11 Restoration of Hand Function in Stroke or Spinal Cord Injury

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Abstract

Neurological injury, such as that resulting from stroke or spinal cord injury, often leads to impairment of the hand. Due to the importance of the hand in so many activities of our lives, diminished motor control can adversely affect quality of life, sometimes substantially. In the past 20 years especially, robotic and mechatronic technology has been developed to alleviate some of the functional losses resulting from neurological injury. The devices generally fall into one of two categories based on intended use: assistive technology, programmed to perform specific tasks for the user, and therapeutic technology, designed to facilitate therapeutic practice. Assistive devices are intended for chronic use when neurological recovery has reached a plateau, while the goal of therapeutic devices is to enhance recovery to the point where the devices are no longer needed. In the past, assistive robots have largely been developed to serve the needs of individuals with spinal cord injury, while therapeutic devices have targeted stroke survivors. As technology continues to evolve, however, it may be appropriate to consider greater application of assistive devices for stroke survivors, especially those with severe, chronic hand impairment. Conversely, as the population with incomplete tetraplegia grows, development of therapeutic devices for retraining hand movement in these individuals may become more feasible.

Keywords

Hand function • Stroke • Spinal cord injury • Assistive technology • Therapeutic technology

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V. Dietz et al. (eds.), *Neurorehabilitation Technology*,
DOI 10.1007/978-1-4471-2277-7_11, © Springer-Verlag London Limited 2012

11.1 Hand Neuromechanics

The hand is a wonderfully versatile instrument. We use our hands to communicate; to express ourselves through art, music, and writing; and to manipulate objects. In fact, our hands are our primary means of interacting with our environment.

The utility of the hand arises from its neuromechanical complexity. The hand, distal to the wrist, is comprised of 19 bones. The bones are connected through joints which provide 21 degrees of freedom (DOF). The thumb contains five DOF, and each finger has another four. The rotational axes of some of these consecutive DOF run at oblique angles to each other and are offset. This arrangement facilitates certain movements, such as thumb opposition [1].

A total of 27 muscles control these DOF. Three of these muscles, flexor digitorum profundus (FDP), flexor digitorum superficialis (FDS), and extensor digitorum communis (EDC), are each comprised of multiple compartments, which give rise to tendons for each finger. Most of these musculotendon units cross multiple joints and, thus, can influence multiple DOF simultaneously (Fig. 11.1). Many interact with anatomical structures such as annular ligaments serving as pulleys or aponeuroses such as the extensor hood, which runs across the dorsal side of the phalanges of the fingers. Four to sometimes five tendons insert into the extensor hood of each digit.

The extrinsic muscles, such as FDP, FDS, and EDC, originate proximal to the hand. These are the long, relatively large (in terms of cross-sectional area) muscles of the hand which provide most of the power. Tendons convey forces from these muscles across the wrist to the digits. The intrinsic muscles, such as the lumbricals and interossei, have both their origins and insertions within the hand. These muscles are generally smaller and tend to direct the forces generated at the fingertips and thumb tip. Due to the largest hand muscles being located in the forearm, high forces can be created in the hand while maintaining dexterity. Voluntary forces at the index fingertip can exceed 60 N, and thumb tip forces can exceed 100 N. Joint rotational velocity can exceed 1,200°/s.

Fig. 11.1 Illustration of the tendinous network on the dorsal side of the hand (Drawn by Jose Ochoa Escobar)

With these substantial numbers of muscles and DOF, motor control of the hand is complex. For example, significant activation of all seven muscles which actuate the index finger is needed to create even an isometric flexion force at the fingertip [2]. While neurological coupling between the finger muscles does occur [3], individuated finger movement can be performed to a remarkable extent in humans, especially for the thumb and index fingers [4]. Indeed, seemingly similar muscles for the same digit, such as EDC and extensor indicis, may be selectivity excited for different movements [5], and different compartments of even the same muscle may be activated independently [6].

This independence reflects the disproportionately large regions of the motor cortex and the corticospinal pathways devoted to the hand muscles [7]. Indeed, multiple representations of the hand [8] or of tasks involving the hand [9] have been located in the motor cortex. Specificity of cortical excitation is such that motoneurons for intrinsic hand muscles receive monosynaptic input from the cortex [10]. The major influence of cortical drive upon the hand motoneurons is further evidenced by the more limited role of brainstem pathways. While rubrospinal projections to cervical motoneurons may be prevalent in lower primates [11], these pathways are much sparser and of questionable physiological significance in humans [12].

Of course, coordinated motor control also depends heavily on sensory feedback information. Accordingly, the hand is richly innervated with sensory nerves. It has been estimated that 17,000 cutaneous mechanoreceptors are present in the glabrous skin alone of the hand [13]. Proprioceptive acuity, especially in the thumb, is superior to other body segments, such as the toes [14]. To support this sensory precision, a disproportionately large portion of somatosensory cortex is devoted to the hand [15].

