Implementation of Impairment-Based Neurorehabilitation Devices and Technologies Following Brain Injury

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Abstract

The implementation of electromechanical devices for the quantification and treatment of movement impairments (abnormal muscle synergies, spasticity, and paralysis) resulting from brain injury is the main topic in this chapter. The specific requirements for the use of robotic devices to quantify these impairments as well as treat them effectively are discussed. A case is made that electromechanical devices not only generate a vehicle to augment treatment intensity but more importantly allow for the precise measurement and treatment of specific impairments using scientifically underpinned approaches. Acceptance of these new technologies is dependent on proof of their effectiveness in treating movement impairments and on future clinical trial evidence for accompanying improvements in activities of daily living and quality of life. Furthermore, the need of a concerted effort to simplify these new technologies, once essential treatment ingredients have been determined, is seen as being a key component for their acceptance in the clinic on a large scale. Finally, it is crucial that we demonstrate that electromechanical technologies are indeed more effective in delivering rehabilitative care, by reducing required treatment time in

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V. Dietz et al. (eds.), *Neurorehabilitation Technology*,
DOI 10.1007/978-1-4471-2277-7_19, © Springer-Verlag London Limited 2012

expensive clinics while maintaining, and even improving, functional outcomes. This is a requirement for future technology development and acceptance in the clinic and at home, especially in a health care environment where rehabilitation costs become more and more prohibitive.

Keywords
Brain injury • Stroke • Rehabilitation • Robotics • Technology • Spasticity • Synergies • Movement impairment

19.1 Introduction

Sensorimotor deficits and restricted mobility are among the more prevalent problems encountered by individuals following brain injury such as stroke. While the expression of stereotypical muscle synergies, spasticity, and paralysis are common to many forms of brain injury, it is only in recent years that we have begun to understand how each of these sensorimotor deficits may impact movement. It is with the advent of rehabilitation robotics and associated robotic technologies that scientists have begun to rigorously study both the specific impairments and their contribution to movement dysfunction. Additionally, as understanding of sensorimotor deficits has increased, new knowledge has been applied to the development of rehabilitation interventions capable of directly targeting fundamental impairments. In recent years, widespread use of rehabilitation robotics has demonstrated improvements in motor function and strength in the paretic upper limb. However, all of these interventions have fallen short of generating significant improvement in activities of daily living (ADL) [1–3]. The lack of significant results in the area of ADL can be attributed to numerous factors such as low resolution of ADL measurements and small sample sizes in early investigational clinical trials. However, the most likely explanation may be that most robotic interventions lack a solid scientific underpinning. For example, many rehabilitation robotic therapies aim to reproduce existing therapeutic approaches such as practicing functional tasks but with the added benefit of greater intensity and duration [1–3]. Reproduction of existing hands-on rehabilitation approaches ignores the quantitative strength of robotics to identify the impairments responsible for movement dysfunction (scientific underpinning) and therefore will not likely advance neurorehabilitation beyond its current state. On the other hand, recent work has demonstrated that robotic devices can characterize fundamental impairments such as the presence of abnormal muscle synergies [4], weakness [5, 6], or spasticity [7–15] and has demonstrated their relationship to functional movement [16]. With quantitative identification of impairments, a robotic rehabilitation approach can be developed, intervening in a specific and rigorous fashion directly targeting the impairments that are responsible for ADL limitations. Early evidence for the use of robotics in providing high-resolution measures of motor impairment in the upper limb of individuals with stroke will be provided, as well as preliminary results from novel robot-mediated interventions that can complement conventional neurotherapeutic interventions. In short, we will show that new robotic technologies are ideal for the delivery of novel science-underpinned therapeutic interventions that can be implemented in current rehabilitation clinics as well as provide such interventions in a more controlled fashion and with greater intensity than conventional rehabilitation. Furthermore, considerations for successful transition to clinical practice will be highlighted including methods to increase acceptance by the therapist and patient such as merging entertainment with impairment-based rehabilitation robotics through the implementation of virtual gaming environments.

19.2 Quantification of Impairment

19.2.1 Quantification of Abnormal Synergies and Weakness Using Electromechanical Devices

A central abnormality in unilateral hemispheric brain injury is the loss of independent control of joint movement that is evident in the form of stereotypic movement patterns [17–19]. It is believed that these stereotypic movement patterns are an expression of abnormal muscle coactivation patterns or muscle synergies. We have presented quantitative evidence for the existence of abnormal muscle coactivation patterns using electromyography (EMG) from elbow and shoulder muscles in the paretic arm of individuals with stroke during static force exertions in various directions and of various magnitudes [20]. Using static or isometric mechanical measurements, we were able to improve the quantification of abnormal muscle coactivation patterns with a six-degree-of-freedom load cell [21, 22]. Using this approach, we studied the expression of isometric elbow and shoulder torque patterns during the generation of maximum voluntary torques one direction at a time. During the execution of this single-task protocol in a primary direction, we observed relative weakness in the paretic limb compared to the contralateral limb, and we found strong abnormal coupling between elbow flexion and shoulder abduction/extension/external rotation and elbow extension and shoulder adduction/internal rotation in the paretic limb of individuals with stroke [22, 23]. Conversely, control subjects, and individuals with stroke in their nonparetic arm, only generated nominal torques in secondary degrees of freedom. In subsequent studies, we measured maximum voluntary elbow torques under three different conditions: in combination with 10% and 50% of maximum shoulder abduction torque and in combination with 10% of maximum shoulder adduction torque [21]. The torque combinations most affected were those that required the subject to deviate from the abnormal torque patterns observed during the single-task paradigm. Specifically, individuals with stroke exhibited an impaired ability to generate elbow extension torque with the paretic limb when increasing shoulder abduction (i.e., the 50% shoulder abduction level). The opposite trend was observed for elbow flexion torque. Individuals with stroke exhibited an enhanced ability to generate elbow flexion torque in the paretic limb with increasing levels of shoulder abduction torque. These abnormal torque patterns are analogous to the abnormal upper extremity movement synergies described in the clinical literature (see Table 19.1) [17]. These results demonstrated the existence of a strong and abnormal linkage in the paretic limb between elbow flexion and shoulder abduction and between elbow extension and shoulder adduction. Quantification of this fundamental impairment was only possible through the implementation of multi-degree-of-freedom force/torque sensing technologies. Application of these new technologies would then set the stage for the execution of dynamic experiments and subsequent robotic development.

