculoskeletal ultrasound (US) has the advantage to assess all structures directly involved in a rheumatoid process such as the soft tissues (e.g., synovium, tendons, nerves, muscles), bone, and joints. US visualizes structures in real-time and has the ability to improve the interaction between the doctor and the patient. It involves no ionizing radiation; the examination is much cheaper compared to MRI, comfortable to the patient and is becoming more easily available in rheumatology practices all over the world. The examination can be quick, several joints can be scanned in one session and the process is easy to repeat. Power Doppler US can assess vascularity of the synovium – a surrogate marker for rheumatoid disease activity (Fig. 22.5). Some limitations of musculoskeletal ultrasound include intra and inter-reader variability, long and steep learning curve for operators, inter-machine variability and lack of a universally acceptable scale to assess RA disease activity and damage. Also, US cannot penetrate bone, and hence the image can only assess the bone edge, and at best a small part of it. Its sensitivity for detecting bone erosions is markedly site-dependent – high in easily accessible hand joints but low in anatomically complicated joints such as shoulder [50, 51].

Within the last two decades, the interest in musculoskeletal US has been growing – both its clinical use and also the number of research studies being conducted – especially to assess hand involvement in rheumatoid arthritis. US can visualize inflammation by detection of thickening of the synovial membrane of inflamed joints, bursae or tendon sheaths by grey-scale, and also by quantifying increased synovial blood flow using power Doppler [5, 52]. A recent study by Nishino et al. has shown that in 30 patients with RA, ultrasonographic presence of synovitis and tenosynovitis significantly correlates with grip-HAQ scores. Therefore, synovitis and tenosynovitis that is shown by ultrasound imaging can be an important

indicator of the patients' hand function. It can also visualize destructive RA changes by identifying erosions. These two properties – measurement of disease "process" (synovial vascularity) as well as "outcome" (erosions) – are making US the imaging modality of choice for hand arthritis, rapidly surpassing the plain X-rays as the "gold standard." Also, several investigators have reported ultrasound's superior sensitivity for visualizing bone erosions in MCP, PIP and metatarsophalangeal (MTP) joints than X-ray [51, 52].

Apart from detecting synovitis and bone damage in hand joints, US can also detect presence of synovial fluid in joints, bursae and inflammation in tendon sheaths as well as entheseal insertion (enthesitis) and it can also assess the integrity of tendons and ligaments [53, 54]. Within the past decade, US has been used more and more by rheumatologists to tap the joint synovial fluid under direct visualization.

Studies comparing US and MRI in rheumatoid hands have shown strong agreement between these two modalities in terms of detecting synovial inflammation [5, 52]. Wakefield and colleagues found high specificity (0.98) but moderate sensitivity (0.15–0.44) for detection of finger tenosynovitis, when MRI was used as the reference standard [53]. US, however, is inferior to MRI for detection and follow-up of erosions at the wrists and hands [55]. However, in situations where joint accessibility is optimal (e.g., hands), bone erosions detected by US correlate to a high degree with MRI scans [50, 51] and also with computed tomography (CT) scan [56].

Serial musculoskeletal US examinations have been used to monitor RA progression by assessing disease activity as well as by structural damage. Using corticosteroids [57, 58] or TNF-a inhibitors [59, 60] in the treatment of RA lead to decrease in the US scores of synovitis (Doppler signal and B-mode synovial membrane thickness) in parallel with other markers of disease activity, indicating their potential for monitoring joint inflammation [61]. Strunk et al. found that intra-articular injections of methylprednisolone reduced synovial perfusion by power Doppler US after approximately 7 days, while effusions and synovial hypertrophy were often still persistent [62]. However, a study by Boesen, also using intra-articular methylprednisolone, or etanercept, failed to show any change the degree of synovitis as assessed by power Doppler signal or by MRI after 4 weeks of treatment [63]. Separate studies using etanercept and adalimumab showed that both agents were able to reduce the US scores of localized inflammatory process and/or structural damage [64, 65]. However, they did not separate "inflammation" from "damage," and hence their conclusions should be viewed cautiously.

Backhaus et al. performed repeated X-ray, MRI and US of fingers to follow the natural course of US bone erosions [5]. By 2 years and 5 years of follow-up, MRI and US signs of synovitis decreased, while the number of bone erosions detected by both modalities increase [5, 66]. More patients showed erosive progression on US than on X-ray, suggesting that US has greater sensitivity to change. Hoving et al. found erosive progression in a similar number of patients by X-ray and US in a 6-month follow-up study of RA wrist, MCP and PIP joints [55]. Bajaj et al. followed 21 early RA patients for 6 months and found US to be much more sensitive in finding erosive and progressive disease compared to X-rays, with excellent inter-observer agreement (Kappa 0.96–1.0) [67].

