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INVITED REVIEW

Robotic Approaches for Rehabilitation of Hand Function After Stroke

ABSTRACT

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The goal of this review was to discuss the impairments in hand function after stroke and present previous work on robot-assisted approaches to movement neurorehabilitation. Robotic devices offer a unique training environment that may enhance outcomes beyond what is possible with conventional means. Robots apply forces to the hand, allowing completion of movements while preventing inappropriate movement patterns. Evidence from the literature is emerging that certain characteristics of the human-robot interaction are preferable. In light of this evidence, the robotic hand devices that have undergone clinical testing are reviewed, highlighting the authors' work in this area. Finally, suggestions for future work are offered. The ability to deliver therapy doses far higher than what has been previously tested is a potentially key advantage of robotic devices that needs further exploration. In particular, more efforts are needed to develop highly motivating home-based devices, which can increase access to high doses of assisted movement therapy.

Key Words: Robotics, Stroke, Hand Function

Functional improvement of the upper paretic limb after stroke is determined mainly by improvement of the paretic hand,[1,2] yet restoration of hand function after stroke often lags behind restoration of more proximal joints, and impairments are often resistant to therapeutic intervention. Currently, even after extensive therapeutic interventions in acute rehabilitation, the probability of regaining functional use of the impaired hand is low.[3] At 3 mos post-stroke, only 12% of stroke survivors report no difficulty with hand function and 38% of survivors reported major difficulty with hand function.[4] Unfortunately, stroke survivors may require a very high level of hand motor control before they actually use the limb in activities of daily living (ADLs). This might explain why stroke patients who appear to have adequate movement ability when observed in the laboratory often do not incorporate the limb into ADL with the expected regularity.[5,6] Instead, stroke patients often must rely on compensatory strategies using the less affected limb.

Studies based on repetitive training of simple flexion and extension finger movements have reported improvements in hand function after stroke.[7,8] The potential advantages of incorporating robotic devices into repetitive training center on enriching the training experience by applying forces to the hand, similar to when a human therapist assists movements. The robot can allow completion of movements throughout the range of motion (ROM) and also can prevent inappropriate movements. In the following sections, the authors discuss the impairments and treatment strategies used by therapists and review previous work with robotic hand devices. A recent comprehensive review noted that only 25% of 30 different hand robots had been clinically tested, concluding that many designs were too complex for clinical use.[9] The authors agree with this assessment and focus their discussion only on devices for the fingers and thumb that have been tested clinically with training studies using stroke subjects. In addition, the authors discuss converging evidence regarding how these robots should be controlled and illustrate the capabilities of robotic devices by highlighting their work in this area.

IMPAIRMENTS

In the early stage of stroke, the normal resting tone on the more affected side is diminished, sometimes totally flaccid, and the muscles are unable to produce adequate force for even small movements. If the individual has volitional movement, there is often a loss of automatic control that requires an intentional command to move the limb, requiring extra cognitive and motor effort. All of this contributes to what most patients will term *weakness*. In addition, individuals with stroke frequently experience decreased tactile sensation and diminished proprioception. Without sensation, there is poor feedback of the activity being performed, leading to poor task coordination. This combination of altered sensation and decreased motor control of the hand and arm impacts the ability to perform normal daily tasks. Individuals frequently resort to repeatedly using the lesser involved limb to compensate for the "weak" hand in functional activities such as picking up, holding, and manipulating items. The challenge in rehabilitation therapy is training independence in functional activities when one hand and arm cannot move adequately.

Paucity of movement, increases in flexor tone, and strength imbalances between antagonistic muscle groups result in a stereotypical flexed hand and wrist.[10] Animal and human studies have shown that when muscle and soft tissue are subjected to prolonged changes in length and position, physiologic and anatomical changes occur in the tissue, resetting it to a shortened position.[11,12] The implications for stroke survivors are significant, with the most common functional consequence involving the development of joint contractures. Muscle and soft tissue shortening, increased tissue stiffness, and involuntary activation of flexors at rest all impair the ability to extend the fingers.[13] Some individuals with stroke will develop spasticity and exaggerated reflex activity, which can also contribute to the movement impairment.[13]

Most stroke survivors regain the ability to flex the fingers voluntarily, but recovery of voluntary extension is limited. At the elbow, there are conflicting studies on the roles of hypertonicity and spasticity in limiting voluntary movement.[14,15] At the fingers, inappropriate activity in flexors can interfere with voluntary extension movements in certain subjects.[16] However, it is clear that active movement is also impaired by inability to activate extensors[16,17] and abnormal co-contraction of flexors during voluntary extension tasks.[18,19] Interjoint coordination and finger fractionation can also be impaired.[20]

CONVENTIONAL TREATMENT APPROACHES

Treatment approaches to address tissue shortening entail providing a prolonged stretch to involved muscle groups in a lengthened position to facilitate resetting the muscle to an elongated position.[21,22] Hand splints and orthoses are commonly used to address tissue shortening of the wrist and fingers,[23] but recent studies have not found this approach to be effective.[24,25] The use of botulinum toxin is used clinically to decrease tone. But solely decreasing tone does not seem to change active function of the hand and arm[26]; there needs to be active effort on the part of the subject to have an influence on activity.[27]