Table 19.1 Upper limb synergies in hemiparetic stroke [17]

Flexor synergy	Extensor synergy
Flexion of the wrist and fingers	Extension of the wrist and flexion of fingers
Flexion of the elbow	Extension of the elbow
Supination of the forearm	Pronation of the forearm
Abduction of the shoulder	Adduction of the arm in front of the body
External rotation of the shoulder	Internal rotation of the shoulder
Shoulder girdle retraction and/or elevation	Shoulder girdle protraction

Our first dynamic study investigated the effect of synergies on movement as a function of support condition (supported versus unsupported) on planar reaching and retrieval movements by comparing the kinematic and kinetic characteristics of gravity-eliminated (supported on a frictionless table) and free (unsupported) upper limb movements [23–25]. Support of the upper limb in the supported condition was provided by a low-friction air-bearing apparatus and by activation of the shoulder musculature in the unsupported condition.

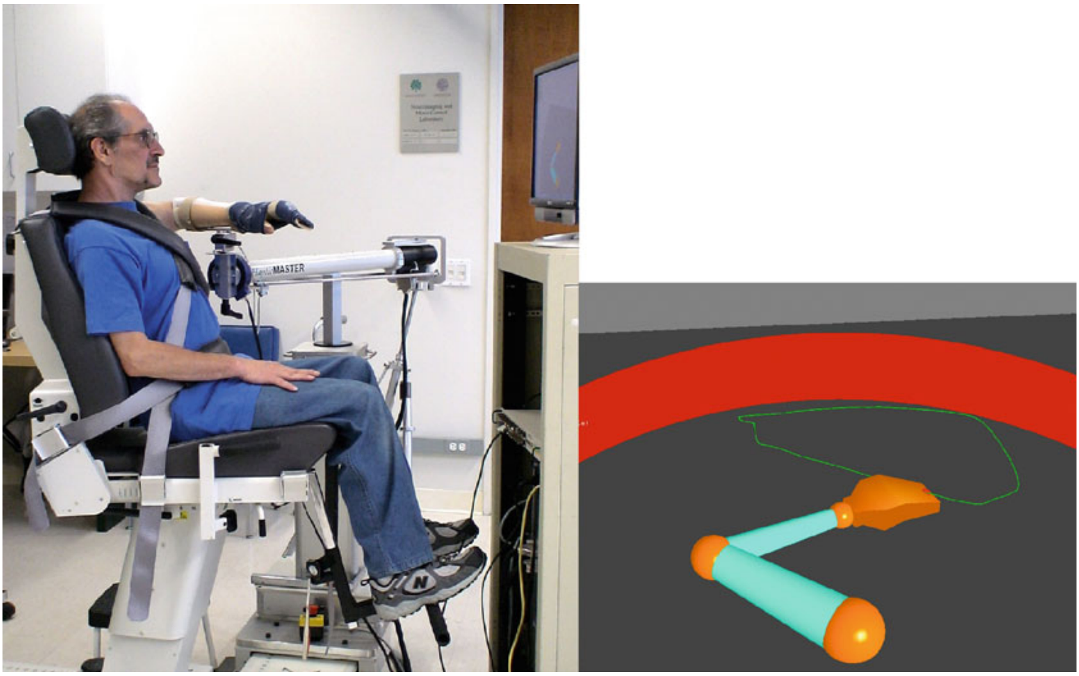

Fig. 19.1 (*Left*) Illustrating ACT-3D robot with gimbal and orthosis. (*Right*) Example of the visual feedback. The haptic table is shown by the *darker gray*, which the arm is resting on. In the envelope protocol (see measurement of work area below), subjects will use the *red arc* as their goal, with the *green tracer* shown to give them a reference to their performance in previous circles (With kind permission from Springer Science+Business Media: Sukal et al. [4])

For either limb of control subjects, as well as the nonparetic limb of individuals with stroke, we found that movement parameters were broadly invariant with the support condition. In contrast, movements of the paretic limb exhibited a strong dependence on the supported condition. Specifically, active support of the paretic limb resulted in significant reductions in estimated peak dynamic joint torques for targets requiring elbow extension or shoulder flexion, while the peak elbow flexion and shoulder extension joint torques associated with the acquisition of proximal targets were relatively unaffected. The clinical implication of these findings is that a target-dependent restriction in the work area of the hand exists and reflects a reduced range of active elbow extension that is linked to the unsupported state of the limb. We concluded that the target-dependent effect of the support condition on movements of the paretic limb reflects the existence of abnormal coactivation of the elbow flexors and shoulder extensors, abductors, and external rotators in individuals with chronic hemiparesis. These findings led to the realization that implementing variable shoulder loading conditions would be crucial to fully quantifying the effects of abnormal elbow–shoulder coupling on the functional workspace of the hand.