In a small randomized controlled study on an anti-TNF agent use in RA, Taylor et al. found that baseline US-determined synovial thickening and the degree of vascularity in the MCP joints correlated with radio- graphic joint damage at 1 year in the placebo group, but not in the anti-TNF group [68]. Naredo et al. followed an inception cohort of 42 RA patients starting disease modifying anti-rheumatic drug therapy [69]. There was no significant correlation between the baseline ultrasound, clinical, laboratory, and functional parameters with the 1-year DAS28, HAQ and radiographic scores. However, the time-integrated values of power Doppler US parameters demonstrated a highly significant correlation with DAS28 (r = 0.63), and radiographic progression (r = 0.59–0.66) than clinical and laboratory parameters (r < 0.50) after 1 year. Furthermore, a US power Doppler joint index was the strongest predictor of disease activity at the following visit, whereas pain and HAQ scores were the strongest predictors of functional

status at the following visit [69]. Brown et al. [70] reported that US (and MRI) signs of joint inflammation are common in patients thought to be in clinical remission and baseline US synovial hypertrophy as well as power Doppler scores, and MRI synovitis scores in individual joints were significantly related to progressive radiographic damage. They also demonstrated that there was a significant association between power Doppler scores at baseline and structural progression over 12 months in asymptomatic MCP joints, with 12 times higher odds of structural progression in joints with increased power Doppler signal (OR 12.2). Gartner et al. investigated 1320 joints of 90 patients with RA, 60 of who were in clinical remission [71]. They assessed proximal interphalangeal, metacarpophalangeal joints and the wrists of each patient with grayscale and Doppler US. The overall percentage of joints that showed synovitis in either power Doppler or grayscale did not vary between patients with active RA and patients with RA in remission. However, patients who had higher activity with power Doppler US had significantly worse scores in HAQ disability index, showing that high-grade PD signals on ultrasound had functional consequences in patients with RA [71].

Musculoskeletal ultrasound is a valid method for monitoring synovitis and, in hands, also for erosive progression. However, questions remain about their reproducibility, intra- and inter-observer variability, as well as the "smallest detectable change." The same questions can be asked about power Doppler imaging. Also, it remains to be verified whether US can predict long-term disease progression, joint erosions and preservation of function better than the traditional clinical or serological scores.

Magnetic Resonance Imaging (MRI) of Hand

Despite magnetic resonance imaging (MRI) technology being available for the last four decades, experience of using it in patients with RA is relatively new [72, 73]. MR scans show soft tissue abnormalities, such as synovitis, tendonitis, and bone marrow edema that cannot be seen on conventional radiographs (Fig. 22.6). Over the last two decades, a number of studies have reported on the ability of MRI scans to document erosions with a greater sensitivity than conventional radiographs [74–76]. These studies have also demonstrated that bone and soft tissue abnormalities (i.e., bone marrow edema and synovitis noted above) seen by MRI often progress to radiographic erosive disease.

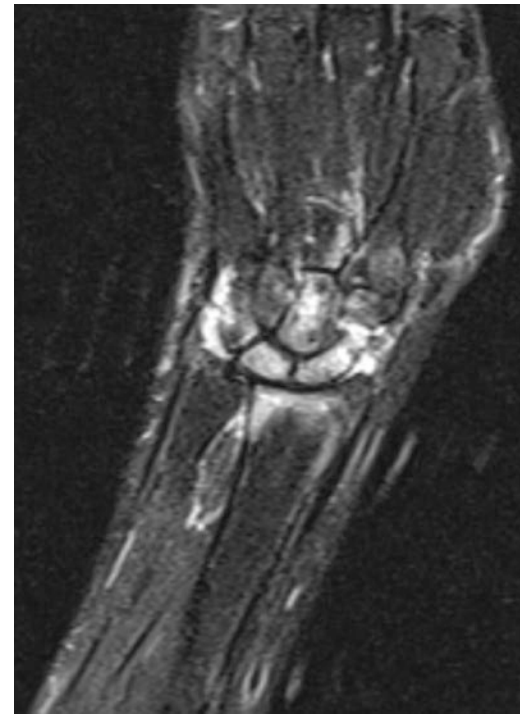

Fig. 22.6 MRI findings in a patient with rheumatoid arthritis. T2 weighed MRI image of widespread bone marrow edema in the carpal bones with a patient with rheumatoid arthritis and the radius

Functional capacity is more dependent on disease activity rather than on structural damage early in the RA disease process, while in longstanding disease, poor function has been more dependent on structural damage, even with improvement in inflammation [77]. Therefore, prevention of joint damage has been a goal of treatment, and identifying those patients whose disease is more likely to progress is critical. MRI technology with its superior sensitivity (compared to traditional radiology) to bone damage, at least in theory, should be able to identify such patients early.

While a lot of literature is available on the unquestioned superior sensitivity of MRI scans compared to conventional radiographs to assess erosions, several questions about the use of this technique in daily clinical practice remain. For example, what is the value of MRI findings of synovitis, bone marrow edema, or erosions in predicting damage on future conventional radiographs? Most of the studies are cross-sectional and indicate that, compared with traditional radiographs, MR scans are not only more sensitive in identifying erosions, but also allow diagnosis of them early in the course of the disease [72, 73, 76]. However, only well-designed longitudinal studies on large cohorts of RA patients can define the prognostic value of MR findings of synovitis, bone marrow edema, and erosions in predicting radiographic damage, and very few are available. Also, most of these studies use high-field MR (1.5 T) machines and not the extremity (0.2 T) MR machines used for scanning peripheral extremity parts, such as wrists and the MCP joints.

McQueen and colleagues studied an inception cohort of 42 patients with early RA from presentation (median of 4 months from symptom onset) to 6 years, using clinical assessments of disease activity and function as well as radiographs and high-field MR scans of the dominant wrist [74]. At baseline, 45% of these patients had erosions on MR compared with 15% on radiographs, and 75% showed MR erosions compared to only 21% on plain radiographs by year one. They scored the MR scans according to a locally validated scoring system and showed that the total MR score at baseline (combining scores for erosions, bone edema, synovitis, and tendonitis) was predictive of erosions on radiographs (Sharp scores) at 1, 2, and 6 years.

