Published in final edited form as:
Neurorehabil Neural Repair. 2009 October ; 23(8): 862–869. doi:10.1177/1545968309332927.

Progressive Shoulder Abduction Loading is a Crucial Element of Arm Rehabilitation in Chronic Stroke

Michael D. Ellis, PT, DPT, **Theresa Sukal-Moulton, DPT**, and **Julius P. A. Dewald, PT, PhD**
Department of Physical Therapy and Human Movement Sciences (MDE, TS, JPAD), Department of Physical Medicine and Rehabilitation (TS, JPAD), and Department of Biomedical Engineering (JPAD), Northwestern University, Chicago, Illinois.

Abstract

Background—Total reaching range of motion (work area) diminishes as a function of shoulder abduction loading in the paretic arm in individuals with chronic hemiparetic stroke. This occurs when reaching outward against gravity or during transport of an object.

Objectives—This study implements 2 closely related impairment-based interventions to identify the effect of a subcomponent of reaching exercise thought to be a crucial element in arm rehabilitation.

Methods—A total of 14 individuals with chronic moderate to severe hemiparesis participated in the participant-blinded, randomized controlled study. The experimental group progressively trained for 8 weeks to actively support the weight of the arm, up to and beyond, while reaching to various outward targets. The control group practiced the same reaching tasks with matched frequency and duration with the weight of the arm supported. Work area and isometric strength were measured before and after the intervention.

Results—Change scores for work area at 9 loads were calculated for each group. Change scores were significantly larger for the experimental group indicating a larger increase in work area, especially shoulder abduction loads equivalent to those experienced during object transport. Changes in strength were not found within or between groups.

Conclusions—Progressive shoulder abduction loading can be utilized to ameliorate reaching range of motion against gravity. Future work should investigate the dosage response of this intervention, as well as test whether shoulder abduction loading can augment other therapeutic techniques such as goal-directed functional task practice and behavioral shaping to enhance real-world arm function.

Keywords

Stroke; Upper extremity; Shoulder loading; Biomechanics; Rehabilitation; Muscle strength; Robotics

In patients with moderate to severe hemiparetic stroke, abnormal biceps muscle coactivation[1] and triceps muscle inhibition[2] occurs during deltoid activation and is associated with abnormal joint torque coupling of shoulder abduction with elbow flexion. These abnormal muscle coactivations and joint torque coupling patterns have been verified in both isometric[1-3] and reaching[4,5] tasks reflecting constraints in the ability of individuals with stroke to reach outwards and were described originally as stereotypical movements combining

---

Address correspondence to Michael D. Ellis, PT, DPT, Northwestern University, Department of Physical Therapy and Human Movement Sciences, 645 N. Michigan Ave, Suite 1100, Room 1159, Chicago, IL 60611. m-ellis@northwestern.edu..

shoulder abduction with elbow flexion.[6,7] Recent evidence suggests that outward reaching in individuals with stroke is greatly reduced as a function of arm loading[8] and is associated with, and augments conventional clinical measures of, impairment, activity, and participation limitation.[9]

Considering the impact of abnormal joint torque coupling on arm function, we sought to determine if an impairment-based intervention targeting abnormal joint torque coupling could improve reaching range of motion at functionally relevant arm loading levels. We chose an impairment-based approach to address the emerging need in upper extremity rehabilitation to identify the operative components in effective upper extremity rehabilitation therapies.[10] The impairment-based approach allowed us to specifically test for the effect of a subcomponent of exercise without the confounding effects of other therapeutic factors. A systematic review of randomized controlled trials using robotics, such as the ACT^{3D} (chair and base from Biodex Medical Systems, New York; modified HapticMaster robot from Moog, Netherlands) employed in this study,[8] concluded that a principal attribute of robot-assisted therapies is the application of high intensity repetitive movements.[11] While attributes such as high intensity repetition and goal-oriented task practice have been suggested previously as key elements of stroke rehabilitation,[12] it was evident in the review of rehabilitation robotics by Kwakkel et al[11] that the common implementation of conventional care or placebo as a control group, and the lack of incorporation of quantitative kinematic/kinetic outcome measures, made it difficult to identify other crucial elements of upper extremity rehabilitation therapies. In this study, we attempted to address these limitations by implementing a randomized controlled design with a closely related comparison group and a clinically meaningful kinematic/kinetic outcome measure to clearly test for the effect of a specific element of upper extremity interventions. The objective of the study was to determine if progressive shoulder abduction loading is a key element of therapeutic reaching exercise and therefore should be considered for incorporation into activity- and participation-based rehabilitation approaches to maximize the otherwise untapped potential of impairment reduction.