There has been a definite trend in using "task-specific training" that incorporates context-specific training and complex tasks involving many degrees of freedom (DOFs). The goal is to maximally promote skill acquisition, strength, speed, coordination, timing, and modulation of effort. Early inpatient rehabilitation effort is geared to maximize independence in preparation for the return home and includes performing basic self-care and dressing tasks, moving in and out of bed, rising up and down from a chair, and walking indoors and in the community. When the more involved upper limb exhibits diminished capacity to move, compensatory techniques are often taught at the expense of directing treatment toward the involved limb. However, training of skilled reaching, grasping, and carrying items of different sizes, weights, shapes, and textures is incorporated when the patient demonstrates emerging movement. Much verbal encouragement is provided to incorporate the use of the involved hand, but the effectiveness of cueing depends upon a patient's motivation, as well as cognitive and physical ability. Training setup provides different contexts for learning, including focus on bimanual tasks where the involved hand is used to stabilize objects. Electrical stimulation is frequently combined with training effort, particularly for the wrist and finger extensors.[28] Robots can also be combined with training effort to improve performance during task practice.

MANY APPROACHES TO ROBOTICALLY ASSISTED HAND MOVEMENT

Robotic hand devices that can be used independently by patients in both acute and postacute settings can be a valuable adjunct to conventional approaches that focus on compensation, whereas wearable devices can be integrated directly into task-specific training. Early efforts with proximal arm robots found them to be safe, well tolerated by patients, and capable of improving motor control of proximal arm function.[29–36] However, systematic reviews and meta-analyses have found no change in ADL ability after robotic therapy.[37–39] This might have been predicted because most previous studies did not involve active hand training. Researchers have been slow to address hand function partly because of the complexity of the hand. Whereas the fingers and thumb have 21 DOFs, the arm from the wrist to shoulder has only 7 DOFs. This complexity in the hand leads to many difficult decisions as to which joints to directly control and which grasp patterns to retrain. Furthermore, it's unknown whether hand training isolated from the rest of the limb is better or worse than use of the robot within the context of whole limb movements. Tradeoffs between device complexity and ease of use need to be reconciled. The fact that there is very little objective evidence to guide these decisions is one reason there are a wide range of approaches and strategies being developed (Fig. 1).

One class of devices uses an "endpoint control" strategy, whereby forces are applied to the distal segments of the digits. Endpoint control robots offer the advantages of individual control of each digit and easy setup but suffer from limited control of proximal joints in the digits, which could result in abnormal movement patterns. The first hand rehabilitation device to

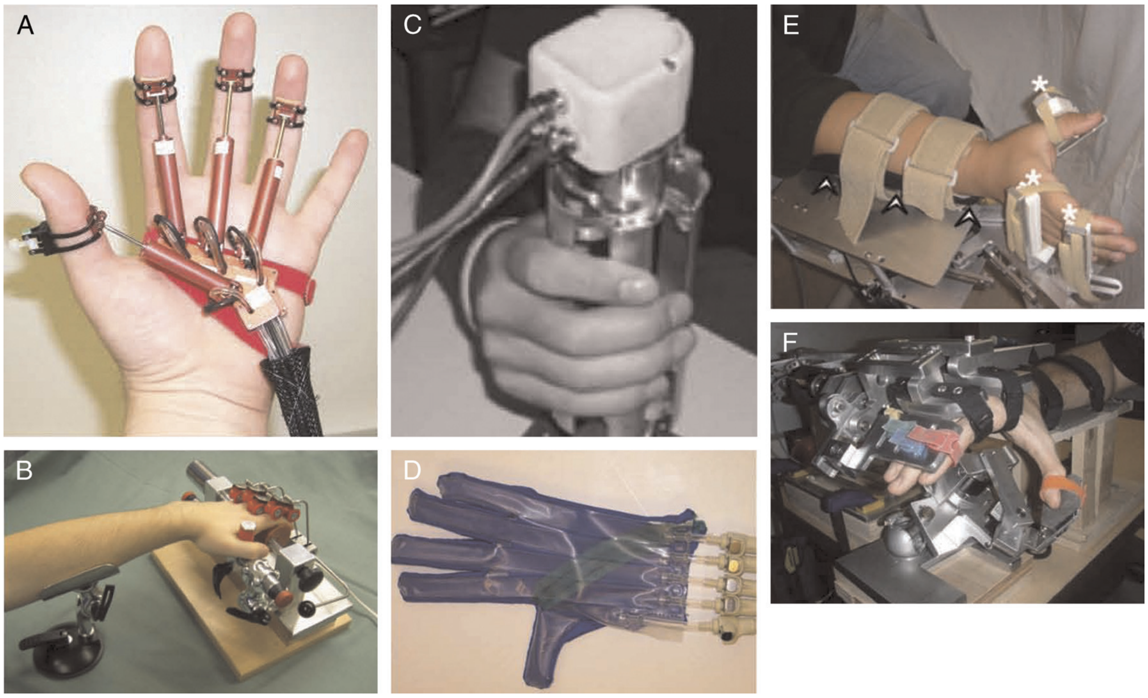

FIGURE 1 *A, Rutgers Hand Master II, an endpoint controlled robot. B, Reha-Digit, an actuated object driven by cams under each finger. C, InMotion Hand Robot, a cylindrical object with variable diameter. D, PneuGlove, a pneumatic-powered glove. E, Hand Wrist Assistive Rehabilitation Device, exoskeleton. F, HEXORR, exoskeleton. HEXORR indicates Hand Exoskeleton Rehabilitation Robot.*