11.2 Pathophysiology

With its heavy reliance on cortical innervation, control of the hand is especially affected by reduction of cortical input, such as after stroke or spinal cord injury. The resulting loss of motor control can have a profound impact on self-care, employment, and societal participation.

11.2.1 Stroke

Stroke is the leading cause of major long-term disability within the United States. Estimates number the current stroke population within the United States at greater than six million [16], a value that is only expected to grow as the population ages. Roughly 30–50% of these stroke survivors will have chronic hemiparesis, involving the hand in particular [17]. Deficits in voluntary digit extension are especially common [18].

A stroke is produced by either occlusion of blood vessels or hemorrhage in the brain. The extent and location of the resulting brain lesion or lesions can vary widely. Thus, it is often stated that no two strokes are alike. Yet, despite this diversity, stereotypical patterns of impairment emerge. In those stroke survivors with chronic hand impairment, the initial paresis and flaccidity are typically replaced by hyperexcitability of specific hand muscles. This hyperactivity may be manifest in several ways.

A signature presentation is a phenomenon termed spasticity. Externally imposed stretch of a spastic muscle results in a spinal reflex under conditions which would not produce a reflex response in nonspastic muscles. In the hand, spasticity is predominantly observed in the finger flexors, such as FDS and FDP. Interestingly, spasticity is largely absent in the long thumb flexor (flexor pollicus longus), even in individuals with spasticity in the finger flexor muscles [19], possibly due to the loss of the direct cortical input to the thumb muscles after stroke.

While a number of hypotheses have been proposed as to the origin of spasticity, one compelling theory is that the motoneuron pool of the spastic muscle sits at an elevated resting potential. Thus, excitation from the IA afferents during the stretch is sufficient to elevate some of the motor units above the firing threshold. In support of this supposition, one study found that 83% of the low-threshold motor units observed in the paretic biceps brachii exhibited spontaneous discharge [20]. In contrast, none of the units in the control subjects showed this spontaneous firing. Indeed, static stretch alone of certain muscles can be sufficient to generate neuromuscular excitation in some stroke survivors [21]. Absolute muscle length and change in muscle length both influence the magnitude of the spastic response. For example, flexion of the wrist, thereby shortening FDS and FDP, can dramatically reduce the magnitude of the stretch reflex triggered by imposed extension of the MCP joints [22]. The reflex response can be triggered by heteronymous, as well as the aforementioned homonymous, reflex pathways following stroke [23].

This hyperactivity may also be present during voluntary contraction. Attempts to open the hand using long finger extensors may actually result in net finger flexion due to excessive coactivation of the finger flexors. Thus, the first phase of grasp, opening the hand to position it around the object, may be substantially impaired. Object release may also be affected as deactivation of the finger flexors may be abnormal. Stroke survivors have been shown to have prolonged relaxation time in FDS following a grasp, both for the impaired and less impaired sides [24]. Deactivation time does shorten following administration of cyproheptadine, an antiserotonergic agent, possibly suggesting a role for monoamines in increasing the probability of firing within the motoneuron pool.

Despite the hyperexcitability of the flexor muscles, weakness is profound in the hand. Even in moderately impaired subjects, grip strength in the impaired hand is only 50% of that of the ipsilesional hand. The relative weakness in the fingers is asymmetrical, especially in severe hand impairment. For this population, index finger extension force is only 9% of the normal force value, while flexion forces reach roughly 27% of normal levels [25]. As absolute flexion force is normally much greater than absolute extension force in the fingers, this greater relative impairment exacerbates motor deficits. Thus, limited extension of the digits is a primary impediment to function following stroke [26].

Weakness may result from a number of sources, such as muscle atrophy (although ultrasound analysis revealed relatively little atrophy in the hand muscles) and change in muscle fiber type and composition; the primary cause, however, is neurological. Stroke survivors with chronic hemiparesis are often unable to fully activate the existing muscle fibers [27]. Even the fibers which can be voluntarily excited may not be fully activated due to reduced peak firing rates in motor units [28]. Additionally, activation patterns are abnormal, with the aforementioned excessive coactivation of agonists/antagonists, along with a substantial reduction in EMG modulation. Hand muscle activation patterns change surprisingly little for intended force generation in different, even opposite, directions in stroke survivors.

11.2.2 Spinal Cord Injury

Spinal cord injury (SCI) is one of the leading causes of chronic disability in the young. Around 260,000 individuals in the United States have SCI, with 12,000 new cases added each year [29]. The mean age at incidence is 40.2 years, and life expectancy is an additional 34 years for an injury occurring at that age. Interestingly, the increasing prevalence of SCI due to falls has led to a bimodal distribution of SCI incidence disproportionally skewed toward the young and the old. Falls are now the second most common cause of SCI, after automobile accidents [29].