Methods

Participants

A total of 14 individuals ranging from 50 to 78 years of age, with upper extremity Fugl-Meyer Motor Assessment (FMA)[13] scores between 10 and 43, participated in the study (demographics, see Table 1). All participants were recruited from a departmental research database under search criteria for score on the FMA. Inclusion criteria for the study was a score within the range of 10 to 50 out of a possible 66, to exclude people with near complete paralysis or lack of impairment and to capture those individuals most likely to express the impairment of abnormal joint torque coupling.[8,9] All participants were screened for inclusion in the study by a physical therapist who was blinded to the study. Potential participants were excluded if they had difficulty with sitting for long durations (self report), recent changes in the medical management of hypertension (self report), any acute or chronic painful condition in the upper extremities or spine, or greater than minimal sensory loss in the affected arm as determined by a tactile localization and awareness of movement task. Passive range of motion of the affected arm was measured to verify full passive extension of the elbow and at least 90 degrees of passive shoulder flexion, abduction, and neutral internal/external rotation to participate in the study. Overpressure at the end of the range of motion was used as a medical screening to verify the absence of an inflammatory condition at the shoulder, elbow, wrist, and fingers. All participants provided informed consent in accordance with the Declaration of Helsinki prior to participation in this study, which was approved by the Institutional Review Board of Northwestern University.

Randomization

Participants were randomly assigned to either the experimental or comparison/control group. Randomization was balanced every 2 participants to ensure equal distribution to groups because of the anticipated small sample size of this study, which was constrained by the 2-year award supporting this work. The allocation of assignment to groups was concealed to the participants.

Primary Outcome Measure: Work Area

Work area of the affected arm was tested for each participant in the laboratory before and after the intervention, following an established protocol[8] by the primary author who was not blinded to the group assignment. Work area is a quantitative measurement of motor impairment (combined shoulder-elbow active range of motion) performed in a functional context (multiple arm loads). It is administrated in a standardized fashion and uses 3D kinematic and kinetic analyses as opposed to subjective interpretations of movement to reduce experimenter or clinician bias. The quantitative measurement has been cross-validated with qualitative clinical assessments of impairment, activity and participation limitation, and has been shown to augment conventional clinical evaluation of upper extremity function.[9] Two baseline evaluations separated by 1 week were taken in the 2 weeks prior to the onset of the intervention followed by 1 evaluation at the end of the 8-week intervention period. Two measurements were taken at baseline to measure stability of the primary outcome at baseline. In preparation for the evaluation of work area, participants sat in an experimental chair with their arm resting in a forearm-hand orthosis attached to the ACT^{3D} (Figure 1). The orthosis maintained the wrist and hand in a neutral position and the participant's trunk was immobilized also minimizing shoulder girdle movement by a set of straps attached to the experimental chair. The shoulder was positioned at 90 degrees of abduction when the tested arm was resting on the haptically rendered table (virtual table maintained by the device and displayed in visual feedback). Participants were manually placed in an initial known position of 40 degrees of shoulder flexion or horizontal adduction and 90 degrees of elbow flexion using a goniometer for the ACT^{3D} software to calculate the position of the shoulder and create a graphic representation of the arm illustrated on a computer screen in front of the participant. During work area measurement, participants were asked to move the tip of their hand in a circular motion producing the largest envelope possible with their paretic arm while it was fully supported by, and gliding on, the horizontal haptic table. The task was performed slowly at approximately 5 degrees/second of elbow and shoulder joint angular velocity to minimize the effects of hyperactive stretch reflexes or spasticity at the elbow and shoulder joints. Participants performed the task in both clockwise and counterclockwise directions, of which each was randomized. Since the work area measurement attempts to capture the total available reaching range of motion, envelopes generated from all trials at a given arm-loading level were superimposed and the area of the combined envelope was calculated.[8] Rest was given between each trial to eliminate fatigue,[14] and verbal feedback was given to encourage the participant to achieve the maximum movement excursion while moving slowly. Next, the experimental chair was elevated by approximately 2 inches, and participants were required to actively support their arm just above the horizontal haptic table resulting in 90 degrees of shoulder abduction as it was when supported by the haptic table. Once the arm was lifted from the haptic table, data collection began and a deterrent audible cue rang any time the participant's arm inadvertently deflected off, or intentionally rested upon, the haptic surface. The protocol was repeated while the ACT^{3D} provided forces along its vertical axis to alter the amount of arm weight that the participant was required to support. A total of 9 shoulder-abduction loading levels were randomized for testing (see Figure 2 for example of work area). Shoulder abduction loading was expressed as a percentage of arm weight that the participant was required to support during the tasks, which ranged from 0% to 200% of arm weight in increments of 25%. If a participant was unable to lift the arm off of the haptic table, all heavier shoulder-abduction loading conditions were skipped. Two participants could not complete the heaviest loading levels. This was expected because of the variability of relative weakness[5] in abductors among individuals with stroke represented in this sample. Furthermore, it should be noted that a participant could have enough abductor weakness such that work area can only be measured while fully supported on the haptic table. This generally is the case in flaccid hemiparesis, which explains why we excluded this group from our sample population. Kinematic data obtained by the ACT^{3D} were collected for all trials and saved for future analysis.