be tested was the Rutgers Hand Master II, developed by Bouzit and colleagues (Fig. 1*A*).[40] It is powered by pneumatic pistons that are placed in the palm of the hand and simulate contact forces with objects in virtual-reality environments. In clinical testing, four chronic stroke subjects trained for 30 hrs over 3 wks. Gains in movement parameters (ROM, speed, and movement fractionation) were noted in most subjects, and two participants had gains in the Jebsen-Taylor Test of Hand Function.[41] Another study from this group with three subjects yielded similar results.[42] HandCARE is an endpoint control device that uses cable loops for each digit driven by a motor and pulley arrangement.[43] A novel clutch mechanism allows one motor to train all five digits together or in different combinations. In pilot testing, two stroke subjects received 16 sessions of 20 mins of training.[44] Subjects practiced closing and opening the hand against an elastic load that assisted extension or practiced producing force in individual digits while suppressing force in the other digits. Both subjects showed gains in finger coordination and finger independence after training. The Amadeo is a commercially available endpoint control robot that uses digit caps that are moved along fixed trajectories (www.tyromotion.com/en/products/amadeo). A pilot study of 12 subjects with chronic hemiparesis after stroke treated for 18 hrs over 6 wks found the Amadeo to be well tolerated, with improvements in motor impairment.[45]

An alternate approach applies torques to each joint of the finger in a fixed ratio. This also allows control of each digit individually while offering more control of proximal joints. However, the ratio of torques applied to the joints within a digit are not adjustable, so abnormal joint kinematics are still possible. This approach was pioneered by Luo and colleagues, who developed a body-powered orthosis based on prosthetic technology.[46] Cables from the tips of a glove travel along the dorsal side of the glove and are routed to a shoulder harness so that biscapular abduction and glenohumeral flexion of the contralateral limb apply tension to the cables, forcing all the fingers simultaneously into extension. This group has also developed a pneumatically powered glove that contains air bladders in the palm that extends the fingers simultaneously when inflated.[47] In a clinical trial, 15 stroke subjects were randomized to 18 hrs of training with the body-powered orthosis, pneumatic-powered glove, or no assistance.[48] Significant improvements were noted in some of the clinical scales, although biomechanical measures of extension ROM and speed did not improve. Investigators concluded that robotic assistance did not improve outcome compared with unassisted training. A more advanced version of the pneumatic glove, PneuGlove, incorporates individual control of each digit (Fig. 1*D*).[49] Fourteen chronic stroke subjects received 18 one-hour sessions of training with virtual and real objects. Seven subjects received assistance from PneuGlove, whereas the others practiced without assistance. Significant improvements in all clinical scales were noted in all subjects, but again, there was no advantage of using the robot. Adamovich and colleagues[50] have integrated the Cybergrasp (Immersion Inc, San Jose, CA) into a virtual-reality training environment. The Cybergrasp uses cables attached to the distal phalanx of each digit and routed through a linkage mounted to the back of the hand. Extension force in each cable is controlled with five motors located remotely. Eight chronic stroke subjects received eight 3-hr training sessions with robotic assistance.[51] In general, subjects showed gains in kinematics and clinical scales of upper limb function.

Another class of devices is "actuated objects" that can expand or contract. These devices offer the advantages of simplicity and easy patient setup, but a large ROM is difficult to implement. The Haptic Knob uses an actuated parallelogram structure that presents two movable surfaces that are squeezed by the subject.[52] The InMotion Hand Robot uses a double crank and slider mechanism driven by an electric motor, all encased in a cylindrical object (Fig. 1*C*).[53] The motor guides grasping movements by controlling the radius of the cylinder held in the palm. The InMotion Hand Robot was one of four robots used in a multisite study comparing robotic therapy to dose-matched conventional treatment in 127 chronic stroke subjects.[54] They found that the robotic training was comparable with dose-matched conventional therapy but superior to usual and customary care in motor function scales at the 36-wk follow-up time point. The Reha-Digit developed by Hesse and colleagues[55] involves a camshaft that rotates in the palm of the hand, opening and closing the fingers (Fig. 1*B*). Additional rollers on the back of the fingers prevent abnormal postures. In a pilot study, eight subacute stroke patients were randomized to 4 wks of 20 min/day of passive robot ranging or an equivalent dose of exercises that involved holding a dusting cloth in the paretic hand and using the less affected limb to push the paretic limb over a table surface. Compared with the bimanual exercises, the robotic treatment produced greater gains in the Fugl-Meyer (FM) Test of Motor Function and less increases in tone (Ashworth Scale).