Studies have shown that the MR finding of bone marrow edema is even more important than erosions for predicting future erosion on radiographs. Using a site-specific analysis of MR scans done in the cohort described above, McQueen showed that the baseline MR bone marrow edema at a specific carpal bone was highly likely to be associated with MR erosion at that site after 1 year and 6 years (OR = 6.5; 95% CI 2.78–18.1) and the baseline MR bone edema score was predictive of the 6-year total Sharp score [74]. A model incorporating baseline MRI scores for erosion, bone marrow edema, synovitis, and tendonitis, plus the C-reactive protein (CRP) level and the erythrocyte sedimentation rate, explained 59% of the variance in the 6-year total Sharp score (R2 = 0.59, adjusted R2 = 0.44) [74]. Synovitis as seen on MR imaging can be scored by a validated method and was a predictor of the MR erosion score at 6 years (R2 = 0.15, $p = 0.03$), but not of the total modified Sharp score in the same cohort. This finding is similar to a study by Østergaard et al., who showed that MR synovitis, measured by estimation of synovial volume, was a predictor of MR erosions after 1 year [78].

Despite this observation, several caveats need to be considered. The positive predictive value of MR scores in the McQueen cohort was low (67%), implying that one-third of patients with a high total score on MRI at baseline did not develop erosions on radiographs at 2 years. However, the negative predictive value was high, showing that 90% of patients with a low initial score did not develop erosions at the wrists by 2 years. Also the MRI findings of erosions, bone marrow edema, and synovitis may not be specific for inflammatory arthritis such as RA. In a study utilizing high-field MRI in assessing osteoarthritis of the hands, at least half of early OA and one third of chronic OA patients had bone edema. Erosions were even more common and were present in at least 75% of early OA and 50% of chronic OA patients. 73% of OA patients had excess fluid in the joint space and gadolinium enhancement suggestive of inflammation was found in every joint studied in patients with early OA [79].

Burgers et al. published a study in 2016 investigating the correlation between MRI-detected inflammation and functional status of patients with early arthritis. The study included 514 patients who underwent MRI imaging of the wrist, metacarpophalangeal, and metatarsophalangeal joints. They used HAQ as the functional outcome measurement and found that total MRI-inflammation score was associated with the HAQ score ($b = 0.014$, $p < 0.001$), as were tenosyno-

vitis ($b = 0.046$, $p < 0.001$), synovitis ($b = 0.039$, $p < 0.001$), and bone marrow edema scores ($b = 0.015$, $p < 0.001$). In multivariable analyses, tenosynovitis score was the only one that is independently correlated with the HAQ score. They also found that MRI-detected inflammation at wrists or MCP joints was associated significantly with impairments in hand functioning [80].

The MR scoring system is complex since it includes the sum of the scores for erosions, bone marrow edema, synovitis, and tendonitis at several areas within the wrist. It is very time-consuming, needs experts for reproducible results and, hence, is not practical to use for daily clinical studies. Simple presence or absence of bone erosion on MRI or bone marrow edema may not be predictive of long-term radiographic or functional outcome since bone edema may be transient and only 26% of erosions detected on MRI progress to erosions on radiographs at 2 years. The Outcome Measures in Rheumatoid Arthritis Clinical Trials (OMERACT) group has published a scoring system for high-field MRI systems (RA MRI score or "RAMRIS"), which incorporates MR features of erosion, edema, and synovitis [81]. This system remains impractical for daily clinical use since it is time-consuming, complex, and exhibits significant variability in scores even with expert readers. The reading variability with the RAMRIS scoring system can introduce a measurement error that is expressed as the "smallest detectable difference (SDD)" and, in general, only changes greater than the SDD are considered clinically important in longitudinal studies.

Ejbjerg and colleagues have compared the SDD of the OMERACT MRI scores (RAMRIS) with the Sharp\van der Heijde score on radiographs in a 1-year longitudinal study [81]. They found that the SDD for the 5 joint (2–5 MCP and dominant wrist) RAMRIS score was 2.1 compared with an SDD of 4.2 for the 15 joint RAMRIS. The SDD for the Sharp\van der Heijde score was 6.1. Defining radiographic progression as patients exceeding the SDD, more patients were detected to progress by MRI of the dominant wrist and bilateral 2–5 MCPs than by radiography. No difference in structural progression between MRI and radiographs was noted if the dominant wrist was not included in the MRI study and only MCPs and MTPs were scanned. The authors concluded that low field extremity MRI was more sensitive than radiographic scoring for detecting progressive joint damage [82].

Bird et al. evaluated the progression of joint erosion over 2 years in 47 RA patients with established disease, comparing a large field-of-view MRI of the second through fifth MCP joints with conventional bilateral hand radiographs [81]. The MRI studies were scored using the RAMRIS methodology and the radiographs by the Larsen score. In contrast to the Ejbjerg study, bilateral hand radiographs detected more patients with progressive joint erosion than by dominant hand MRI. MRI did demonstrate greater sensitivity to damage progression in the MCP joints alone, but this advantage was lost when the joints of both hands were evaluated by conventional radiographs. This study suggests that, in established RA, limited field MRI may be no better in evaluating progression of joint damage than conventional radiographs.