Secondary Outcome Measure: Isometric Strength and Associated Muscle Activity

Isometric strength and the associated muscle activity were measured for shoulder abduction/adduction, flexion/extension, and elbow flexion/extension before and after the intervention by a physical therapist who was blinded to group assignment. The secondary outcome of strength and electromyography (EMG) was chosen because it is well suited to augment the interpretation of the primary outcome results through its capacity to offer further insight into the neural mechanisms underlying reaching limitations. Since it was a secondary outcome measure, strength was only measured once at baseline and again at posttesting. During the measurement of strength, each participant was seated in a Biodex chair with shoulder and waist strapping to restrain trunk and shoulder girdle movement during testing. The same arm configuration as the home position, as described above, was used for isometric strength testing. The forearm, wrist, and hand were fixed to a 6-DOF load cell (Model #45E15A, JR3 Inc, Woodland, CA) using fiberglass casting and a Delrin ring mounted at the wrist. Prior to data collection in each arm position, the load cell was calibrated/zeroed with the participant fully at rest (quiescent EMG recordings). Orthogonal forces and moments measured by the load cell were filtered and converted on-line to torques at the elbow and shoulder. Real-time visual feedback was provided to the participant, via computer monitor, of the torque produced at the shoulder or elbow joint. Maximum voluntary torque (MVT) was measured in 3 random blocks consisting of shoulder abduction/adduction, flexion/extension, and elbow flexion/extension. EMG signals were recorded during all trials from the brachioradialis; biceps brachii; lateral and long heads of triceps brachii; anterior, intermediate, and posterior deltoid; and vertical fibers of pectoralis major. Correct electrode placements were verified by examination of EMG activity. Active differential electrodes (Delsys, 16-channel Bagnoli EMG System, Boston, MA) with 1-cm interelectrode distance were used to record surface EMG from the upper extremity muscles. Data obtained were stored offline for future analysis.

Intervention

The primary author administered both the experimental and control interventions because of both the standardized quantitative control of the protocol and the practical fiscal constraints of the 2-year award supporting the study. The intervention protocol consisted of reaching movements to targets in 5 standardized directions near the end of reaching range of motion and spanning a large portion of the work area while supporting a percentage of the weight of the arm. The experimental intervention task was substantially different from the evaluation of work area in that it was tailored specifically to the participant in regards to impairment expression (initial shoulder abduction loading level) and was comprised of direction- and location-specified outward reaches, as opposed to the global multijoint range of motion task measured as the primary outcome measure. The initial shoulder abduction loading level was determined during the first intervention session following a standardized quantitative procedure leaving little room for experimenter bias. The initial arm-loading level experienced for each target direction was the level at which the participant could reach, under maximal effort, only 50% of the distance to the outward target without setting the arm back down on the horizontal haptic table. Participants were trained at this armloading level until they could reach to within 10% of the distance to the target in at least 8 out of 10 repetitions. The shoulder abduction loading was then increased in intervals equal to 25% of arm weight to a new level where participants could reach only 50% of the distance to the target as they improved over the 8-week intervention period. The standardized target placement was not altered as part of the intervention progression. Occasional/random feedback of movement performance was provided to the participants following the execution of each trial. Each intervention session consisted of 3 sets of 10 repetitions for each of the movement directions. Rest periods of up to 30 seconds between trials and a fixed 1-minute rest between sets were provided to avoid fatigue because of the substantial intensity of the exercise. The order of the sets was randomized for each session. A total of 3 sessions per week were implemented over an 8-week period with the goal being to progressively increase the percentage of arm weight actively supported by the participant while reaching toward each target.

The control group followed the same protocol as the experimental group but was never required to actively support any weight of the arm above the haptic table. Instead, control participants performed the same reaching tasks while supported by, and gliding along, the frictionless haptic table. Participants were consistently encouraged to fully acquire the targets in every repetition of practice. The intensity experienced by the control group was matched to the experimental group at the level of frequency (same total number of repetitions) and duration (same duration of session).