A final class of devices is exoskeletons, whereby the DOFs of the device are aligned with the DOFs of the anatomical joints. Exoskeletons have direct control of individual joints, which can minimize abnormal hand postures; however, given the high DOF of the hand, a compromise has to be made regarding which joints to control. The Hand Wrist Assistive Rehabilitation Device is a 3-DOF exoskeleton robot that directly controls finger rotation about the metacarpophalangeal joint (MCP), thumb abduction/adduction, and wrist extension/flexion (Fig. 1*E*).[56] A clinical trial with 13 chronic stroke subjects reported significant behavioral gains and increased task-specific cortical activation during trained tasks.[57] Importantly, subjects who replaced half of the treatment sessions with unassisted practice did worse than subjects who used the robot in all treatment sessions. The Hand Mentor (Kinetic Muscles Inc, Tempe, AZ) is a commercially available exoskeleton device that uses an artificial muscle to simultaneously extend or flex the fingers and wrist.[58] A clinical trial randomized 17 subacute stroke subjects to 60 hrs of repetitive task practice, or 30 hrs of task practice combined with 30 hrs of robot-assisted therapy.[59] Both subject groups reported similar significant improvements in the hand function domain of the Stroke Impact Scale.

To summarize previous work, a wide variety of devices are under development, and some are commercially available. Some gains in motor control and/or clinical scales were found after robotic training in nearly all of the studies. Several studies with active control groups did not find an advantage of robotic training over unassisted practice or conventional therapy,[48,49,54,59] whereas studies with the Reha-Digit[55] and Hand Wrist Assistive Rehabilitation Device[57] found advantages of the robots over conventional unassisted training. Clearly, more work is needed to identify the optimal type of robotic interaction, but the evidence overall is in favor of further study.

HOW TO CONTROL THE ROBOTS

A vast variety of human-robot interactions can be programmed into even the simplest robotic device. Therefore, an important question arises: Which algorithm is best? Evidence is emerging that certain characteristics of assisted movement training are preferable.

1. The robotic assistance should minimally interfere with input-output timing between correct muscle activation and movement. The strongest evidence for this comes from electrophysiology experiments using a paired associative stimulation protocol. These studies demonstrated that afferent feedback from movement can facilitate plasticity in the motor cortex if it arrives synchronously with ongoing motor output.[60,61] This synchrony can be achieved with robotic devices in bimanual tasks if movement of the less affected limb controls movement of the paretic limb[34,62] or if the movement of the paretic limb is controlled by electromyograms from paretic limb muscles.[63–65] A third approach is to provide assistance that is dependent on limb position but is independent of time.[66] An example of this approach is gravity compensation for proximal arm neurorehabilitation.[67–69] If the gravity compensation is properly graded, active movement is enhanced, leading to stronger afferent feedback.
2. The robot needs to adapt to the subject's performance.[70,71] This is particularly relevant in the hand, where flexor tone can vary within a session. This is usually done by adapting the robotic assistance level on each trial. If the subject is falling short of the movement target, the assistance is increased, and if the target is achieved, the assistance is decreased. Support for this approach comes from studies that show that the motor learning system minimizes error and effort when learning a task.[72] If the movement task is being completed with assistance from a robot, the subject will attempt to reduce effort over subsequent trials. The subject's strategy is to maintain acceptable error with the least amount of effort. A control law that does not account for this "slacking" behavior will eventually take over the task from the subject.
3. The robot should keep the user engaged and prevent fatigue and frustration. Supporting evidence comes from the motor learning field, where the "challenge point" hypothesis states that there is an optimal difficulty level for promoting motor learning.[73] Essentially, if the task is too easy, the subject becomes disengaged, and if the task is too difficult, the subject becomes frustrated. Currently, this assessment is performed subjectively by therapists, but efforts are underway to use biosensors to quantitatively measure the psychologic state real-time.[74] If successful, this information can be used in adaptive algorithms that control robotic assistance level.
4. The robot should produce physiologically accurate movement patterns. Abnormal hand postures, such as clawhand or MCP hyperextension, are not functional and can lead to joint and soft tissue strain. Logically, robotic interventions should not allow these abnormal postures. Even if abnormal postures or movement patterns are part of an effective compensatory strategy, retraining of normal patterns may produce the most limb use at home.[75]