In an effort to implement variable load conditions at the shoulder, a HapticMASTER robot (Moog Inc., The Netherlands) was modified by adding a gimbal with position sensors and a six-degree-of-freedom load cell to its end effector. The individual's forearm and hand are attached to the gimbal using a hand–forearm orthosis (Fig. 19.1). The modified HapticMASTER robot was then integrated with a Biodex experimental chair (Biodex Medical Systems, Shirley, NY) to form the first-generation Arm Coordination Training 3-D (ACT-3D) device shown in Fig. 19.1. This unique combination of technologies allows for the measurement of shoulder abduction loading and induced shoulder and elbow coupling during reaching. It provides a

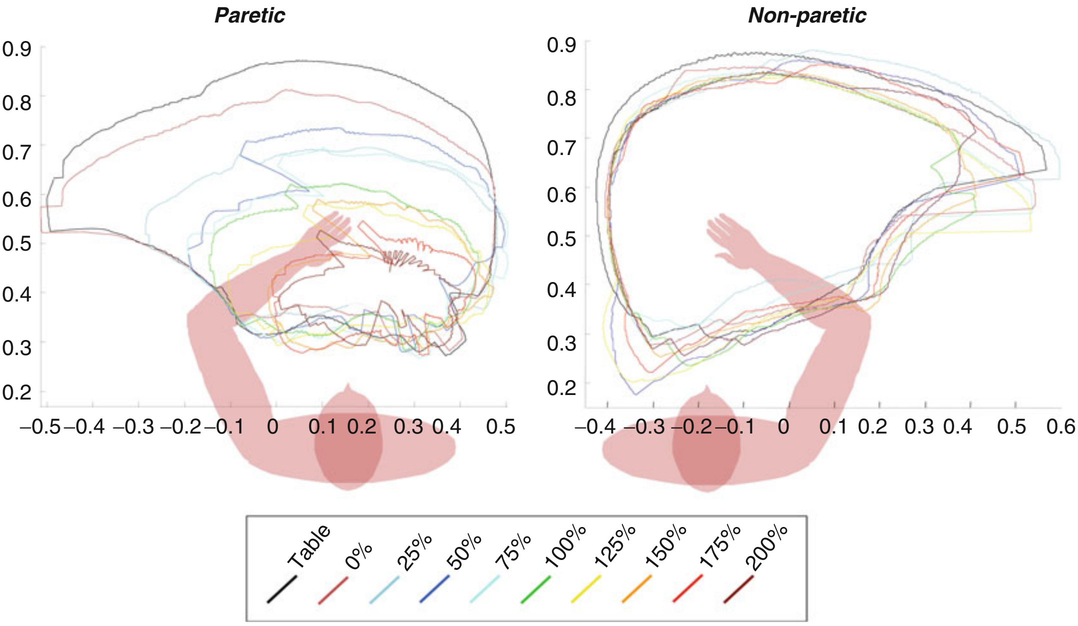

Fig. 19.2 Envelope traces consisting of shoulder/elbow flexion/extension combinations during various levels of limb support in the paretic limb (left arm) of a single subject. Conditions listed in the legend are percentages of limb weight. Note the significant reduction in work area for increasing levels of shoulder abduction/external rotation. Axis units are in meters (With kind permission from Springer Science + Business Media: Sukal et al. [4])

sophisticated quantification tool to characterize movement disabilities in individuals who have had brain injury resulting from a stroke. The advantage of this system is that it incorporates the ability to control the level of shoulder abduction/adduction loading while measuring movement abilities in the 3-D workspace, features unavailable in the early isometric and dynamic studies [21–24]. In an unprecedented way, the ACT-3D has allowed us to investigate the progressive debilitating impact of shoulder abduction loading on reaching range of motion. When quantifying the effect of shoulder abduction loading on the work area of the hand, individuals with stroke and control subjects were asked to slowly trace with their hands the largest possible envelope on a horizontal plane (at shoulder level) by moving their arm several times in a clockwise and counterclockwise direction. The largest work area for each level of abduction loading was calculated from multiple trials. Subjects performed the reaching movements while sliding over a haptically rendered table or under conditions where the virtual effect of gravity was enhanced or reduced by providing forces along the vertical axis of the ACT-3D. The direction of these forces dictated the amount of resulting shoulder abduction loading and was varied from 100% of limb support to 100% or more of limb weight added to the shoulder load.