Data Analysis

The total work area for each level was calculated offline using customized software in the Matlab environment (The Mathworks; Natick, Massachusetts). Work area was defined as the total area in square meters contained within the perimeter of the largest envelope generated by the superimposed clockwise and counterclockwise envelopes that were generated during each of the loading conditions.[8,9] Areas for all participants were normalized to the area they were able to achieve while supported by the haptic table to account for differences in arm length and small contractures. Statistical analyses were performed using Data Desk (Data Description, Inc.; Ithaca, NY).

A 2-factor analysis of variance (ANOVA) with interactions was used to determine the effect of group (control vs experimental) and level (0%, 25%, … 200%) on a normalized work area (dependent variable) during the baseline-1 evaluation to establish the homogeneity of the 2 groups as baseline. The normality of the data was confirmed using the Kolmogorov-Smirnov test. Post hoc comparisons were based on Scheffe's test. A secondary metric, strength, was also used to determine homogeneity of groups. An unpaired 2-tailed *t* test was used to test the difference between groups for each torque direction. For all statistical tests, a significant effect or difference was defined as a P value $\leq .05$.

A 2-factor repeated measures ANOVA was used to determine the effect of session (repeat; baseline 1 vs baseline 2) and level (0%, 25%, … 200%) on nonnormalized work area (dependent variable) for both groups to determine if there was a stable baseline. The normality of the data was confirmed using the Kolmogorov-Smirnov test. Post hoc comparisons were based on Scheffe's test. A significant effect or difference was defined as a P value $\leq .05$.

A 2-factor ANOVA with interactions was used to determine the effect of group (control vs experimental) and level (0%, 25% … 200%) on work area change scores (dependent variable; change score (m^2) = work area^{post} − work area^{pre}) to determine the impact of progressive shoulder abduction loading on reaching ability. The more rigorous analysis of change scores was chosen instead of a repeated measures analysis of prescores/postscores. The normality of the data was confirmed using the Kolmogorov-Smirnov test. Post hoc comparisons were based on Scheffe's test. A significant effect or difference was defined as a P value $\leq .05$.

A 2-tailed unpaired *t* test was used to test the difference between groups on change scores for each of the 6 torque directions (torque change score (Nm) = $\text{MVT}^{\text{post}} - \text{MVT}^{\text{pre}}$). The Wilcoxon test was used when data were not normally distributed as found by the Kolmogorov-Smirnov test. A secondary within-group analysis was conducted using a 2-factor repeated measures ANOVA to determine the effect of session (repeat; pretest vs posttest) and group on absolute joint torque (dependent variable) for each of the 6 torque directions to confirm the prior analysis. In an effort to determine possible changes in muscle cocontraction at the elbow joint that cannot be detected by our torque signals, agonist/antagonist EMG ratios were also calculated and compared between sessions. An agonist/antagonist ratio was required since intervention-induced changes in cocontraction could reflect facilitation of the agonist, inhibition of the antagonist, or a combination of both. The EMG ratio was calculated with the following formula: normalized agonist EMG/normalized antagonist EMG = x. The x value was the value used for statistical analyses and can also be expressed in a ratio notation such as x:1 or x to 1. A 2-factor repeated measures ANOVA was used to determine the effect of session (repeat; pretest vs post-test) and group on agonist/antagonist ratio (dependent variable) for elbow flexion and elbow extension MVTs.

Results

Statistical analysis of normalized work area during baseline evaluation indicated that there was no effect of group ($P = .09$) or interaction effect of group and level ($P = .99$). Similarly, there was no difference in strength between groups for any of the 6 torque directions. Thus, the 2 groups were similar at baseline. Regarding the stability of the baseline measurement, the statistical analysis of nonnormalized work area indicated no effect of repeated session for the experimental group ($P = .15$) or control group ($P = .68$) and no interaction effect of repeated session and level for the experimental group ($P = .48$) or control group ($P = .56$). These analyses demonstrated that, for the primary outcome measure, the evaluation was repeatable and stable for both groups, which was consistent with previous reports of this outcome measure in individuals with chronic stroke.[8]

Although rate and magnitude of progression were not measured outcome variables, it is important to acknowledge that individuals in the experimental group usually progressed through only a few of the total available shoulder abduction loading conditions, which was likely due to the constrained duration of the 8-week intervention period. For example, a participant who began the intervention at the 50% limb-loading level and ended the training at the 100% limb-loading level would have progressed through 2 of the 9 available levels (0%-200%). It did not appear that progression, as indicated by the number of active support levels progressed, slowed down or plateaued by the end of the 8-week intervention.