The resulting functional impairments are dependent upon the location and extent of damage to the spinal cord. Compression, blunt trauma, and shearing, in addition to severing, of the cord are all potential mechanisms of SCI. Injury within the cervical region of the cord leads to tetraplegia, involving impairment of all four limbs. An estimated 55% of new cases will result in tetraplegia, while the other 45% will experience paraplegia due to injury below the cervical level. As acute treatment has improved, the number of incomplete spinal cord injuries has risen. With an incomplete injury, some of the neural tracts traversing the level of injury remain viable, such that some sensation and/or motor function is preserved [30]. Fifty percent or more of new SCI cases involve incomplete injury [29, 31].

Motoneurons below the level of the injury site often remain viable. In the lower extremity, this can give rise to potentially disabling spasticity and spasms. This is much less common in the upper extremity, but abnormal interlimb reflexes, in which stimulation of lower limb nerves can produce excitation of hand muscles, may be present [32]. In low tetraplegia (C5–C8), some muscle tone may be prevalent, although extensor muscle tone seems to be as prevalent as flexor muscle tone, unlike the situation in stroke survivors. In high tetraplegia (C1–C4), flaccidity is common in the hand muscles.

Still, some motoneurons will be damaged, even multiple segments below the level of the injury. One study observed up to a 90% loss of motor units in the thenar muscles of the thumb in subjects at the C4–C5 level [33]. While axonal sprouting may help to increase the number of muscle fibers innervated, denervation atrophy often leads to disuse atrophy, further reducing strength. Even in cases of incomplete cervical SCI, atrophy of 70% of the triceps brachii muscle can be seen [34]. In contrast to stroke, substantial atrophy of the hand muscles is a common sequela of SCI.

Muscle imbalance can also lead to impairment. For example, C7 return can bring extension but with a lack of flexor activity to counteract the extensors. As noted previously, controlled force production or movement of the digits requires the coordinated activation of many muscles, including seeming agonist/antagonist pairs such as EDC and FDP. Without the activation of the digit flexors, quality of hand movement is poor. For individuals with C8 tetraplegia, control of the extrinsic muscles is spared, but the intrinsic muscles may be paralyzed. The resulting imbalance again impairs hand function.

Tract damage coupled with a reduced number of targets for cortical neurons may be accompanied by substantial brain plasticity. The loss of ascending sensory input also contributes to these changes in which areas of the brain formally associated with the hand become associated with other tasks or parts of the body. For example, one study reported expansion of cortical neurons responsive to touch of the face into regions normally responsive to the hand in adult monkeys following transaction of the cervical dorsal columns [35].

The loss of descending input also leads to changes in the basic firing pattern of motor units. Reduced nerve conduction velocities, diminished tetanic force production, and elongated twitch times were reported in the thenar thumb muscles for individuals with chronic tetraplegia [36]. Some researchers have attributed these changes not only to alterations in descending neural excitation but also to a reduction in the serotonin normally transported through descending axons [37].

The lack of muscle contraction can lead to hand edema, as venous return is limited, thereby restricting movement. If the paralyzed hand muscles are not stretched and range of motion is not performed at the corresponding joints, contractures may develop as the resting muscle length shortens to accommodate the new hand posture. Additionally, connective tissue may form around the tendon or joint capsules, further impeding joint rotation. While contracture of flexor hand muscles was often encouraged in the past to facilitate a tenodesis grasp, current practice focuses on trying to prevent these contractures while maintaining a functional tenodesis grasp for those with low tetraplegia.

11.3 Rehabilitation Technology

Technology has been developed in an effort to facilitate hand rehabilitation for both stroke and SCI survivors. The nature of the technology has been shaped by its intended use. In some cases, the primary goal was to create tools that could provide assistance for tasks which could no longer be performed by the user. Such assistive devices are intended for chronic use. Alternatively, therapeutic devices were built to facilitate rehabilitation over a finite set of training sessions, with the ultimate goal of promoting recovery so that the device is no longer needed.

Development of assistive technology has especially been spurred by the needs of individuals with tetraplegia, where both hands are often substantially impaired. The loss of control of both hands can be extremely disabling due to the importance of the hands to daily living. Thus, the relatively large mass and bulk of the added equipment needed to provide assistance may be better tolerated in this population, as the potential increase in function is so great. Additionally, a number of individuals with tetraplegia are extensive wheelchair users, particularly of power wheelchairs. These wheelchairs provide a platform for supporting external equipment to assist hand function.

In contrast, technology for stroke survivors has focused on therapeutic devices. While the ipsilesional hand may exhibit some deficits [38], these deficits are relatively mild in comparison with the contralesional hand. Thus, the functional limitations of the upper extremities following stroke are generally not as great as in tetraplegia, and subsequently the drive to incorporate assistive devices is not as large. Additionally, the majority of stroke survivors are ambulatory, which makes the additional weight and bulk of assistive devices potential detriments to function.