HAND EXOSKELETON REHABILITATION ROBOT

In this section, the authors review their work in detail, not because there is evidence that their robot is superior to others but to provide an in depth example of the unique capabilities of robots that they believe should be further investigated. Guided by the four design principles described previously, the authors have developed the Hand Exoskeleton Rehabilitation Robot (HEXORR) for assisting simple grasp patterns, such as gross flexion and extension movements (Fig. 1*F*).[76] Although high-DOF systems will be needed to retrain highly dextrous tasks, many functional hand tasks (power grasp, C grasp) can be addressed with simpler, lower DOF devices, such as HEXORR. A motor is aligned with the MCPs of the fingers (digits 2–5), and the phalanges are strapped to a four-bar linkage driven by the motor. This design allows control of flexion and extension of the MCP and proximal interphalangeal joints in physiologically normal patterns. The distal interphalangeal joints of the fingers are left free. A second motor is aligned with the carpometacarpal joint of the thumb and drives a crank-slider mechanism. The thumb phalanges are strapped to this mechanism, which allows flexion and extension movement of the thumb, predominantly at the interphalangeal and carpometacarpal joints. The thumb plane of motion can be altered to incorporate levels of adduction-abduction. The four-bar and crank-slider mechanisms promote normal interjoint coordination across 11 joints with only two motors. Digital encoders measure hand position and torque sensors measure the interaction torques between the hand and the motors. Active algorithms compensate for gravity and friction, allowing free movement in the device with minimal resistance from the robot (0.2 Nm to initiate movement). This "backdrivability" allows accurate implementation of torque control algorithms whereby the robot applies a prescribed torque profile and the subject is free to control movement.

In preliminary testing with neurologically normal subjects, the hand kinematics inside and outside the robot were comparable.[76] Subjects performed gross flexion and extension movements throughout the full ROM while kinematics were measured with a data glove (Cyberglove II; Immersion Inc). In 12 of the 15 finger and thumb joints examined, active ROM was not statistically different between inside and outside the robot. In the other three joints, lower ROM inside of the robot was mostly because of misalignment of the fifth digit owing to its shorter length. Interjoint coordination within the digits was found to be normal inside the robot. Therefore, HEXORR allows a large ROM and guarantees relatively normal movement patterns.

Control Modes

Robots can implement novel assistance profiles customized to each subject. The overall goal is to provide assistance force to increase movement amplitudes while not taking over the task from the subject to the point that the subject becomes passive. Movement amplitude is measured inside the robot with rotation sensors, whereas determination of the subject's contribution is done with torque sensors. For example during extension, the torque sensor records if the subject is contributing to movement with extension torque or if the hand is resisting movement with flexion torque. The mechanical work done by the subject over the course of the movement quantifies the degree of contribution or resistance, with positive overall work indicating that the subject was contributing more than resisting, whereas negative work indicates the limb was being mostly dragged along by the robot.

The authors used a novel assistance approach called tone compensation, in which the assistance profile was based on the torque required to passively extend the fingers and thumb. It has been well documented that flexor hypertonia causes elevated resistance to passive finger extension that is dependent on both position and velocity.[16] First, the torque required to slowly extend the fingers is measured by the robot and tabulated into an angle *vs.* torque profile that can be delivered by the robot. By compensating for flexor tone, even low levels of activation in extensors will produce extension movements. This restoration of the normal input-output pathway for producing extension movements may reinforce this pathway, increasing the ability of the subject to activate extensors.[60,61] In preliminary testing in stroke subjects, tone compensation increased finger active ROM by 43% compared with unassisted movement.[76] The work done by the hand was reduced by 22% with tone compensation, but the total work remained clearly positive, indicating that the subjects were still contributing to the movements.

Preliminary Training Results

Phase II clinical studies are needed to identify the patient populations that will be most appropriate for each robot.[77] The authors performed this type of study to determine which subjects would be most responsive to HEXORR training.[78] Four chronic stroke subjects received 18 sessions of robot therapy. Most of the training involved playing a Gate Game, which consists of vertical bars that sweep across the screen toward balls controlled by finger and thumb movements. Subjects extended and flexed the fingers so that the balls passed through gates in the vertical bars. During gates that required extension movement, tone compensation was provided. The initial tone compensation profile was the motor output required to open the hand slowly during passive movement. The experimenter altered the tone assistance by manually adjusting a scaling factor based on the subject's performance during the game.

All subjects showed gains in active finger ROM measured in the robot, and all but one subject had gains in active thumb ROM. Most of these gains