Regarding the primary outcome measure, analysis of absolute work area change scores between groups indicated that there was an effect of group ($P = .0001$) and an interaction effect of group and level ($P < .05$). Post hoc analysis indicated that there was a significantly greater increase in work area (larger change score) for the experimental group at the limb-loading levels of 50% ($P = .05$), 100% ($P = .04$), 125% ($P = .05$), and 175% ($P = .01$). The change scores at these levels represented work area improvements in the experimental group of 26%, 38%, 54%, and 68%, respectively. Furthermore, there was a trend in larger change scores for the experimental group at the 75% ($P = .09$) and 150% ($P = .10$) levels. Mean change scores, measured in square meters and standard errors for each level in both groups, are illustrated in Figure 3.

Analysis of the secondary outcome measure of isometric strength indicated that there was no difference between groups for change scores in isometric strength at either the shoulder or the elbow. Additionally, repeated-measures analysis showed no effect ($P > .05$) of group, repeated session, or interaction between group and repeat for all torque directions. The associated ratios of agonist to antagonist EMG cocontraction during elbow MVTs did not change following the intervention in either group. For example, in the experimental group, during maximum elbow extension, normalized agonist extensor activity averaged 77 ± 3% and 75 ± 5% for lateral head of the triceps, and 63 ± 4% and 64 ± 4% for long head of triceps during pre-testing and posttesting sessions, respectively, while concurrent normalized antagonist flexor activity averaged 13 ± 3% and 14 ± 4% for brachioradialis, and 16 ± 4% and 16 ± 3% for biceps brachii during pretesting and posttesting sessions, respectively. Depending on which extensor and which flexor was used in the calculation, this resulted in average pretest agonist/antagonist ratios ranging from 3.9:1 to 5.9:1 and average posttesting agonist/antagonist ratios ranging from 4.0:1 to 5.3:1. More specifically, lateral head of the triceps EMG divided by brachioradialis EMG was the larger ratio (5.9:1 and 5.3:1) while the long head of the triceps' EMG divided by biceps brachii EMG was the smallest ratio (3.9:1 and 4.0:1). Ultimately, there were no significant preintervention to postintervention changes in any single agonist to antagonist ratio for either group.

Discussion

This study demonstrated that functionally relevant reaching range of motion (work area) can be improved in individuals with chronic hemiparetic stroke and, most importantly, identified a crucial element of interventions attempting to improve functional reaching abilities. Considering that intensity was controlled through frequency- and duration-matching between the 2 groups, the progressive shoulder abduction loading element of the reaching intervention can be credited for the significant increase in work area observed in the experimental group following the intervention. The ability of participants to progress to heavier abduction loading levels during the intervention period and, furthermore, the carryover of coordination improvements to a much different motor task (work area evaluation), serves as an example of preserved motor acquisition[15] and motor transfer,[16] despite impaired motor output following stroke. This highlights the untapped potential of targeting specific impairments that may be used to refine contemporary activity- and participation-level interventions. Considering related previous work,[17] we suggest that increases in work area may be attributed to a reduction in shoulder-elbow discoordination or improvements in independent joint control, most notably, at functional shoulder abduction loading levels (100%-200% arm weight usually equates to sub-maximal abduction), and explained by neural adaptation of the motor system.

Strengthening and Multijoint Coordination Exercise in Stroke

Increases in work area in the experimental group cannot be explained by gains in single-joint strength at either the shoulder or the elbow, but instead by improvements in multi-joint coordination or independent joint control. The between-group analysis of strength change scores and the secondary within-group repeated measures analysis of pre-/post-strength scores suggests that variations in maximum strength cannot be used to explain the substantial increases in work area observed in the experimental group. This could be viewed as inconsistent with previous work that demonstrated gains in isometric single-joint strength following an isometric exercise protocol that was similarly designed to train individuals with stroke to produce multijoint torque patterns (shoulder abduction, flexion, and elbow extension) away from the abnormal abduction/ elbow flexion pattern.[17] Considering the intervention in the present study, it is likely that strength gains did not occur due to the submaximal single-joint loading that participants were exposed to. In the isometric study by Ellis et al,[17] participants were routinely pushing against a rigid object as they attempted to produce multijoint patterns. One of the tasks included maximal shoulder flexion in combination with maximal elbow extension. In the current dynamic intervention, there was no resistance to any movements in the horizontal plane whether they were shoulder flexion, elbow extension, or a combination of both. Despite the tremendous difficulty of performing the reaching tasks, the only “resistance” experienced by the participants in the present study was submaximal levels of shoulder abduction. This highlights the possibility that while maximal multijoint isometric exercises result in improvements in single-joint strength and reductions in shoulder-elbow dis-coordination at maximal efforts, they may not have carried over into improvements in functional reaching as occurred in the present intervention where abduction loads were at a sub-maximal level and more consistent with the loads experienced during everyday functional reaching tasks. Strength changes may have been a byproduct of the maximal resistive nature of the previous study, where the crucial element of exercise responsible for reducing shoulder-elbow discoordination may have simply been the repetitive attempt to generate isometric multijoint patterns outside of the synergistic pattern, as was done dynamically in the present study.