11.3.1 Assistive Devices

As the dexterity of the hand is still difficult to replicate in mechatronic devices, assistive technology has traditionally focused on facilitating a specific subset of tasks. For example, a set of adaptive tools have been created which can insert into a splint worn on the wrist. These tools include modified utensils, brushes, and electric razors. In this manner, the hand is no longer required for grasping these tools; basic activities of daily living, such as feeding and grooming, can be performed with residual control of the arm. While this adaptive equipment can be very effective, it does require proper motor control of the arm as well as typically some assistance to change tools in order to perform a different task. Facilitation of grasp and manipulation of other objects is limited.

To provide a greater degree of assistance, such as might be required by those with a higher-level cervical injury, and to allow for greater task flexibility, robotic assistants have been produced. These robots could be located at a workstation, mounted directly to the user's wheelchair, or placed atop a mobile platform (and thus move autonomously). One of the first successful assistive robots was the Handy 1 [39], a robot workstation that could be used for eating, drinking, grooming, and even art projects (Fig. 11.2). The Handy 1 employed a Cyber 310 robotic arm, which had five DOF in addition to a gripper end effector. It was controlled through a PC 104, and the user could operate the device through a single switch. Newer robots have been incorporated into updated feeding assistants. My Spoon (SECOM Co., Ltd., Tokyo, Japan) and a feeding robot designed explicitly for Korean food [40] are currently being produced. These devices are more compact than their predecessors and offer control options for the user. Other robotic workstations have been designed to provide alternative services. For example, the Desktop Vocational Assistant Robot (DeVAR) was created to provide assistance within an office environment. It consisted of a commercial PUMA-260 robot coupled to a Griefer prosthetic hand from Otto Bock Healthcare (Duderstadt, Germany).

Fig. 11.2 The Handy 1 workstation, intended to help users with eating, drinking, and grooming. First developed by Mike Topping at Staffordshire University (Reprinted with permission from: Topping [92]. © Emerald Group Publishing Limited; all rights reserved)

To increase the range of tasks and situations in which they could be employed, robotic systems were developed which could be mounted directly to a wheelchair. The KARES system created at the Korea Advanced Institute of Science and Technology (KAIST) has six DOF in its robotic arm and a gripper at its end [41]. KARES could perform tasks such as grasping objects and turning off and on light switches under direction from the user. Its successor, KARES II, had a mobile

Fig. 11.3 The *i*ARM wheelchair-mounted assistive robot, seen here assisting a user to mail a letter (Photo courtesy of Exact Dynamics, Didam, the Netherlands)

platform, which could extend the workspace of the robot, and compliant control which facilitated interactions with the environment [42]. The Raptor Wheelchair Robot System was developed by the Rehabilitation Technologies Division of Applied Resources Corp. (RTD-ARC) expressly as an assistive device. It received US Food and Drug Administration (FDA) approval and was sold commercially beginning in 2000 [43]. The Raptor arm had four DOF with a gripper which permitted grasping of objects. The most commercially successful wheelchair-mounted device has been the MANUS, which has evolved into the *i*ARM (Exact Dynamics, Didam, the Netherlands). The *i*ARM provides six DOF and a gripper end effector and can be powered from a wheelchair battery [44]. It is designed for close interaction with the user (see Fig. 11.3). A wide variety of control options are available dependent upon the capabilities and preferences of the user.

Attempts have also been made to provide mobile robotic assistants which could move independently from the wheelchair. The MoVAR device, developed at Stanford University and the Rehabilitation Research and Development Center at the VA Palo Alto Health Care System, consisted of a PUMA robot arm affixed to a powered omnidirectional base [45]. Autonomous mobile robots, intended for a number of possible applications, could also provide valuable functions for individuals with tetraplegia. For example, the assistant Care-O-bot®3 (Fraunhofer IPA) or the courier Pyxis HelpMate (Pyxis Corporation) had the potential to benefit those with tetraplegia by retrieving and transporting objects.

Recently, some assistive devices have been developed expressly for the hand to facilitate grasp and release [46]. The Rehabilitation Glove, created at the Royal North Shore Hospital in Sydney, Australia, uses intelligent polymers to actuate a glove worn by the user. The Soft Extra Muscle Glove (Bioservo Technologies, Isafjordsgatan, Sweden) could help individuals with incomplete tetraplegia by amplifying their grasping force.

One of the key limitations preventing widespread employment of assistive devices is the control of these devices. Our hands are able to perform a wide variety of tasks with limited conscious input. With assistive technology, user intent must be conveyed to the device in a translatable manner. For example, to bring a cup of water to the mouth for drinking, the robot needs to not only know that this is the intended action but also the location and orientation of the cup, the grasping force to be used, the speed at which it should be moved, and the path to be taken to avoid collisions. While some of these decisions can be made by the device, to truly have the desired flexibility, these parameters should be modifiable by the user. Providing this type of control for external devices remains challenging, especially for individuals with limited motor control. Thus, while joysticks and trackballs may be good input devices for some users, they may not be feasible for individuals with high tetraplegia. Instead, inputs like head trackers, eyelid switches [47], and a tongue-driven mouse [48] have been created to maximize the utility of residual motor control for indicating user intent.