While high-field MRIs are more sensitive than conventional radiography at detecting erosions in RA, a significant percentage of these MRI erosions do not appear to progress in longitudinal studies [74]. To date, studies of RA therapy using MRI data have not used the MRI results to guide therapeutic decisions and it remains to be seen whether erosions detected on MRI alone will have any value in guiding therapy over and above other routine assessments. In one study of early RA (<12 months of disease), comparing methotrexate with methotrexate plus intra-articular steroids, the development of erosions on a 1.5 T MRI with contrast enhancement over the course of a year was found to correlate with the level of synovitis in the MCP joints assessed by MRI [75]. In particular, joints without evidence of synovitis did not develop new erosions on MRI during follow-up. Despite the value of the MRI for predicting and detecting erosions in this study, treatment decisions were driven by clinical evidence of synovitis, and not by findings on MRI. Also, this study used gadolinium enhancement to assess the severity of synovitis, which is

not used in rheumatology practices using low-field extremity MRI examination in the office.

In another small, blinded study comparing the outcomes of 20 early RA patients treated with an "induction regimen" of methotrexate with or without infliximab for 1 year, 1.5 T MRI imaging of the second through fifth MCP joints was evaluated for synovitis, bone marrow edema, and erosion using intravenous gadolinium enhancement [83]. Despite the small number of subjects in the trial, there was a significant difference between the two treatment groups in both synovitis and bone edema on MRI examinations obtained as early as 14 weeks, and sustained through 54 weeks. Findings on MRI did correlate with measurements of clinical outcomes, including ACR response, Disease Activity Score (DAS), and Health Assessment Questionnaire (HAQ).

In areas other than RA, MRI may be an effective element of clinical management. A study was able to show that even a mid-field 0.5 T MRI of the knee was able to predict the need for arthroscopic repair of a meniscal tear with high sensitivity and specificity [84].

There is little evidence to date linking disability or other functional outcomes to specific extremity MRI findings. As noted in the section on X–rays, there is a close association between the development of radiographic erosions and disability among populations of patients with RA. Because extremity MRI may be more sensitive in detecting erosions than radiographs, it is possible that this imaging approach could predict functional outcomes earlier and more accurately than radiographs. However, there are no published studies to support this concept. In addition, the presence of radiographic erosions correlates only roughly with functional outcomes in individual patients and the significant false-positive rate of extremity MRI could offset the potential benefit of extremity MRI in predicting function outcomes.

Quinn et al. reported that patients with early arthritis treated with infliximab and methotrexate improved clinically and functionally compared with those taking methotrexate alone; high-field MRI evidence of synovitis mirrored these clinical and functional improvements [85]. Benton et al. studied patients with early RA and found that baseline total MRI score and the presence of bone edema by high-field MRI of the wrist predicted the physical function part of SF36 (PF-SF36) at 6 years [86]. In fact, 16% of the PF-SF36 score was explained by baseline total MRI score and 22% of the PF-SF36 score was explained by the presence of bone edema. However, the results of HAQ at 6 years were not predicted by MRI results and baseline Ritchie index and baseline HAQ predicted 6-year HAQ as well as MRI (20% of 6-year HAQ was explained by these other baseline assessments). The authors noted that the best predictor of 6-year function was a regression model that included bone edema by MRI, CRP, DAS, HAQ, and modified Sharp score. This model predicted 23% of the 6-year PF-SF36. Thus, although this study found correlations between certain functional outcomes and baseline high-field extremity MRI findings, the ability to predict outcomes was modest. In addition, it is unlikely that a clinician using extremity MRI in the office will utilize the radiographic and MRI scoring systems or the regression model described in this study. Importantly, this study was performed prior to the introduction of anti-tumor necrosis factor therapies.

In summary, limited data are available to answer the question whether MRI abnormalities are predictive of poor hand functional outcome. Radiographic erosions are considered a surrogate marker for poor functional outcome in longstanding RA and findings on MRI could be considered a surrogate marker for radiographic erosions. Whether MRI erosions in the absence of radiographic erosions are associated with poor hand functional capacity has not yet been evaluated. Large ongoing clinical trials utilizing MRI may provide such data [87].

Summary

Great progress has been made since the days when conventional radiographs were the only imaging modality available for assessing hand involvement in various arthritides, and they were hailed as the "Gold Standard". DXR and DXA

assess hand bone density alone, but US and MRI have the ability to assess the soft tissues as well as other structures in the hand and are rapidly vying for the title of "gold standard" in these clinical situations. A lot of work still needs to be done to translate the data generated by these modern imaging modalities to hand functional outcomes in patients with inflammatory arthritis.

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Appendix 1: ABILHAND (Manual Ability Measure)

Answers to the questions

- 0 = Impossible
- 1 = Difficult
- 2 = Easy
- N/A = Activities not attempted in last 3 months

Questions: How difficult are the following activities?

1. Picking-up a can
2. Handling a stapler
3. Writing a sentence
4. Using a screwdriver
5. Screwing a nut on
6. Replacing a light bulb
7. Cutting meat
8. Peeling potatoes with a knife
9. Taking a coin out of the pocket
10. Sharpening a pencil
11. Filing one's nails
12. Handling a four-color ballpoint pen with one hand
13. Grasping a coin on a table
14. Wrapping up gifts
15. Turning a key in a keyhole
16. Peeling onions
17. Brushing one's hair
18. Tearing open a pack of chips
19. Turning off a tap
20. Fastening the zipper of a jacket
21. Opening a screw-topped jar
22. Hammering a nail
23. Fastening a snap (jacket, bag, …)
24. Threading a needle
25. Taking the cap off a bottle
26. Cutting one's nails
27. Combing one's hair

ABILHAND was originally developed using the Rasch measurement model. It allows ordinal scores to be converted into linear measures located on a unidimensional scale. The raw ordinal data is converted to linear measures expressed in logits (log-odds probability units). The higher the logit number, the greater the patient's perceived ability. Activities not commonly performed in the previous 3 months were not scored and were encoded as missing. It was validated in rheumatoid arthritis, systemic sclerosis, and chronic stroke.