However, it has been reported that the impairment with the greatest contribution to arm function is overall arm strength,[18] implying that improvements in strength would carryover into improvements in function. Furthermore, strength training has been shown to be effective in improving impaired strength in both individuals with hemiparetic stroke[19,20] and similarly impaired individuals with spastic hemiparetic cerebral palsy.[21] Although improvements in strength are possible in these populations, the link between improvements in strength and improvements in arm function is less clear in individuals with stroke.[22] However, in their single-subject case study, Patten and colleagues suggest[22] that it is the dynamic nature of the strengthening exercise that is likely responsible for improvements in arm function. The exercises done in the present study were also of a dynamic nature with the experimental group experiencing progressive shoulder abduction loading that may be considered a dynamic strengthening component. However, our results suggest that even when the impairment of strength remains the same, reductions in the impairment of shoulder/ elbow discoordination may best explain substantial improvements in reaching ability. EMG was not measured during the work area measurement; therefore, it is impossible to determine if there were reductions in abnormal coactivation of elbow flexors, reductions in the inhibition of elbow extensors, or a combination of both that would explain why range of motion improved so greatly despite no change in elbow strength. However, we suggest that multijoint coordination, as opposed to single-joint strength, is the overwhelming factor responsible for reductions in functional reaching magnitude after stroke in patients with enough strength to elevate the arm against gravity.[5] Also, the measurement of elbow extension strength in an individual with hemiparesis might not be clinically meaningful if the demands on the shoulder are not taken into account. Intervention-induced improvements in elbow extension strength measured while the arm is passively supported are unlikely related to improvements in elbow extension strength measured while the arm is actively elevated against gravity because of substantial abnormal activation of flexors[1] and inhibition of extensors[2] that occurs during active abduction. Therefore, rehabilitation clinicians must consider the importance of multijoint coordination, both when evaluating patients and when choosing the best interventions for improving functional reaching abilities in patients who have recovered sufficient strength to deal with upper extremity weight and inertia.

Similar to strength, increases in work area in the experimental group cannot be explained by changes in passive tissue properties of the upper extremity. By comparing absolute work area on the haptic table before and after the intervention, and considering that work area in these individuals is relatively unimpaired while supported,[4] the possibility of increases in passive range of motion can be addressed. There was no difference in work area while supported by the haptic surface. Therefore, any increases in normalized work area while actively lifting the arm were most likely not related to changes in tissue properties that could affect passive range of motion. Similarly, given the very slow movement velocities controlled for during the determination of work area before and after the implemented interventions, changes in stretch reflex excitabilities are not believed to have contributed to the results reported in this study either.

Reduction of Abnormal Torque Coupling and Neural Mechanisms

Increases in work area are likely due to a reduction in abnormal coupling of shoulder abduction with elbow flexion. More specifically, we suggest that during reaching at sub-maximal shoulder abduction levels, there may have been a reduction in abnormal coactivation with elbow flexors and a concurrent reduction of the inhibition of elbow extensors. While we did not measure EMG during the dynamic work area evaluation, a recent study measured changes in muscle coactivations during an active-assistive intervention targeting single-joint elbow flexion and extension. However, this study did not include abduction loading (the arm was supported on a rigid horizontal surface).[23] Although changes in muscle coactivations were found by Hu et al,[23] it is unlikely that they would positively impact reaching work area at functionally relevant abduction loads because of the 2 dimensional constraint (gliding along a rigid horizontal surface) of the intervention that was similar to the present study's control group. An additional recent study reported a reduction in abnormal shoulder abduction/elbow flexion kinematic coupling following an intervention, however, was also limited in its interpretation by the fully limb-supported nature of the measurement device.[24] In the study by Dipietro et al[24] the arm began in 45 degrees of abduction and was fully supported on a horizontal surface by the device. The reported improvements in reaching magnitude were comprised of increases in shoulder abduction and elbow extension kinematics but failed to account for joint kinetics. Reaching with the weight of the limb supported by a horizontal surface does not account for the abnormal production of shoulder adduction when an individual with stroke attempts to extend the elbow. This is observed when comparing work area while supported on a rigid surface, to work area when an individual with stroke is required to elevate the limb above the horizontal surface while arm weight is fully supported by the device (0% condition in this study). Work area is reduced at the 0% abduction loading level due to a relative activation of abductors to counter abnormal coactivation of adductors during elbow extension.[8] Dipietro et al[24] were therefore unable to determine if the observed reductions in kinematic coupling would carry over into reaching under normal abduction loading conditions. Ultimately, the abduction loading element, lacking in interventions that constrain movement to a rigid horizontal surface, is required to elicit a substantial enough reduction in abductor/elbow flexor coactivation to result in improvements in reaching range of motion at functionally relevant abduction loads.