One means of providing facile control of multiple DOF of an assistive device is to use neurological signals directly from the user. Implantable electrode arrays of up to 100 electrodes can be placed directly into the human motor or premotor cortex. These cortical signals are mapped into intended movements which can then be employed to drive external devices. For example, recordings from motor cortex have been successfully used in monkeys to drive a robot to move to specific locations in space [49]. Another group implanted cortical electrodes in individuals with tetraplegia to control a mouse on the computer screen [50]. A noninvasive alternative is to use electroencephalogram (EEG) signals to drive assistive technology. The EEG signals have been used to control an actuated hand orthosis by an individual with tetraplegia [51].

11.3.2 Therapeutic Devices

While assistive technology has continued to evolve to improve functionality, obviously, the best outcome would be for the user to regain sufficient motor control such that the assistive technology is no longer needed. Thus, in recent years, there has been a substantial shift in research focus from assistive robots to therapeutic devices which would facilitate rehabilitation of the impaired movement.

This thrust has been spurred by research showing that the central nervous system exhibits much greater plasticity than previously imagined. Even the mature nervous system is constantly changing and adapting to new circumstances. For example, repeated practice of hand movements, such as performed by musicians, can lead either to seemingly beneficial cortical changes in sensorimotor representation and processing [52, 53] or to harmful changes, such as in focal dystonia [54].

Experimental evidence suggests that intensive repetitive training of new motor tasks is required to induce long-term brain plasticity [55]. This finding seems to be applicable to motor relearning after brain injury, such as from stroke, as well. In animal models of brain injury, practice appears to be the primary factor leading to synaptogenesis and brain plasticity [56–58]. Thus, even long after injury, the central nervous system retains some degree of plasticity. Numerous studies employing the constraint-induced technique, in which focus is placed on intensive practice with the impaired arm while use of the ipsilesional arm is restricted, have shown improvement in hand capabilities [59–62]. Similarly, following stroke, repetitive practice has been shown to lead to functional improvement [62]. Imaging performed during constraint-induced training studies has shown evidence of cortical plasticity following the training [63, 64].

While the importance of practice to motor relearning after injury is widely accepted, the optimal type of practice remains a matter of debate. Some proponents have favored simpler movements, which can be repeated more frequently. For example, one study looked at repetitive wrist flexion/extension and forearm pronation/supination, supported by the Bi-Manu-Trak, a device with a single DOF which could be used to support either the wrist or forearm motion [65]. Subacute stroke survivors participated in trials in which they performed these movements over 6 weeks. The gains in upper extremity Fugl-Meyer scores [66] were substantial (mean 18 points) compared to the gains in another group receiving electrical stimulation therapy (3-point gain). In a later study, however, similar improvements were seen in both the group receiving therapy with the arm trainer and with the group receiving electrical stimulation [67]. Byblow and Stinear looked at the benefits of repeated practice of a simple wrist flexion/extension movement. In this paradigm, the less impaired wrist drove the impaired wrist through custom-developed mechanical coupling [68]. A follow-up study confirmed some beneficial effects for this therapy when combined with other activities [69]. Furthermore, the results of another study showed no benefit to adding functional grasps to training of arm movements [70]. These studies, however, did not measure functional task performance.

Alternatively, a number of researchers and therapists have recommended task-specific training, in which participants focus on the tasks they wish to be able to perform in their daily lives. According to this view, just as one practices a tennis serve to improve one's serving, so should stroke survivors practice opening a jar or a task of similar importance to them. Indeed, retraining of walking after stroke consists of repeated walking. In the upper extremity, functionally based training has been shown to lead to some improvements over strength-based training, for example [60]. Reaching toward physical objects as part of a task was seen to lead to enhanced quality of movement as opposed to simply reaching to a location in space in stroke survivors [71]. Practice, however, is often limited by time or stamina. The possibly greater complexity of functional tasks may limit the number of repetitions that can be performed. Additionally, it may prove more difficult to generate functional tasks for which partial success, which helps maintain engagement of the client during a challenging exercise, is possible. The nonfunctional exercise, e.g., opening and closing the hand, may be achieved to varying degrees while the criteria for success for a functional task, e.g., opening a pill bottle, may appear more binary for a client.