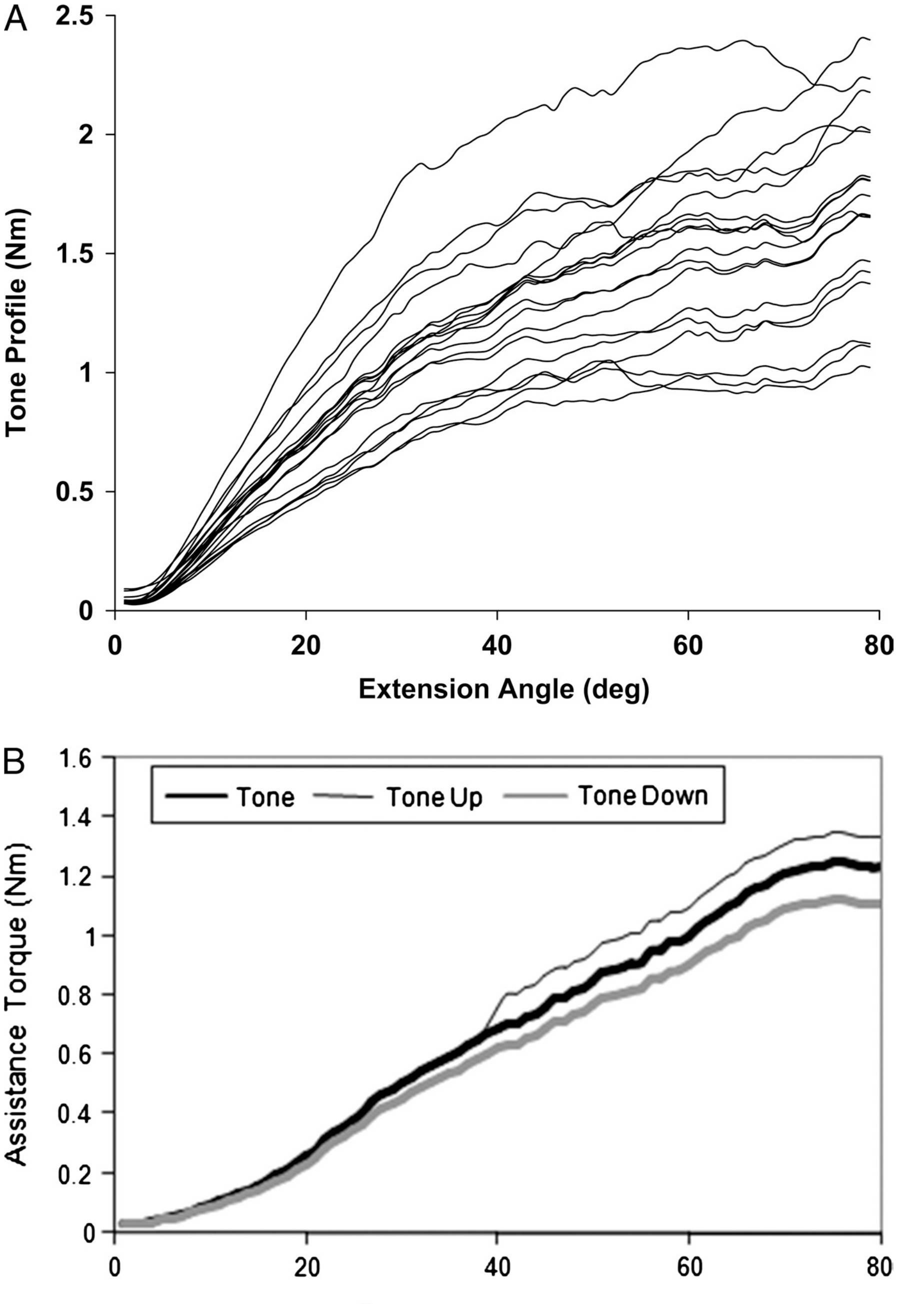

FIGURE 2 *A, Variations in tone within a single subject over the course of 18 training sessions. The tone profile is the extension torque required to open the hand. Zero extension angle corresponds to the fully flexed position (90 degrees of metacarpophalangeal joint flexion). B, Method used by HEXORR to shape the assistance profile. The thin black line shows how the tone profile is offset up if the subject only reaches 40 degrees of extension in the three previous trials. The gray line is how the profile is scaled down if the subject reaches the target on more than one of the three previous attempts. HEXORR indicates Hand Exoskeleton Rehabilitation Robot.*

carried over to ROM gains outside the robot. Clinical measures included the FM Impairment Scale, Box-and-Blocks, and the Action Research Arm (ARA) test of function. All clinical scales showed clear improvements in two higher level subjects (baseline FM score, 33 and 42). FM scores increased by 8 and 6 points after training, whereas Action Research Arm test scores increased by 4 points in each subject. However, there were no gains in two lower level subjects (baseline FM score, 23 and 23). One of these nonresponders was 25 yrs post-stroke and showed large increases in tone during training, requiring additional passive stretching between active trials. The other had a very flaccid hand and began to show improvement toward the end of training, suggesting he may benefit from additional training. Although these results are preliminary, data suggest that HEXORR will be most effective in subjects with moderate impairment levels and with some voluntary extension ability.

Autoshaping Tone Compensation Algorithm

Robots can adapt quickly to variations in subject performance. It was apparent from this initial training that tone levels can vary within and between sessions (Fig. 2*A*). To automate changes in the assistance profile, the authors developed a novel, autoshaping algorithm for HEXORR that adapts to the performance of the hand during the Gate Game. If the user successfully reaches the gate two or three times within three consecutive gates, the assistance is scaled down by 10% (Fig. 2*B*). If the user succeeds on one gate out of three, the assistance remains unchanged. Finally, if the user fails at all three gates, the algorithm calculates the average extension angle achieved over the three trials and increases assistance at this point via an offset. To avoid large steps in assistance, the offset is incorporated gradually over a small portion of the assistance curve. The combination of increasing assistance via