Although the intention of this study was not to determine the neural mechanisms by which the shoulder-elbow discoordination impairment was reduced, this line of investigation would greatly benefit from future mechanistic approaches such as the use of brain imaging techniques before and after the intervention. Previous work has illustrated that both structural[25] and behavioral[26-29] cortical reorganization occurs following an intervention and is related to improvements in impairment and function. While abnormal abduction/elbow flexion coupling is hypothesized to be attributed to increased bulbospinal system influence,[2] cortical reorganization may explain its reduction following the progressive shoulder abduction loading intervention. Intervention-induced reallocation of unaffected corticofugal fiber bundles, even from the contralesional cortex, may result in increased upper extremity control.

Implications

This study used a closely related randomly assigned comparison group to identify a crucial element of poststroke upper extremity rehabilitation. The implementation of a multidegree of freedom robotic system (ACT^{3D}) provided a quantitative measurement of functional outcome, and additionally, a rigorous and repeatable means of initiating and progressing the experimental and comparison interventions. The experimental design and level of quantitative control allowed for the identification of progressive shoulder abduction loading as a crucial element responsible for the improvements in reaching ability and potential reductions in multijoint discoordination. This work illustrates that distal joint control (elbow) is dependent on proximal joint task requirements (active abduction), thus impacting the way in which strength and coordination can be evaluated and treated in a clinically and functionally meaningful fashion. Future clinical research should investigate if progressive shoulder abduction loading augments current state-of-the-art interventions known to result in real-world functional improvements. Additionally, clinical scientists should seek to identify the neural substrate responsible for reduced abnormal joint torque coupling and the associated improvements in reaching work area. These efforts will facilitate the continued refinement of therapeutic techniques and identify structures and functions within the nervous system that may be targeted by rehabilitation clinicians and will most likely result in reduced physical impairment and improved real-world arm function in individuals with stroke.