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Appendix 2: Boston Questionnaire (Brigham and Women's Carpal Tunnel Questionnaire/the Carpal Tunnel Syndrome Instrument)

Questionnaire for Assessment of Severity of Symptoms and Functional Status

Symptom Severity Scale

The following questions refer to your symptoms for a typical 24-h period during the past 2 weeks (circle one answer to each question).

How severe is the hand or wrist pain that you have at night?

1. I do not have hand or wrist pain at night
2. Mild pain
3. Moderate pain
4. Severe pain
5. Very severe pain

How often did hand or wrist pain wake you up during a typical night in the past 2 weeks?

1. Never
2. Once
3. Two or three times
4. Four or five times
5. More than five times

Do you typically have pain in your hand or wrist during the daytime?

1. I never have pain during the day
2. I have mild pain during the day
3. I have moderate pain during the day
4. I have severe pain during the day
5. I have very severe pain during the day

How often do you have hand or wrist pain during the daytime?

1. Never
2. Once or twice a day
3. Three to five times a day
4. More than five times
5. The pain is constant

How long, on average, does an episode of pain last during the daytime?

1. I never get pain during the day
2. Less than 10 min
3. 10–60 min
4. Greater than 60 min
5. The pain is constant throughout the day

Do you have numbness (loss of sensation) in your hand?

1. No
2. I have mild numbness
3. I have moderate numbness
4. I have severe numbness
5. I have very severe numbness

Do you have weakness in your hand or wrist?

1. No weakness
2. Mild weakness
3. Moderate weakness
4. Severe weakness
5. Very severe weakness

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Do you have tingling sensations in your hand?

1. No tingling
2. Mild tingling
3. Moderate tingling
4. Severe tingling
5. Very severe tingling

How severe is numbness (loss of sensation) or tingling at night?

1. I have no numbness or tingling at night
2. Mild
3. Moderate
4. Severe
5. Very severe

How often did hand numbness or tingling wake you up during a typical night during the past 2 weeks?

1. Never
2. Once
3. Two or three times
4. Four or five times
5. More than five times

Do you have difficulty with the grasping and use of small objects such as keys or pens?

1. No difficulty
2. Mild difficulty
3. Moderate difficulty
4. Severe difficulty
5. Very severe difficulty

Functional Status Scale

On a typical day during the past 2 weeks, have hand and wrist symptoms caused you to have any difficulty doing the activities listed below? Please circle one number that best describes your ability to do the activity.

Activity	No difficulty	Mild difficulty	Moderate difficulty	Severe difficulty	Cannot do at all due to hand or wrist symptoms
Writing	1	2	3	4	5
Buttoning of clothes	1	2	3	4	5
Holding a book while reading	1	2	3	4	5
Gripping of a telephone handle	1	2	3	4	5
Opening of jars	1	2	3	4	5
Household chores	1	2	3	4	5
Carrying of grocery bags	1	2	3	4	5
Bathing and dressing	1	2	3	4	5

The overall symptom-severity score is calculated as the mean of the scores for the 11 individual items and the overall score for function status is calculated as the mean of all eight items. The range of total scores is between 1 and 5 and high score indicate bad function. Item that is left unanswered or that is not applicable is not included in the calculation of the overall score.

Reference

1. Levine DW, Simmons BP, Koris MJ, et al. A self-administered questionnaire for the assessment of severity of symptoms and functional status in carpal tunnel syndrome. J Bone Joint Surg Am. 1993;75:1585–92.

Appendix 3: Duruöz Hand Index (DHI)

Answers to the questions:

- 0 = Yes, without difficulty
- 1 = Yes, with a little difficulty
- 2 = Yes, with some difficulty
- 3 = Yes, with much difficulty
- 4 = Nearly impossible to do
- 5 = Impossible

Answer the following questions regarding your ability without the help of any assistive device

C1—In the kitchen

1. Can you hold a bowl?
2. Can you seize a full bottle and raise it?
3. Can you hold a plate full of food?
4. Can you pour liquid from a bottle into a glass?
5. Can you unscrew the lid from a jar opened before?
6. Can you cut meat with a knife?
7. Can you prick things well with a fork?
8. Can you peel fruit?

C2—Dressing

9. Can you button your shirt?
10. Can you open and close a zipper?

C3—Hygiene

11. Can you squeeze a new tube of toothpaste?
12. Can you hold a toothbrush efficiently?

C4—In the office

13. Can you write a short sentence with a pencil or ordinary pen?
14. Can you write a letter with a pencil or ordinary pen?

C5—Other

15. Can you turn around door knob?
16. Can you cut a piece of paper with scissors?
17. Can you pick up coins from a table top?
18. Can you turn a key in a lock?

The raw scores of questions are added to get the total score of the scale. The range of total score is between 0 and 90, and high score indicates bad function. Duruöz Hand Index (DHI) was validated to assess hand function in several diseases and hand arthropathies such as rheumatoid arthritis, osteoarthritis, systemic sclerosis, psoriatic arthritis, tetraplegia, stroke, diabetes mellitus, flexor tendon injuries of hands, carpal tunnel syndrome, patient under hemodialysis, juvenile idiopathic arthritis, and geriatric persons.