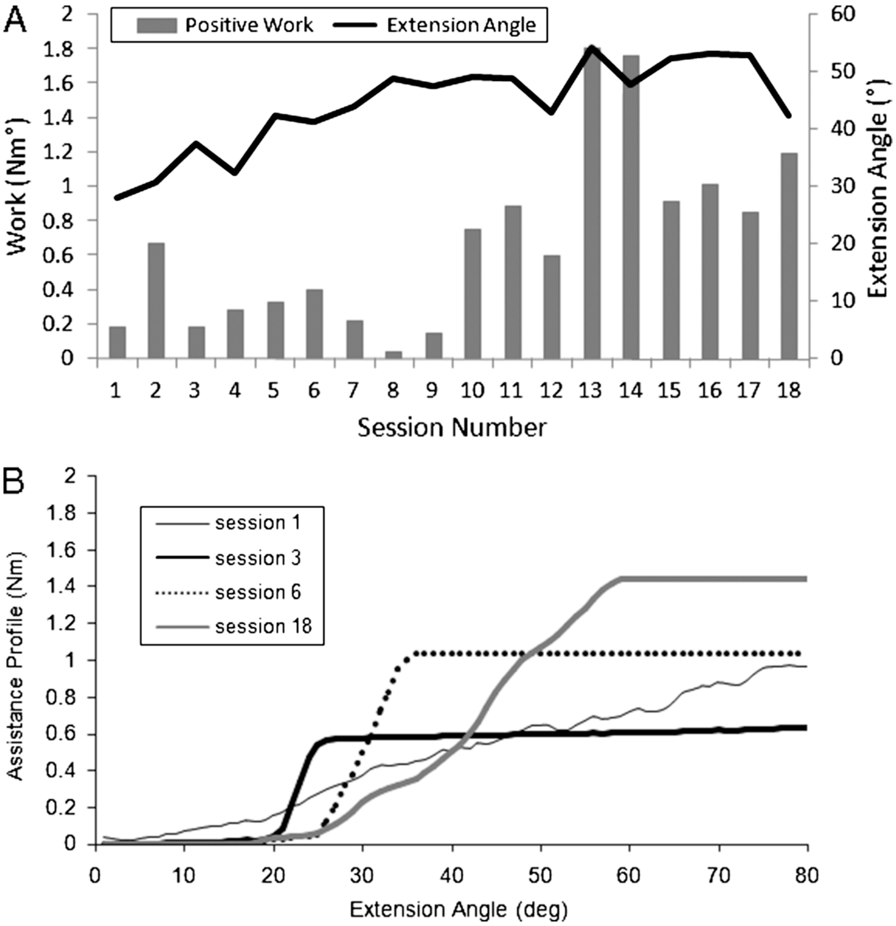

FIGURE 3 *A, Increases in work (bars) and movement amplitude (line) over 18 sessions of HEXORR training in a single subject. B, Evolution of the assistance profile over the same 18 sessions. The target movement amplitude was gradually increased over the 18 sessions. The adaptive algorithm tended to cause the assistance profile to plateau at the target location. By session 18, the slope of the assistance profile was decreased and the onset was shifted to larger extension angles. It is likely that the assistance profiles are compensating for both flexor tone and extensor weakness. HEXORR indicates Hand Exoskeleton Rehabilitation Robot.*

an offset and decreasing assistance via scaling enables real-time shaping of the assistance profile to accommodate the variable nature of hypertonia. The thumb and finger adaptive algorithms worked independently of each other.

The authors recently had a chronic stroke subject complete 18 training sessions in HEXORR over a 7-wk period using the autoshaping tone compensation algorithm. He completed an average of 85 extension and flexion gates per training session. Over the course of treatment, maximum extension angle and positive work increased during the Gate Game (Fig. 3*A*). Large changes in the assistance profile occurred over the course of the sessions as the autoshaping algorithm coevolved with the subject (Fig. 3*B*). The subject showed a 19% gain in the Action Research Arm test, 9% gain in FM score, and 160% gain in Box-and-Blocks.

Comparing Different Control Strategies

Robots can be used to study subject responses to different control strategies. The authors recently performed a comparison study in which three chronic stroke subjects had a single session of HEXORR training to compare two different types of robotic assistance.[79] Subjects played the Gate Game for 30 gates with the tone compensation mode and also with a spring assistance mode. The spring mode provided a linear, spring-like extension force that increased with increasing distance from the target extension angle. With both types of assistance, a self-adapting algorithm adapted assistance levels based on subject performance. All three subjects produced larger finger movements with assistance from the robot, but they also produced much more positive work with tone compensation compared with spring assistance, demonstrating that with tone compensation, subjects were actively driving the movements to a greater extent than with spring assistance. Thus, the authors conclude that the tone compensation mode, more so than spring mode, maintains the input/output map between extension effort and movement while increasing movement amplitudes.