Task performance of any type with the hand can prove challenging after stroke. The 21 DOF are difficult to control, even with a therapist guiding rehabilitation. Thus, a number of mechatronic devices have been developed within the last 10 years to facilitate hand rehabilitation following stroke. One approach has been to focus on a single, fundamental movement of the hand, namely opening and closing. To promote practice of this motion, mechatronic objects have been created which can expand or contract to open or close the hand, such as the hand module for the MIT-MANUS robot [72] and a haptic knob grasped by the user [73].

For devices that directly couple to the hand, one of two strategies has generally been adopted: either the structure of the device remains distal to the fingertip and is externally grounded or it resides on or proximal to the hand and is grounded to the hand or arm. The first category of devices connects to the hand only at the tips of the digits. The great advantages of this approach are that only one interface between the finger and device is needed per digit, minimal mass is added to the hand, and interference between adjacent digits or joints is minimized. For example, a small robot was created to provide either haptic feedback or rehabilitation for the index finger [74]. The robot is affixed to a tabletop and connects to the tip of the index finger. The two active DOF of the robot can control fingertip position throughout the sagittal plane workspace of the finger. Amadeo System (Tyromotion, GmbH, Graz, Austria) and HandCARE [75] also use variations of this approach for stroke rehabilitation (Fig. 11.4); the fingertips are attached to linear tracks or cables, respectively, which directly control fingertip location, thereby affecting, although not rigidly controlling, all of the joints in the digit. There are, however, some disadvantages to this approach. One drawback is that the hand position and orientation must be fixed as the devices are externally grounded. Thus, it is not possible with these devices to incorporate hand training into reach-to-grasp movements, for example, or to permit movement of the user. Training with real objects is largely precluded, and joint-level control is limited.

An alternative approach is to internally ground the device to the hand or arm. Typically, in this design, the actuation force is transmitted across the joint to be controlled, although the PERCRO L-EXOS system from the Scuola Superiore Sant'Anna uses a hybrid approach. The terminal portion of this exoskeleton controls the thumb and index fingers through contact solely with the distal segments of these digits, although the actuators are internally grounded to the forearm. More commonly, a glove or exoskeleton is utilized to connect to the hand and permit force transmission across the joints of interest. To limit complexity, a number of devices of this design

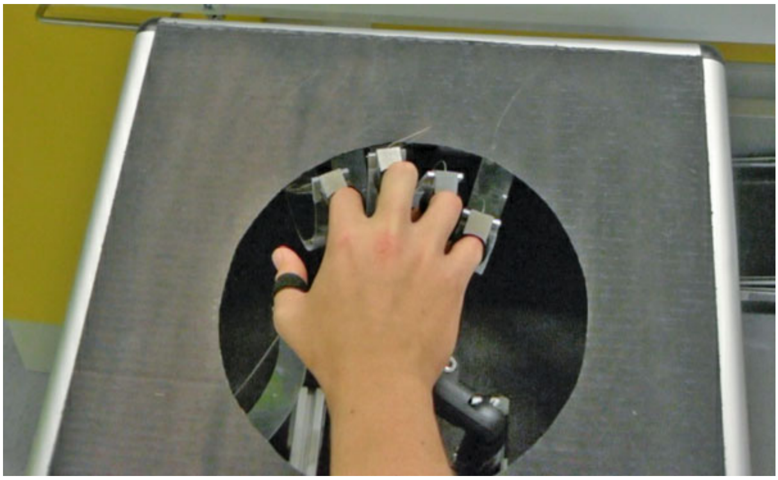

Fig. 11.4 HandCARE3 system. Cables attached to the fingertips can pull the digits open. The springs shown provide a restoring force to push the digits back into flexion when the pulling force is removed (Photo courtesy of Dr. Etienne Burdet of the Imperial College London)

move multiple digits simultaneously. HWARD [76], HEXORR [77], and the Hand Mentor (Kinetic Muscles Inc., Tempe, AZ) are exoskeletons that rotate all four MCP joints of the fingers (and additionally all four PIP joints for HEXORR) together. HWARD and HEXORR use fixed platforms but provide thumb actuation; the Hand Mentor does not actuate the thumb but can move with the arm.

To increase the extent of hand tasks allowed, some devices have provided independent control of each digit. The Rutgers Master II-ND [78] was one of the first devices developed for hand rehabilitation. It uses pneumatic cylinders on the palmar side of the digits to move the fingertips. The PneuGlove [79], in contrast, uses air bladders on the palmar side of a glove to assist digit extension and provide resistance to flexion for each digit. It takes advantage of the asymmetry in impairment of finger extension and flexion in stroke survivors, so that only extension is assisted. Similarly, the CyberGrasp haptic system (Immersion Corporation, San Jose, CA) has been incorporated into a rehabilitation virtual reality paradigm [80]. The CyberGrasp can provide extension forces only to each digit independently through a cable system traversing the back of the hand.