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Appendix 4: Hand Mobility in Scleroderma (HAMIS) Test

Finger flexion
(All fingers must be tight to the object)

- 0-Can bend fingers 2–5 around a pencil (5 mm diam.)
- 1-Can bend fingers 2–5 around a piece of cutlery (15 mm diam.)
- 2-Can bend fingers 2–5 around handlebar (30 mm diam.)
- 3-Cannot manage the previous item

Finger extension

- 0-Can feel the table completely with digits 2–5
- 1-Can feel the pencil (5 mm diam.) with digits 2–5
- 2-Can feel the piece of cutlery (15 mm diam.) with digits 2–5
- 3-Cannot manage the previous item

Thumb abduction

- 0-Can grip around a coffee package (90 mm diam.)
- 1-Can grip around a milk parcel (70 mm diam.)
- 2-Can grip around a bottle (60 mm diam.)
- 3-Cannot manage the previous item

Pincer grip

- 0-Can form a round pincer grip
- 1-Can form a D-shaped pincer grip
- 2-Can form a long narrow pincer grip
- 3-Cannot manage the previous item

Finger abduction

- 0-Can spread the fingers and then fold the hands together to the bottom of the fingers
- 1-Can spread the fingers and then fold the hands together to the first phalanx
- 2-Can spread the fingers and then fold the hands together to the second phalanx
- 3-Cannot manage the previous item

Volar flexion
(The person stands with the arms alongside the body. The object is given from behind)

- 0-Can grasp a spool of thread with a slight flexion of MCP and extended PIP and DIP joints
- 1-Can grasp a spool of thread with a large flexion of MCP and extended PIP and DIP joints
- 2-Can grasp a spool of thread with a large flexion of MCP and flexion of PIP
- 3-Cannot manage the previous item

Dorsal extension

- 0-Can hold the palms together and put the wrists against the stomach
- 1-Can hold the palms together and put the thumbs against the throat
- 2-Can hold the palms together and put the thumbs up to the mouth
- 3-Cannot manage the previous item

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Pronation

- 0-Can put the palms of the hands on the table (MCP 2–5 must touch the surface)
- 1-Can put the palms of the hands on the table (MCP 3–5 must touch the surface)
- 2-Can put the palms of the hands on the table (MCP 4–5 must touch the surface)
- 3-Cannot manage the previous item

Supination

- 0-Can put the backs of the hands on the table (MCP 2–5 must touch the surface)
- 1-Can put the backs of the hands on the table (MCP 3–5 must touch the surface)
- 2-Can put the backs of the hands on the table (MCP 4–5 must touch the surface)
- 3-Cannot manage the previous item (MCP 4–5 must touch the surface

The test equipment consists of standardized cylinders for assessment of finger flexion, finger extension, and thumb abduction. Each hand is assessed separately. The raw scores are added to get the total score of HAMIS. It ranges for each hand between 0 and 27 points. High score represents a high degree of dysfunction.

Reference

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Appendix 5: Hand Functional Index (HFI)

	Grading		
Test items	Right	Left	Criteria
1. Tip of thumb touches hypothenar of 5th finger	0	0	Test performed fully and with no delay
	1	1	Test performed fully but with effort or delay or both
	2	2	Tip of thumb touches
			Proximal phalanx 3 and 4
	3	3	Neither realized
2. Bending of 2nd finger	0	0	Clutched normally
	1	1	Cannot be bent fully: tip reaches palm
	2	2	Fingertip does not reach palm
3–5. Bending of 3rd, 4th, and 5th fingers	0	0	*As 2nd question*
	1	1	
	2	2	
6. Forearm held horizontal; palmar surfaces pressed together point upward	1	1	Test performed fully and no delay
	2	2	Test performed fully with effort or delay, or both
	3	3	Volar and dorsal flexion of wrist 45°
7. Forearm held horizontal; dorsal surfaces pressed together point downward	1	1	Fully; no delay
	2	2	Fully; with effort or delay, or both
	3	3	Palmar and ventral flexion of wrist 45°
8. Both backs of hands simultaneously on the table; elbows held rectangularly; ulnar margin of hand lifted	0	0	Performed fully
	1	1	Backs of hands on table; margin cannot lift
	2	2	Backs of hands not fully on table
9. Radial margins of hands simultaneously placed on table; thumb points downward before table edge; planes of hands inclined inward; no lateral bending of trunk	0	0	Performed fully
	1	1	Planes of hands perpendicular: cannot be inclined inward
	2	2	Planes of hand not vertical

Hand Functional Index (HFI) is the first of the nine questions [1] of Keitel Function Test (KFT) [2]

Raw scores of both hands are added to get the total score of HFI. It ranges between 4 and 42 points. The high score indicates bad function [1]

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Appendix 6: Michigan Hand Outcomes Questionnaire (MHQ)

Instructions: This survey asks for your views about your hands and your health. This information will help keep track of how you feel and how well you are able to do your usual activities.

Answer ***EVERY*** question by marking the answer as indicated. If you are unsure about how to answer a question, please give the best answer you can.

I. The following questions refer to the function of your hand(s)/wrist(s) ***during the past week***. (Please circle one answer for each question.) Please answer ***EVERY*** question, even if you do not experience any problems with the hand and/or wrist.