FUNCTIONAL HOME THERAPY

Home-based devices may prove to be the only way of increasing the dose of movement therapy

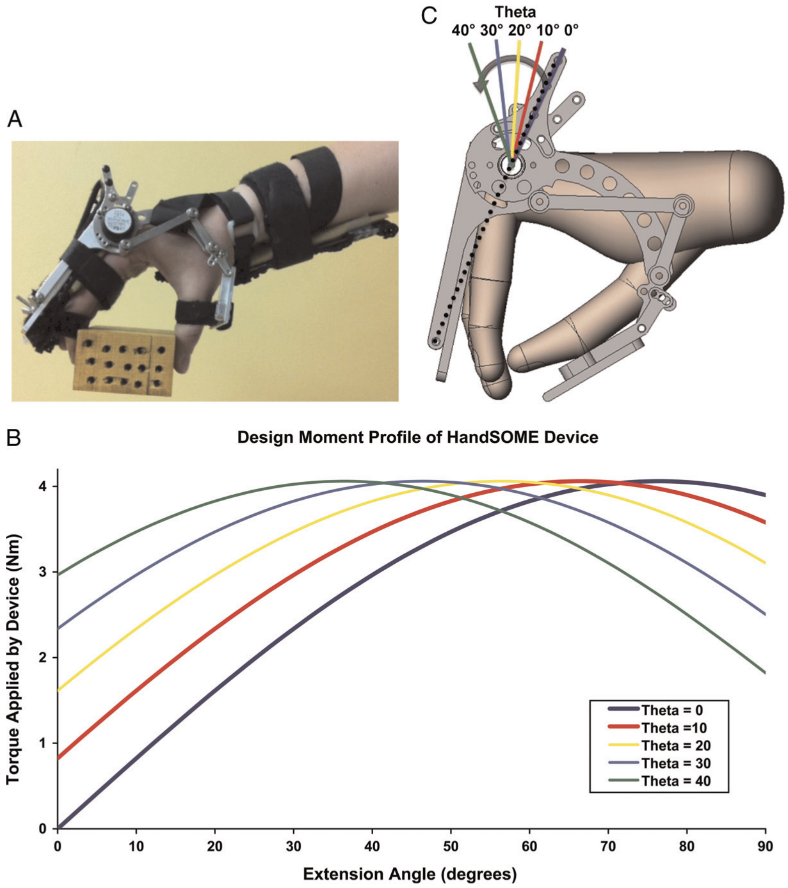

FIGURE 4 *A, HandSOME. Both large and small objects can be manipulated when wearing the device. B, HandSOME assistance profile. Zero extension angle corresponds to the fully flexed position (90 degrees of MCP flexion). The dotted line in the lower right drawing shows the spring path with Θ = 0. Changing the Theta setting changes the shape of the profile by changing the path of the elastic cords. HandSOME indicates Hand Spring Operated Movement Enhancer; MCP, metacarpophalangeal joint.*

enough to produce robust gains in use of the limb in ADL. Although motorized robotic devices such as HEXORR allow testing of complex control algorithms, simple, lightweight passive devices can also assist movement and have the key advantage that they can be used during home ADL practice. The authors have developed a passive device that provides an assistance profile similar to HEXORR. The Hand Spring Operated Movement Enhancer (HandSOME) is similar in concept to the SaeboFlex[80] in that elastic elements are used to compensate for hypertonia (Figs. 4*A*, *B*).[81] The magnitude of the assistance torque is adjusted by changing the number of elastic cords, whereas the shape of the torque profile is adjusted by changing the path of the cords. A four-bar linkage coordinates the movement of the fingers and thumb, guaranteeing normal kinematics during pinch-pad grasp. The HandSOME allows 90 degrees of rotation about the MCP joint of the fingers and a coordinated thumb rotation of 45 degrees at the carpometacarpal joint. A cross-sectional study ($n = 8$) showed that the device improved ROM, with a mean increase of 48.7 ± 1.0 degrees of finger MCP extension.[82] The ability to lift blocks of different widths also improved significantly. Two subjects had no successful lifts unassisted but lifted blocks ranging from ½ to 3 in. wide when wearing HandSOME. Essentially, a nonfunctional hand was made functional by wearing the device. Further study is required to determine the potential long-term effects of therapy with the HandSOME. Efforts are underway to allow a stroke subject to easily don and doff the device independently at home and play a video game controlled wirelessly by the rotation sensor on HandSOME. For severely impaired subjects, HandSOME also has potential as an assistive orthotic device.

CONCLUSION

The challenges of providing assisted movement therapy for the many DOFs of the hand are being met by a wide variety of robotic devices. These devices can implement novel training methods that adapt quickly to changes in patient performance. Precise measurements of patient performance during training offer insights into motor impairments such as hypertonia. Clinical testing has shown that robotic training can improve movement ability and performance on functional scales. However, more studies are needed to determine the most appropriate subject populations and whether robot-assisted movement has advantages over unassisted movement or conventional therapy. The potential of robots to dramatically increase dose has received little attention, with most studies providing less than 30 hrs of robot therapy. Efforts toward home-based devices should be accelerated because they can potentially increase dose many times above what has been tested.

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