An example of work area resulting from a single moderately to severely affected subject (Fugl-Meyer upper extremity score 23/66, and Chedoke–McMaster Arm Scale 3/7) is shown in Fig. 19.2. The different lines correspond to the percentage of limb weight the subject was required to lift during the generation of the envelope. This ranged from 0% where the robot was compensating for the entire weight of the limb to 200% where the subject had to generate abduction torques twice the size of those required to lift the limb against the normal gravitational load. The left panel in Fig. 19.2 shows the reduction in work area in the paretic limb (left arm in this subject) with the greatest work area reduction in the ipsilateral and forward reaching portion of the envelope; this area coincides with the direction requiring primarily elbow extension (the upper

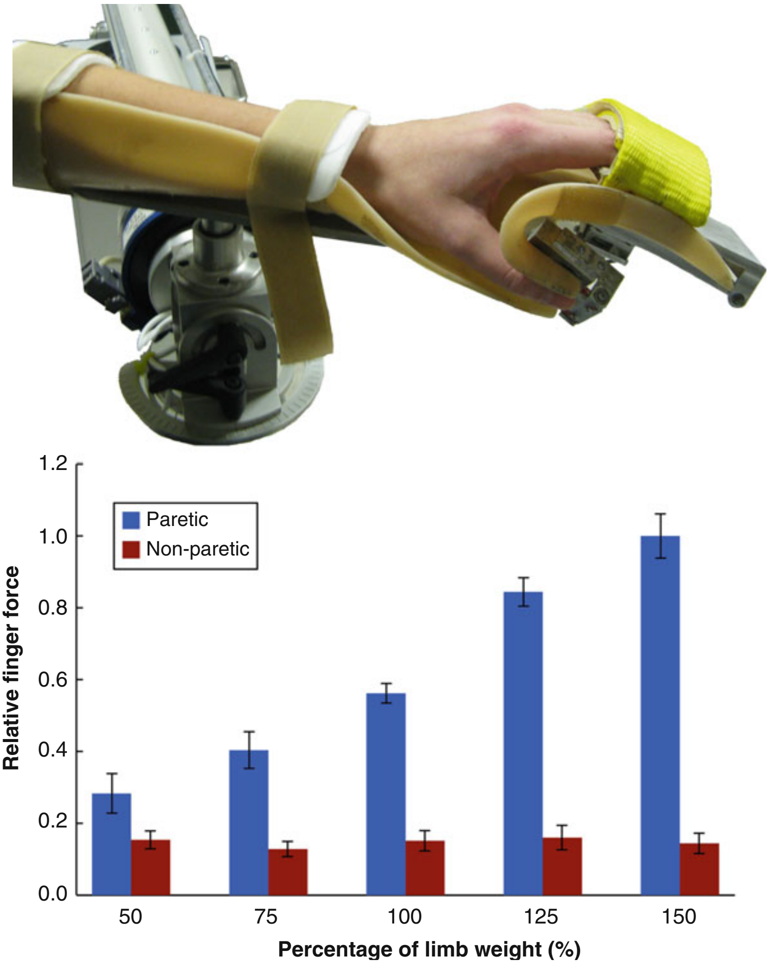

Fig. 19.3 *Top*: Instrumented hand finger orthosis [29]. *Bottom*: Relative level of finger force (normalized for each subject by the largest forces measured over the five limb weight conditions) generated for increasing levels of limb weight. This demonstrates that increasing levels of shoulder abduction generate involuntary increases in finger flexion in the paretic hand. The error bars represent intersubject standard errors (*Top* – From Miller et al. [29]; used with permission)

left portion of the envelopes). This is consistent with the expression of the flexion synergy that dictates the presence of greater coupling with elbow flexion torque for increasing levels of shoulder abduction. The reduction in work area for the same subject is displayed as a function of mean area versus percentage of active limb support. These results are in stark contrast to the nonparetic side, where no change or effect of abduction level related to shoulder and elbow range of motion is observed (see Fig. 19.2). The reductions in upper limb workspace as a function of shoulder abduction load have been shown to exist in individuals with moderate to severe motor impairments following hemiparetic stroke [4]. This is a result of the abnormal coupling between shoulder abduction and elbow flexion or the flexion synergy. This synergy has been reported to also include more distal joints of the paretic arm, namely the wrist and fingers [17].

The paretic wrist and fingers have also been the focus of extensive research [26–28]; however, they have been examined most frequently in isolation from the rest of the upper limb, without consideration for the effect of the flexion synergy. The addition of a wrist/finger force sensing device [29] (Fig. 19.3, top) to the ACT-3D robot has allowed us to study the effect of shoulder abduction loading on wrist and finger forces in both adults and children with spastic hemiparesis. As can be appreciated from the results shown in Fig. 19.3 (bottom), secondary finger/wrist forces increase as shoulder abduction loads increase in individuals with adult-onset stroke.

Future research using the wrist/finger force sensing device will allow for the continued characterization of abnormal coupling at the hand and wrist during 3-D movements. This is likely to result in the development of a progressive shoulder abduction loading rehabilitation protocol focused on the improvement of hand function. The integration of functional electrical stimulation of wrist/finger extensors can also be investigated using this device that allows for the measurement of extension forces generated by various electrical stimulation parameters and with various shoulder abduction loads encountered during activities of daily living.