All three of these systems permit considerable movement of the arm. The PneuGlove and CyberGrasp can be used with either real or virtual objects. Another device, the X-Glove, built at the Rehabilitation Institute of Chicago, employs linear motors that pull on cables running along the dorsal side of the digits to offer independent extension assistance for each digit (Fig. 11.5).

To perform more complicated tasks, mechatronic devices may need to actively control more DOF within the hand. One exoskeleton which does allow independent control of finger joints has been designed for rehabilitation of occupational injuries [81] but may also be useful for stroke rehabilitation. DC motors actuate the exoskeleton, which controls the individual joints through Bowden cables. Thus, the mass of the motors can be located off the hand, although the Bowden cables do introduce considerable friction which may slow response time. An 18-DOF device has been developed at Gifu University in Japan for hand and wrist rehabilitation following stroke [82]. The motors actuating the joints are located directly at the joints (see Fig. 11.6). A single motor can thus rigidly control joint rotation in either the clockwise or counterclockwise direction, although the torques that can be provided are relatively small due to the limited motor size.

11.4 Current Status

While assistive robots may be very beneficial for a targeted population, they serve a relatively small market relative to the technological sophistication of the devices. Numbers of the Handy 1

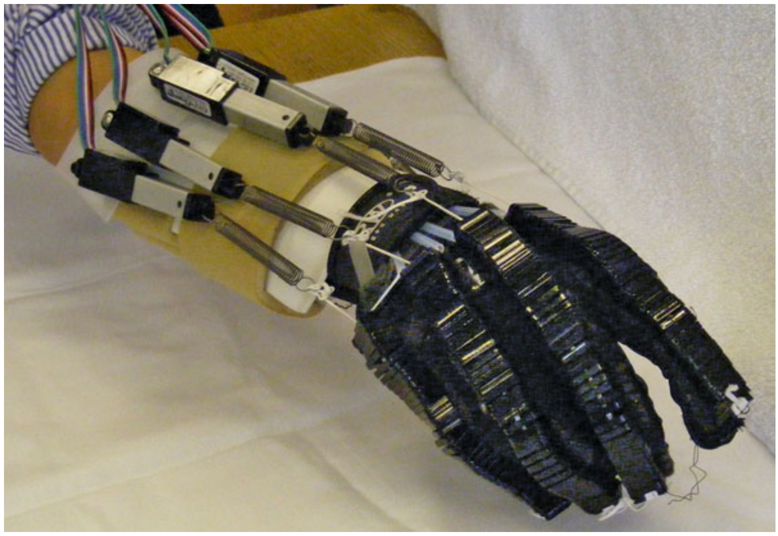

Fig. 11.5 The eXtension-Glove (Rehabilitation Institute of Chicago, Chicago, IL, USA), intended to assist digit extension following stroke. Cable runs through guides on the back of each digit to a linear motor driven by a microcontroller. The entire device is portable

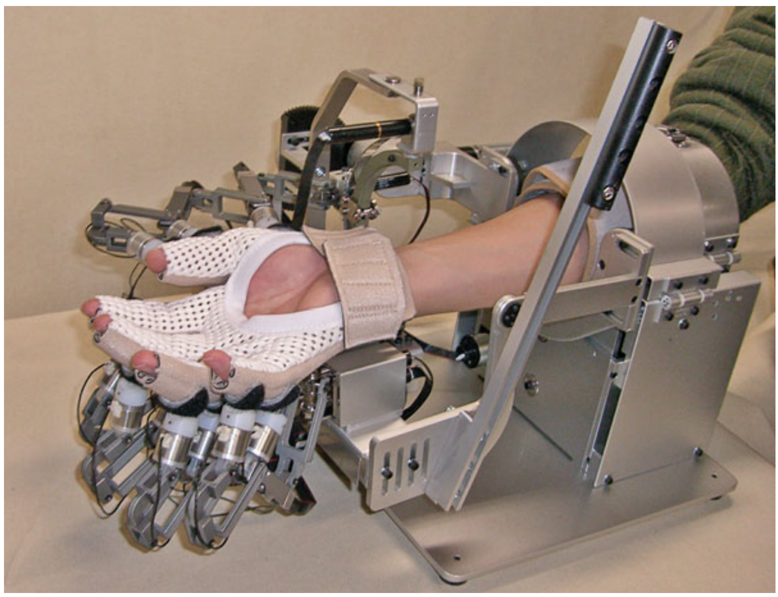

Fig. 11.6 Picture of a hand exoskeleton with 18 actuated DOF. Motors are located at the joints of interest. The exoskeleton can be controlled by the contralateral hand using a master–slave paradigm (Photo courtesy of Dr. Haruhisa Kawasaki of Gifu University)

and MANUS (*i*ARM) sold are in the hundreds rather than thousands or tens of thousands. Thus, research and manufacturing costs have to be spread across a limited number of units, and overall costs remain high, thereby limiting the potential for more widespread adoption from individuals who might benefit from use of the technology. Assistive technology targeting low tetraplegia, such as C7–C8, may be able to take advantage of residual function to reduce complexity and cost. Wearable devices which facilitate grasp and release, for example, would be helpful for this population.