A. The following questions refer to your ***right*** hand/wrist.

	Very good	Good	Fair	Poor	Very poor
1. Overall, how well did your *right* hand work?	1	2	3	4	5
2. How well did your *right* fingers move?	1	2	3	4	5
3. How well did your *right* wrist move?	1	2	3	4	5
4. How was the strength in your *right* hand?	1	2	3	4	5
5. How was the sensation (feeling) in your *right* hand?	1	2	3	4	5

B. The following questions refer to your ***left*** hand/wrist.

	Very good	Good	Fair	Poor	Very poor
1. Overall, how well did your *left* hand work?	1	2	3	4	5
2. How well did your *left* fingers move?	1	2	3	4	5
3. How well did your *left* wrist move?	1	2	3	4	5
4. How was the strength in your *left* hand?	1	2	3	4	5
5. How was the sensation (feeling) in your *left* hand?	1	2	3	4	5

II. The following questions refer to the ability of your hand(s) to do certain tasks ***during the past week***. (Please circle one answer for each question.) If you do not do a certain task, please estimate the difficulty with which you would have in performing it.

A. How difficult was it for you to perform the following activities using your ***right hand?***

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	Not at all difficult	A little difficult	Somewhat difficult	Moderately difficult	Very difficult
1. Turn a door knob	1	2	3	4	5
2. Pick up a coin	1	2	3	4	5
3. Hold a glass of water	1	2	3	4	5
4. Turn a key in a lock	1	2	3	4	5
5. Hold a frying pan?	1	2	3	4	5

B. How difficult was it for you to perform the following activities using your ***left hand***?

	Not at all difficult	A little difficult	Somewhat difficult	Moderately difficult	Very difficult
1. Turn a door knob	1	2	3	4	5
2. Pick up a coin	1	2	3	4	5
3. Hold a glass of water	1	2	3	4	5
4. Turn a key in a lock	1	2	3	4	5
5. Hold a frying pan?	1	2	3	4	5

C. How difficult was it for you to perform the following activities using ***both of your hands***?

	Not at all difficult	A little difficult	Somewhat difficult	Moderately difficult	Very difficult
1. Open a jar	1	2	3	4	5
2. Button a shirt/blouse	1	2	3	4	5
3. Eat with a knife/fork	1	2	3	4	5
4. Carry a grocery bag	1	2	3	4	5
5. Wash dishes	1	2	3	4	5
6. Wash your hair	1	2	3	4	5
7. Tie shoe laces/knots	1	2	3	4	5

III. The following questions refer to how you did in your ***normal work*** (including both housework and school work) during the ***past 4 weeks***. (Please circle one answer for each question.)

	Always	Often	Sometimes	Rarely	Never
1. How often were you unable to do your work because of problems with your hand(s)/wrist(s)?	1	2	3	4	5
2. How often did you have to shorten your work day because of problems with your hand(s)/wrist(s)?	1	2	3	4	5
3. How often did you have to take it easy at your work because of problems with your hand(s)/wrist(s)?	1	2	3	4	5
4. How often did you accomplish less in your work because of problems with your hand(s)/wrist(s)?	1	2	3	4	5
5. How often did you take longer to do the tasks in your work because of problems with your hand(s)/wrist(s)?	1	2	3	4	5

IV. The following questions refer to how much ***pain*** you had in your hand(s)/wrist(s) ***during the past week***. (Please circle one answer for each question.)

A. The following questions refer to ***pain*** in your ***right*** hand/wrist.

1. How often did you have pain in your ***right*** hand(s)/wrist(s)?
   1. Always
   2. Often
   3. Sometimes
   4. Rarely
   5. Never

   If you answered ***never*** to ***question IV-A1*** above, please skip the following questions and go to the next page.
2. Please describe the pain you had in your ***right*** hand(s)/wrist(s).
   1. Very mild
   2. Mild
   3. Moderate
   4. Severe
   5. Very severe

	Always	Often	Sometimes	Rarely	Never
3. How often did the pain in your *right* hand(s)/wrist(s) interfere with your sleep?	1	2	3	4	5
4. How often did the pain in your *right* hand(s)/wrist(s) interfere with your daily activities (such as eating or bathing)?	1	2	3	4	5
5. How often did the pain in your *right* hand(s)/wrist(s) make you unhappy?	1	2	3	4	5

B. The following questions refer to ***pain*** in your ***left*** hand/wrist.

1. How often did you have pain in your ***left*** hand(s)/wrist(s)?
   1. Always
   2. Often
   3. Sometimes
   4. Rarely
   5. Never

   If you answered ***never*** to ***question IV-B1*** above, please skip the following questions and go to the next page.
2. Please describe the pain you had in your ***left*** hand(s)/wrist(s).
   1. Very mild
   2. Mild
   3. Moderate
   4. Severe
   5. Very severe

	Always	Often	Sometimes	Rarely	Never
3. How often did the pain in your *left* hand(s)/wrist(s) interfere with your sleep?	1	2	3	4	5
4. How often did the pain in your *left* hand(s)/wrist(s) interfere with your daily activities (such as eating or bathing)?	1	2	3	4	5
5. How often did the pain in your *left* hand(s)/wrist(s) make you unhappy?	1	2	3	4	5

V. A. The following questions refer to the appearance (look) of your ***right*** hand ***during the past week***. (Please circle one answer for each question.)