19.2.2 Quantification of Spasticity Using Electromechanical Devices

Spasticity, defined as an increased velocity sensitive stretch reflex [30], has been studied using electromechanical devices for four decades [8, 10, 12, 13, 31–35]. Using robotic devices, spasticity or reflex hyperexcitability has primarily been studied in resting limbs, yet its clinical management has been directed mainly at an assumed impact on active movement. Current directions in the treatment of spasticity include stretching, serial casting, and the use of antispastic agents such as botulinum toxin and baclofen to reduce overactive muscle activity. The rationale for this approach is that by reducing spasticity, movement performance will improve. This conventional approach persists despite the lack of evidence demonstrating that reflex hyperexcitability (measured on a resting limb) actually impacts active movement. Numerous studies on resting limbs have reported increased mechanical resistance (reflex torques) and augmented stretch reflexes during passive joint rotation imposed by single-degree-of-freedom robotic devices, particularly after stroke [7–12, 31–35]. Under passive or resting conditions, spastic limbs can be clearly distinguished from normal limbs where slow stretches generally fail to elicit signs of significant levels of stretch reflex activity [36, 37].

Relatively little is known of spasticity in active contracting muscle despite its obvious relevance to active movement and subsequent treatment. Even a small voluntary background contraction leads to prominent reflex activity and increased passive resistance in normal limbs [35, 38]. Additionally, there is no clear demonstration that reflex EMG and torque magnitude are significantly higher in spastic limbs under analogous background activation conditions [7, 12, 31, 32, 39–41]. Hence, it is unclear how, or if, spasticity contributes to the movement disorder in the affected limbs. It is possible, without clear evidence to the contrary, that the defining features of spasticity are a phenomenon confined to resting limbs. More detailed knowledge of the properties of spastic muscle during active movement is needed to resolve this issue. With the use of robotic technologies, we now have the capability to investigate the impact of spasticity, or hyperactive stretch reflexes, on active movement.

Most of the spasticity quantification literature to date considers hyperactive stretch reflex activity at the single-joint level with the subject relaxed and does not consider its potential effects on multijoint movements such as reaching or retrieval motions. If we hypothesize that spasticity expresses itself as a hyperactive stretch reflex during passive conditions only (i.e., with the subject relaxed) and does not affect stretch reflex activity during active (i.e., movement) conditions [7], then multijoint movements may still be affected. This is especially true during multijoint reaching where elbow extension is the result of coupling or interaction torques generated during shoulder flexion movement and not due to elbow extensor muscle activation [25]. It is likely that under such conditions, abnormal hyperactive stretch reflex activity of "relaxed" elbow flexors (which are not reciprocally inhibited by triceps activity because of the effect of coupling torques) could limit the upper extremity workspace, especially at higher movement velocities. In addition to the role that spasticity may play when joint movement is driven by coupling or interaction torques, as occurs during multijoint movements, it may also be affected by the expression of abnormal muscle synergies (see section above). Spasticity quantification studies at the elbow have been done with the weight of the paretic limb supported by the measurement system [7, 8, 10, 12, 40]. The effect of shoulder abductor activity to lift the arm against gravity and the resulting expression of the abnormal flexor synergy have been shown to impact the stretch reflex excitability in elbow flexors for a single posture and shoulder abduction load level [13]. State-of-the-art robotic technologies, some of which are currently under development in our laboratory, are required to fully elucidate the interaction between stretch reflex excitability and impairments such as abnormal synergies during multiple postures, abduction levels, and movements. Depending on the specific application, robotic devices must possess certain key design characteristics. First, these devices must be capable of rendering haptic environments within which users can interact with desired forces. For example, to investigate the flexion synergy, robotic devices must be capable of providing forces to simulate abduction loading and unloading of the shoulder muscles. These devices must also be capable of switching between compliant and stiff modes, enabling low-impedance movements throughout the workspace while simultaneously providing the capability to apply precise position or speed-controlled perturbations to the user. Additionally, robotic devices seeking to measure the relationship between stretch reflexes and abnormal muscle coactivation patterns must possess an adequate number of degrees of freedom to capture functional behaviors. For planar movements of the upper limb, this translates to at least three degrees of freedom: two for the shoulder and one for the elbow. Finally, an important consideration for robotic devices seeking to capture functional movements is workspace volume. If, for instance, the desired task is a center-out reaching task in multiple directions, it may be necessary to permit full extension of the arm, which will require both shoulder flexion as well as elbow extension and a larger workspace. If however the goal is only elbow extension, a smaller workspace volume may be acceptable.

Ultimately, with careful design considerations and a working knowledge of the relevant physiology, robotic devices can be designed and implemented that allow investigators to answer specific questions in terms of the mechanisms underlying movement impairments. In addition, the same robotic devices can be used for subsequent development of effective robotic treatments that complement conventional neurorehabilitation approaches.

19.3 Impairment-Based Robotic Interventions

19.3.1 Introduction to a Scientifically Underpinned Concept

Impairment-based interventions for individuals with stroke have gone by the wayside over the last decade, in part, due to the success of functional task practice and forced-use paradigms [42] in individuals with mild stroke. However, these approaches do not benefit individuals with more substantial impairment [43]. Individuals with moderate to severe stroke, therefore, need an innovative solution that allows for the amelioration of fundamental impairments such as abnormal synergies and weakness in order to experience functional gains. Recent basic science research discussed above has demonstrated that unavoidable and debilitating distal arm and hand flexion occurs during progressively greater shoulder abduction loads in individuals with moderate to severe stroke. This phenomenon is attributed to abnormal coactivation of groups of muscles and results in stereotypical movements and postures, making it impossible to complete functional upper extremity tasks such as reaching out to pick up a glass of water. Only within the last few years, utilizing new robotic rehabilitation technology like the ACT-3D, has it been possible to design an intervention that directly targets this impairment. Directly targeting abnormal muscle synergies and associated loss of independent joint control with an impairment-based intervention is the most likely avenue for achieving functional restoration in this population. This impairment-based approach represents a scientifically underpinned rehabilitation strategy since the neural mechanism of the impairment is well investigated and its relationship to functional movement is known. Recent evidence from our laboratory supporting this approach will be discussed below and appears to elevate the prognosis of even the most severely impaired individuals with stroke.