Intriguingly, the emergence of aging populations in many developed countries has led to a new push in the area of assistive devices to meet the needs of the growing geriatric populace. Mobile assistants like EL-E [83], HERB (Intel Labs Pittsburgh, Pittsburgh, PA), and ASIMO (Honda Corporation) are being developed in the hopes of serving an older population with potentially restricted mobility and diminished upper extremity function. These assistants could also prove beneficial for individuals with tetraplegia. Research in powered exoskeletons continues to grow as well to meet the expected needs of either the military or the elderly. Devices like the Stride Management Assist (Honda Corporation, Tokyo, Japan) and Sarcos XOS skeleton (Sarcos, Salt Lake City, UT) are designed to augment the capabilities of the wearer. Again, this technology may also be applicable to helping those with SCI.

Assistive technology which is wearable may also be a boon for stroke survivors. Current therapies have had limited success helping those with severe hand impairment. These individuals are generally excluded from trials such as constraint-induced therapy [62], as these therapies have not proven effective for them. Many stroke survivors with severe hand impairment, however, retain some ability to voluntarily close the hand. While grasp is weak, it is present. The problem lies in opening the hand sufficiently to position it for grasp and to reopen the hand to release the object. Seemingly, assistive devices could provide this hand opening. The impaired hand could then participate in simple but functionally important tasks, such as stabilizing objects as they are manipulated by the other hand (e.g., opening a jar) or carrying objects, such as a bag. For stroke survivors, hemiparesis involving both the upper and lower extremities is common. Thus, the inability to carry or hold an object with the contralesional hand can greatly affect activities of daily living or mobility as the ipsilesional hand may be needed to control a cane during walking. Actions like carrying a glass of water from the sink to the table may then not be possible. In fact, some stroke survivors become nonambulatory inside their homes due largely to the lack of useful hand function.

While a number of therapeutic devices continue to be developed for the stroke hand, studies examining efficacy of these devices remain sparse. The majority of these studies consist of single or multiple case studies, such as with the Rutgers Hand Master [78], the Hand Mentor [84], CyberGrasp [85], and HandCARE [86]. Encouraging results were seen in larger studies for HWARD [76] and the haptic index finger device [74], although these studies did not include a true control group. In those studies employing a control group receiving similar amounts of therapy to the group using the device, gains were generally not significantly different between the groups [79, 87, 88]; both groups showed improvement. Equivalent improvement, however, is not necessarily a negative outcome. One of the key benefits of the therapeutic devices is their facilitation of extended practice, either in the clinic or, ideally, in the home. Opportunities for therapy are often limited; for example, individualized outpatient therapy in the United States typically totals less than 3 h per week. The therapeutic devices may enable the repetitive practice necessary for rehabilitation and improve motivation to keep the user engaged.

It is anticipated that more efficacy studies will follow as these technologies become more mature. Key questions remain, however, regarding the best uses of the devices to facilitate rehabilitation: Should the device assist or resist movement? Should movement error actually be augmented? [89] How do we ensure maximum effort of the user without making the task so difficult that the user quits? How complex should the training tasks be?

These therapeutic devices, while developed largely for the stroke population, may be appropriate for individuals with incomplete tetraplegia as well. Indeed, preliminary studies using massed practice therapy in SCI have shown some improvement, both in animal models [90] and in individuals with tetraplegia [91]. Gait therapy for paraplegia increasingly relies on body-weight-supported treadmill training. This is often done in conjunction with therapeutic devices to facilitate leg movement, such as the Gait Trainer I (Reha-Stim, Berlin, Germany), the Lokomat (Hocoma Medical Engineering, Inc., Zurich, Switzerland), or the AutoAmbulator (HealthSouth, Birmingham, AL, USA). Surprisingly, similar practice with the upper extremity is much more limited. A number of the previously described devices that have been developed for stroke therapy could be applied to the SCI population as well.

Conclusions

The neuromechanical complexity of the hand makes it a challenging target for therapy after stroke or SCI. For those individuals in whom the prospect for functional return is limited, a number of assistive mechatronic devices have been developed to perform some of the tasks previously executed with the hands. As robotic grippers become more dexterous, the capabilities of these devices will expand. Additionally, growing research in the area of wearable exoskeletons to assist the geriatric population should benefit as well those with neuromuscular injury, including stroke survivors.

Therapeutic devices for the hand continue to evolve, with new actuators and materials promising even greater gains in the ratio of power to weight. The primary obstacle in terms of hardware, however, remains the interface between the device and the hand. The optimal means of exploiting these mechatronic devices remains to be determined as well. The efficacy of using this equipment in therapeutic hand training of individuals with incomplete tetraplegia warrants exploration.

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