	Strongly agree	Agree	Neither agree **nor** disagree	Disagree	Strongly disagree
1. I am satisfied with the appearance (look) of my *right* hand	1	2	3	4	5
2. The appearance (look) of my *right* hand sometimes made me uncomfortable in public	1	2	3	4	5
3. The appearance (look) of my *right* hand made me depressed	1	2	3	4	5
4. The appearance (look) of my *right* hand interfered with my normal social activities	1	2	3	4	5

B. The following questions refer to the appearance (look) of your ***left*** hand ***during the past week***. (Please circle one answer for each question.)

	Strongly agree	Agree	Neither agree **nor** disagree	Disagree	Strongly disagree
1. I am satisfied with the appearance (look) of my *left* hand	1	2	3	4	5
2. The appearance (look) of my *left* hand sometimes made me uncomfortable in public	1	2	3	4	5
3. The appearance (look) of my *left* hand made me depressed	1	2	3	4	5
4. The appearance (look) of my *left* hand interfered with my normal social activities	1	2	3	4	5

VI. A. The following questions refer to your satisfaction with your ***right*** hand/wrist ***during the past week***. (Please circle one answer for each question.)

	Very satisfied	Somewhat satisfied	Neither satisfied **nor** dissatisfied	Somewhat dissatisfied	Very dissatisfied
1. Overall function of your *right* hand	1	2	3	4	5
2. Motion of the fingers in your *right* hand	1	2	3	4	5
3. Motion of your *right* wrist	1	2	3	4	5
4. Strength of your *right* hand	1	2	3	4	5
5. Pain level of your *right* hand	1	2	3	4	5
6. Sensation (feeling) of your *right* hand	1	2	3	4	5

B. The following questions refer to your satisfaction with your ***left*** hand/wrist ***during the past week***. (Please circle one answer for each question.)

	Very satisfied	Somewhat satisfied	Neither satisfied **nor** dissatisfied	Somewhat dissatisfied	Very dissatisfied
1. Overall function of your *left* hand	1	2	3	4	5
2. Motion of the fingers in your *left* hand	1	2	3	4	5
3. Motion of your *left* wrist	1	2	3	4	5
4. Strength of your *left* hand	1	2	3	4	5
5. Pain level of your *left* hand	1	2	3	4	5
6. Sensation (feeling) of your *left* hand	1	2	3	4	5

Raw scores are converted to a scale from 0 to100 according to a scoring algorithm [1]. Ranges for subscales are the following: hand function (5–25), unilateral ADL (5–25), bilateral ADL (7–35), work (5–25), pain (0–24), aesthetics (4–20), and satisfaction (6–30). Higher scores indicate better hand performance in all domains except pain. In the pain scale, high scores indicate more severe pain.

If 50% or more of the items in a scale are missing, then that particular scale cannot be scored. An overall MHQ score can be obtained by summing the scores for all 6 scales and divide by 6. If scores for more than two scales are missing, an overall MHQ score cannot be computed.

Reference

1. Chung KC, Pillsbury MS, Walters MR, et al. Reliability and validity testing of the Michigan hand outcomes questionnaire. J Hand Surg Am. 1998;23:575–87.

Appendix 7: Quick-DASH (The Disabilities of the Arm, Shoulder and Hand)

Instructions: This questionnaire asks about your symptoms as well as your ability to perform certain activities. Please answer *every question*, based on your condition in the last week, by circling the appropriate number. If you did not have the opportunity to perform an activity in the past week, please make your *best estimate* of which response would be the most accurate.

Answers to the questions

Questions 1–6, 11	Question 7	Question 8	Questions 9–10
1 = No difficulty,	1 = Not at all	1 = Not limited at all	1 = None
2 = Mild difficulty,	2 = Slightly	2 = Slightly limited	2 = Mild
3 = Moderate difficulty,	3 = Moderately	3 = Moderately limited	3 = Moderate
4 = Severe difficulty	4 = Quite a bit	4 = Very limited	4 = Severe
5 = Unable. **(Q = 1–6)**	5 = Extremely	5 = Unable	5 = Extreme
… = So much difficulty			
… = I can't sleep **(Q = 11)**			

Please rate your ability to do the following activities in the last week.

1. Open a tight or new jar.
2. Do heavy household chores (e.g., wash walls, wash floors).
3. Carry a shopping bag or briefcase.
4. Wash your back.
5. Use a knife to cut food.
6. Recreational activities in which you take some force or impact through your arm, shoulder, or hand (e.g., golf, hammering, and tennis).
7. During the past week, *to what extent* has your arm, shoulder, or hand problem interfered with your normal social activities with family, friends, neighbors, or groups?
8. During the past week, were you limited in your work or other regular daily activities as a result of your arm, shoulder, or hand problem?

Please rate the severity of the following symptoms in the last week.

9. Arm, shoulder, or hand pain.
10. Tingling (pins and needles) in your arm, shoulder, or hand.
11. During the past week, how much difficulty have you had sleeping because of the pain in your arm, shoulder, or hand?

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The sum of the responses produces a score, which then is transformed to obtain the Quick-DASH score. The final score ranges between 0 (no disability) and 100 (the greatest possible disability). Only one missing item can be tolerated, and, if two or more items are missing, the score cannot be calculated.

$$\text{QuickDASH Disability / Symptom Score} = \left[\left(\frac{\text{Sum of } n \text{ responses}}{n}\right) - 1\right] \times 25$$

where n is equal to the number of completed responses.

Reference

1. Beaton D, Wright J, Katz J. The Upper Extremity Collaborative Group. Development of the ***Quick*** DASH: comparison of three-item reduction approaches. J Bone Joint Surg Am. 2005;87:1038–46.

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