19.3.2 An Isometric Impairment-Based Approach

Our initial and foundational intervention work [44] sought to determine the amenability of abnormal flexion synergy to an impairment-based intervention. The intervention entailed intensive practice of an isometric multijoint (shoulder and elbow) task comprised of both a multijoint coordination element and a resistance element that ultimately proved to be successful in reducing the impairment but difficult in interpreting the relative importance of therapeutic elements responsible for the observed improvement [44]. The abnormal flexion synergy impairment was directly targeted by having individuals generate multijoint torque patterns outside of the flexion synergy. This was accomplished by maintaining a submaximal percentage of their maximum shoulder abduction while maximally generating shoulder flexion or elbow extension. The involvement of two concurrent torque directions was the multijoint coordination element of the exercise, while the resistive element was the requirement of maximal isometric torque generation. Individuals practiced these multijoint isometric tasks three times per week for 8 weeks. The primary outcome measure was the magnitude of abnormally coupled isometric elbow flexion occurring during maximum isometric shoulder abduction (abnormal flexion synergy). The secondary outcome measure was single-joint isometric strength.

Ultimately, the study demonstrated the effectiveness of implementing an intervention at the level of impairment as opposed to gross function. All participants showed a decrease in the amount of abnormal flexion synergy that was congruent with progressive improvements in generating torque patterns outside of the flexion synergy throughout the course of the intervention. A second meaningful improvement was an increase in single-joint isometric strength for the torque directions comprising the practiced tasks. Participants became stronger following the intervention for shoulder abduction, shoulder flexion, and elbow extension. The concurrent increase in multijoint coordination and increase in single-joint strength offered two inextricable explanations for the measured improvements in arm function. Future work from our laboratory discussed below began utilizing robotics in an attempt to more specifically target abnormal flexion synergy by removing the resistance component from the intervention.

19.3.3 Targeting the Loss of Independent Joint Control with the ACT-3D

Our robotic intervention for individuals with severe stroke sought to identify the effect of the multijoint coordination element without the confounding effects of other potential therapeutic elements such as resistance training as incorporated in our initial isometric intervention work [45, 46]. Utilization of the robotic device, ACT-3D, allowed us to target the flexion synergy and associated loss of independent joint control through the implementation of a dynamic multijoint coordination task that did not involve a resistive element. In a randomized controlled design, 14 participants were assigned to one of two intervention groups. While both groups practiced reaching with the ACT-3D over 8 weeks emulating traditional therapy, only the experimental group was required to support the arm against specified submaximal abduction (vertical) loads. The control group practiced the same reaching tasks but was fully supported on a horizontal haptic table. Therefore, only the experimental group was practicing movement outside of or against the abnormal flexion synergy. Participants in the experimental group were required to support greater percentages of arm weight (corresponding to greater shoulder abduction loads) as reaching abilities improved beyond standardized kinematic performance thresholds. For example, if a participant could reach 80% of

Fig. 19.4 Example of a research participant positioned with the ACT-3D showing the five reaching targets (From Ellis et al. [46]; used with permission)

the distance to the practiced target for 8 out of 11 trials in one set for a given abduction load, the load would be increased by one increment of 25% of limb weight. The same procedure was followed independently for all five of the targets that spanned the reaching work area of each participant based on standardized joint angles (Fig. 19.4). The primary outcome utilized to demonstrate effectiveness was total reaching work area as a function of abduction loading, measured by the ACT-3D, and the secondary outcome was isometric single-joint strength.

We found significantly greater increases in work area for the experimental group. Importantly, the greatest improvements in total reaching work area were at abduction loading levels equivalent to and beyond limb weight such as experienced during the transport of an object during a functional task. The results of the secondary outcome measure of strength were important to the interpretation of why improvements were observed in work area as a function of abduction loading. We found that there was no improvement in single-joint maximum strength, indicating that a reduction of flexion synergy and associated increase in multijoint coordination must have occurred [46]. This research indicated that the abduction loading element was effective in improving arm function. Most importantly, it demonstrated the capacity of a scientifically underpinned impairment-based approach to achieve gains in individuals with chronic severe stroke whom conventional care had failed.

19.4 Successful Translation to Clinical Practice

19.4.1 Device Design That Facilitates Translation

Recent advances in robotic technology have given rise to multiple systems for upper extremity rehabilitation in stroke [4, 47–54]. Such systems combine robotics with computer graphics for delivery of a rehabilitation protocol. Systematic reviews of the effect of robotic-based therapy on upper limb recovery following stroke [1–3] suggest significant improvement in motor control of the paretic upper limb but no significant improvement on functional abilities or activities of daily living.

The majority of these rehabilitation systems are based on traditional therapeutic approaches. Most groups have implemented a task-oriented approach where, for example, subjects complete a pick-and-place or grasp-and-release virtual task [3, 55–65] not unlike conventional therapeutic strategies [66–69]. A few groups have implemented systems based on a more hands-on approach where the reaching movement or task is guided by a predefined trajectory or set of rules [70–72], again, not unlike traditional interventions where the movement is guided by the therapist(s). Some of these systems provide robotic assistance to the task or movement being performed either by moving the arm in a programmed trajectory or by supporting the weight of the limb [60, 64, 73–79], thus taking advantage of the unique features of their device which cannot be mimicked by a person.

Fig. 19.5 The ACT-4D robotic device allows for single-joint perturbations at the elbow combined with adjustable shoulder abduction loading to study the relationship between synergies and abnormal stretch reflex or spasticity following brain injury

The common theme from all of these therapeutic robotic systems is their ability to reproduce traditional-type therapies in order to reduce the workload of the clinician and allow for greater repeatability and increased repetitions. Device design was therefore driven by these needs without specific regard for identifying novel and potentially more effective means of reducing impairments and increasing function in comparison to conventional strategies. The Dewald laboratory has taken a radically different approach based on years of research of the mechanisms underlying upper extremity movement impairment in individuals with brain injury. Based on results from previous studies [6, 20–25, 74], we have designed robotic systems to directly target the fundamental impairments impacting upper extremity function. Attempting to ameliorate the contributing impairments may be a more effective strategy in improving arm function during activities of daily living in individuals with moderate to severe hemiparetic stroke. The ACT-3D [4, 16], which is based on the HapticMASTER (Moog, Inc., The Netherlands), a commercially available haptic device, was designed to allow adjustable shoulder abduction loading, a required attribute to directly target the flexion synergy impairment. Previous studies have demonstrated the effectiveness of targeting the flexion synergy impairment with the ACT-3D and increasing the work area of the upper limb at greater shoulder abduction loads (see previous section) [45, 46]. Although other systems like the T-WREX, ARMin, L-EXOS, and Freebal [4, 49, 53, 58] have adjustable limb weight support abilities, only the ARMin and the ACT-3D systems are able to generate loads in the vertical direction to allow simulation of increased limb weight or object handling. This is a key component for therapeutic interventions attempting to improve arm function during activities of daily living because it allows for continued targeting of the flexion synergy impairment even at higher functional levels such as during object transport.

Based on the promising results obtained with the ACT-3D, our laboratory has continued to design robotic devices that target specific impairments present in individuals with brain injury such as weakness, synergy, and spasticity. A new device, the ACT-4D, was designed to further our understanding of spasticity during movement in stroke (see Fig. 19.5). Concurrently, a new version of the ACT-3D was designed to augment its capabilities both in workspace and strength to allow not only implementation of impairment-based interventions but also investigations of the complex interactions between weakness, synergy, and spasticity in order to better understand the mechanisms underlying movement dysfunction in this population (see Fig. 19.6). In doing so,

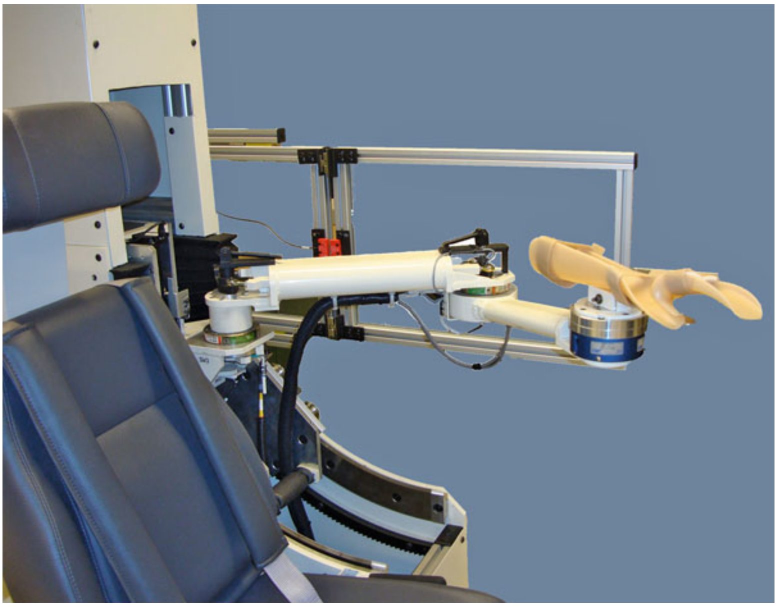

Fig. 19.6 New version of the ACT-3D, designed to allow greater workspace measurements as well as the application of multijoint perturbations in the plane of movement

standardized protocols for the quantitative evaluation of each impairment are being developed and will provide a tool for clinicians to immediately augment conventional qualitative methods of clinical evaluation. Currently, initial efforts are underway to design and implement an affordable passive device that will facilitate translation to practice and even utilization at home.

19.4.2 Acceptance by the Rehabilitation Specialist

Despite exciting advancements in rehabilitation robotics regarding quantitative evaluation of movement impairments and impairment-based interventions, translation to clinical practice has been slow and incremental. The rate of translation can be improved by increasing the quality of evidence made available to practicing clinicians. The field of rehabilitation will readily accept new technologies, such as the impairment-based robotics approach, given that quantitative data of impairment reduction is provided. Recent evidence from our lab supports an impairment-based approach showing that amelioration of flexion synergy and improvement in reaching function are possible [45, 46]. As impairments are remedied, normal movement is restored, and thus, function in everyday activities improves. This represents a methodical, scientifically underpinned strategy to achieving improved function that is in stark contrast to the conventional approach of blindly practicing functional tasks in hopes of unexplained functional improvement. Educating clinicians will need to go beyond marketing tutorials describing bells and whistles of robotic devices and include evidence of how the device is grounded in medical science both in concept, design, and implementation. Convincing evidence from large-scale clinical trials are necessary to demonstrate that an impairment-based robotic intervention is superior to conventional care not just in improving function but in restoring normal movement through impairment reduction. Additionally, improvements observed should be explained by the underlying neurophysiological mechanism. Our laboratory recently has made substantial efforts to merge quantitative evaluation of movement with high-resolution neuroimaging to meet this requirement [80]. With convincing quantitative evidence and sound scientific underpinning, the rehabilitation specialist will readily accept the impairment-based approach catalyzing the translation to clinical practice.

19.4.3 Motivation, Ease of Use, Practical Implications, and Translation into Rehabilitation Clinics

The issue of patient motivation in rehabilitation robotics is one that can be addressed by combining impairment-based robotics with video games. Combining science-underpinned haptic environments with a game has the potential to motivate patients to participate in therapy sessions and push themselves to greater performances. Recent advances in robotic and video game technology have given rise to multiple systems for upper extremity rehabilitation in stroke [4, 47–54]. Such systems combine robotics with computer graphics for delivery of a rehabilitation protocol. An increasingly common approach is the use of virtual reality (VR) games that allow interaction with a 3-D environment simulated in a computer and integrated with haptic feedback. Reviews on the effectiveness of virtual reality programs for stroke rehabilitation [81–83] support their application albeit with limited evidence. All of these reviews recognize the potential for these therapeutic modalities, encouraging further research to establish their validity and provide evidence of their advantages over conventional therapy. The lack of directly targeting specific impairments in current gaming approaches may explain the limited improvements in arm function during activities of daily living. Preliminary results from our laboratory suggest that the combination of video games and robotics to create a haptic interface should emphasize the design of games that include specific reaching targets in the workspace compromised by the expression of the loss of independent joint control following stroke [84]. Therefore, the ultimate goal will be to develop video games that, in combination with state-of-the-art robotic devices, directly address movement impairments while providing a fun and challenging experience.

Another important element that needs to be considered for the ultimate success of robotics in the clinic and possibly at home is its ease of use. Once the necessary ingredients have been determined to measure and reduce movement impairments resulting from brain injury, simple actuated or possibly passive devices should be developed. Setup time for use of such devices should be fast, and measurement and treatment approaches, incorporating gaming, should provide intuitive interfaces that can be ultimately utilized by the individual receiving therapy.

Finally, to facilitate translation of impairment-based electromechanical devices to clinical practice, they should offer evaluation and treatment approaches that are not readily reproducible by rehabilitation specialists. Electromechanical devices must provide for a precise quantitative evaluation of movement impairments resulting from brain injury such as the loss of independent joint control, weakness, and spasticity. Furthermore, devices must utilize standard quantitative measurements of impairment to initiate and progress the intervention. With these attributes, clinicians will be better informed of the impairments causing movement dysfunction and the response of the patient to rehabilitation.

Conclusion

This chapter discusses the use of impairment-based rehabilitation technologies and provides examples of device development that allows both for the evaluation and treatment of movement impairments. Evidence is provided, demonstrating that electromechanical devices have the unique ability to measure loss of independent joint control, weakness, and spasticity following brain injury. In addition to the quantification and study of mechanisms underlying the expression of these impairments, evidence was also provided, demonstrating the effectiveness of specifically targeting fundamental impairments in order to improve arm function during activities of daily living. The novelty of impairment-based robotics was contrasted with the currently advocated use for robotics that is based on its ability to provide greater intensity of existing rehabilitation approaches. Finally, successful translation to clinical practice was discussed, pointing to several key attributes that will facilitate both clinician and patient acceptance. From this chapter, we hope to have demonstrated that new robotic technologies are ideal for the delivery of novel science-underpinned therapeutic interventions that can be implemented in current rehabilitation clinics as well as provide a tool for clinicians to better evaluate and treat patients in a more controlled fashion and with greater specificity and intensity than is currently possible with conventional rehabilitation.

The successful application of impairment-based rehabilitation technologies will depend on two factors. First, robotic devices must prove to provide a quantitative evaluation that precisely defines movement impairments that can serve both as indicators for prognosis and response to rehabilitation. Wielding powerful diagnostic and prognostic tools, rehabilitation specialists will make more informed clinical decisions and achieve better clinical outcomes. Second, the future of rehabilitation robotics lies in our ability to demonstrate the effectiveness of robotic devices in delivering interventions that result not only in amelioration of impairments but also in clear gains in arm function during activities of daily living. This will require implementation of large-sample Phase III and IV clinical trials that encompass controlled impairment-based rehabilitation robotic interventions and conventional care. These trials will have the statistical power necessary to detect significant clinical effects utilizing outcomes measuring activity of daily living that are unavoidably limited by low-resolution ordinal scales of measurement. Additionally, it is with these large Phase III and IV clinical trials that cost-benefit analyses can be completed, demonstrating the fiscal utility of these exciting new impairment-based technologies in a changing health care environment.

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