References

1. Dewald JP, Pope PS, Given JD, et al. Abnormal muscle coactivation patterns during isometric torque generation at the elbow and shoulder in hemiparetic subjects. Brain 1995;118:495–510. [PubMed: 7735890]
2. Ellis MD, Acosta AM, Yao J, et al. Position-dependent torque coupling and associated muscle activation in the hemiparetic upper extremity. Exp Brain Res 2007;176:594–602. [PubMed: 16924488]
3. Lum PS, Burgar CG, Shor PC. Evidence for strength imbalances as a significant contributor to abnormal synergies in hemiparetic subjects. Muscle Nerve 2003;27:211–221. [PubMed: 12548529]
4. Beer RF, Dewald JP, Dawson ML, et al. Target-dependent differences between free and constrained arm movements in chronic hemiparesis. Exp Brain Res 2004;156:458–470. [PubMed: 14968276]
5. Beer RF, Ellis MD, Holubar BG, et al. Impact of gravity loading on post-stroke reaching and its relationship to weakness. Muscle Nerve 2007;36:242–250. [PubMed: 17486581]
6. Brunnstrom, S. Movement Therapy in Hemiplegia: A Neurophysiological Approach. Harper and Row; New York: 1970.
7. Twitchell TE. The restoration of motor function following hemiplegia in man. Brain 1951;74:443–480. [PubMed: 14895765]
8. Sukal TM, Ellis MD, Dewald JP. Shoulder abduction-induced reductions in reaching work area following hemiparetic stroke: neuroscientific implications. Exp Brain Res 2007;183:215–223. [PubMed: 17634933]
9. Ellis MD, Sukal T, Demott T, et al. Augmenting clinical evaluation of hemiparetic arm movement with a laboratory-based quantitative measurement of kinematics as a function of limb loading. Neurorehabil Neural Repair 2008;22:321–329. [PubMed: 18326888]
10. Woldag H, Hummelsheim H. Evidence-based physiotherapeutic concepts for improving arm and hand function in stroke patients: a review. J Neurol 2002;249:518–528. [PubMed: 12021939]
11. Kwakkel G, Kollen BJ, Krebs HI. Effects of robot-assisted therapy on upper limb recovery after stroke: a systematic review. Neurorehabil Neural Repair 2008;22:111–121. [PubMed: 17876068]
12. Van Peppen RP, Kwakkel G, Wood-Dauphinee S, et al. The impact of physical therapy on functional outcomes after stroke: what's the evidence? Clin Rehabil 2004;18:833–862. [PubMed: 15609840]
13. Fugl-Meyer AR, Jääskö L, Leyman I, Olsson S, Steglind S. The post-stroke hemiplegic patient. 1. a method for evaluation of physical performance. Scand J Rehabil Med 1975;7:13–31. [PubMed: 1135616]
14. Dobkin BH. Fatigue versus activity-dependent fatigability in patients with central or peripheral motor impairments. Neurorehabil Neural Repair 2008;22:105–110. [PubMed: 18285599]
15. Doyon J, Benali H. Reorganization and plasticity in the adult brain during learning of motor skills. Curr Opin Neurobiol 2005;15:161–7. [PubMed: 15831397]
16. Seidler RD, Noll DC. Neuroanatomical correlates of motor acquisition and motor transfer. J Neurophysiol 2008;99:1836–1845. [PubMed: 18272874]
17. Ellis MD, Holubar BG, Acosta AM, et al. Modifiability of abnormal isometric elbow and shoulder joint torque coupling after stroke. Muscle Nerve 2005;32:170–178. [PubMed: 15880629]
18. Harris JE, Eng JJ. Paretic upper-limb strength best explains arm activity in people with stroke. Phys Ther 2007;87:88–97. [PubMed: 17179441]

19. Pak S, Patten C. Strengthening to promote functional recovery poststroke: an evidence-based review. Top Stroke Rehabil 2008;15:177–199. [PubMed: 18647724]
20. Patten C, Lexell J, Brown HE. Weakness and strength training in persons with poststroke hemiplegia: rationale, method, and efficacy. J Rehabil Res Dev 2004;41:293–312. [PubMed: 15543447]
21. Dodd KJ, Taylor NF, Damiano DL. A systematic review of the effectiveness of strength-training programs for people with cerebral palsy. Arch Phys Med Rehabil 2002;83:1157–1164. [PubMed: 12161840]
22. Patten C, Dozono J, Schmidt S, et al. Combined functional task practice and dynamic high intensity resistance training promotes recovery of upper-extremity motor function in poststroke hemiparesis: a case study. J Neurol Phys Ther 2006;30:99–115. [PubMed: 17029654]
23. Hu X, Tong KY, Song R, et al. Variation of muscle coactivation patterns in chronic stroke during robot-assisted elbow training. Arch Phys Med Rehabil 2007;88:1022–1029. [PubMed: 17678665]
24. Dipietro L, Krebs HI, Fasoli SE, et al. Changing motor synergies in chronic stroke. J Neurophysiol 2007;98:757–768. [PubMed: 17553941]
25. Gauthier LV, Taub E, Perkins C, et al. Remodeling the brain. Plastic structural brain changes produced by different motor therapies after stroke. Stroke 2008;39:1520–1525. [PubMed: 18323492]
26. Liepert J, Bauder H, Wolfgang HR, Miltner WH, Taub E, Weiller C. Treatment-induced cortical reorganization after stroke in humans. Stroke 2000;31:1210–6. [PubMed: 10835434]
27. Luft AR, McCombe-Waller S, Whitall J, et al. Repetitive bilateral arm training and motor cortex activation in chronic stroke: a randomized controlled trial. JAMA 2004;292:1853–1861. [PubMed: 15494583]
28. Schaechter JD, Kraft E, Hilliard TS, et al. Motor recovery and cortical reorganization after constraint-induced movement therapy in stroke patients: a preliminary study. Neurorehabil Neural Repair 2002;16:326–338. [PubMed: 12462764]
29. Sawaki L, Butler AJ, Xiaoyan L, et al. Constraint-induced movement therapy results in increased motor map area in subject 3 to 9 months after stroke. Neurorehabil Neural Repair 2008;22:505–513. [PubMed: 18780885]

Figure 1.
Example of a Research Participant Positioned With the ACT^{3D}

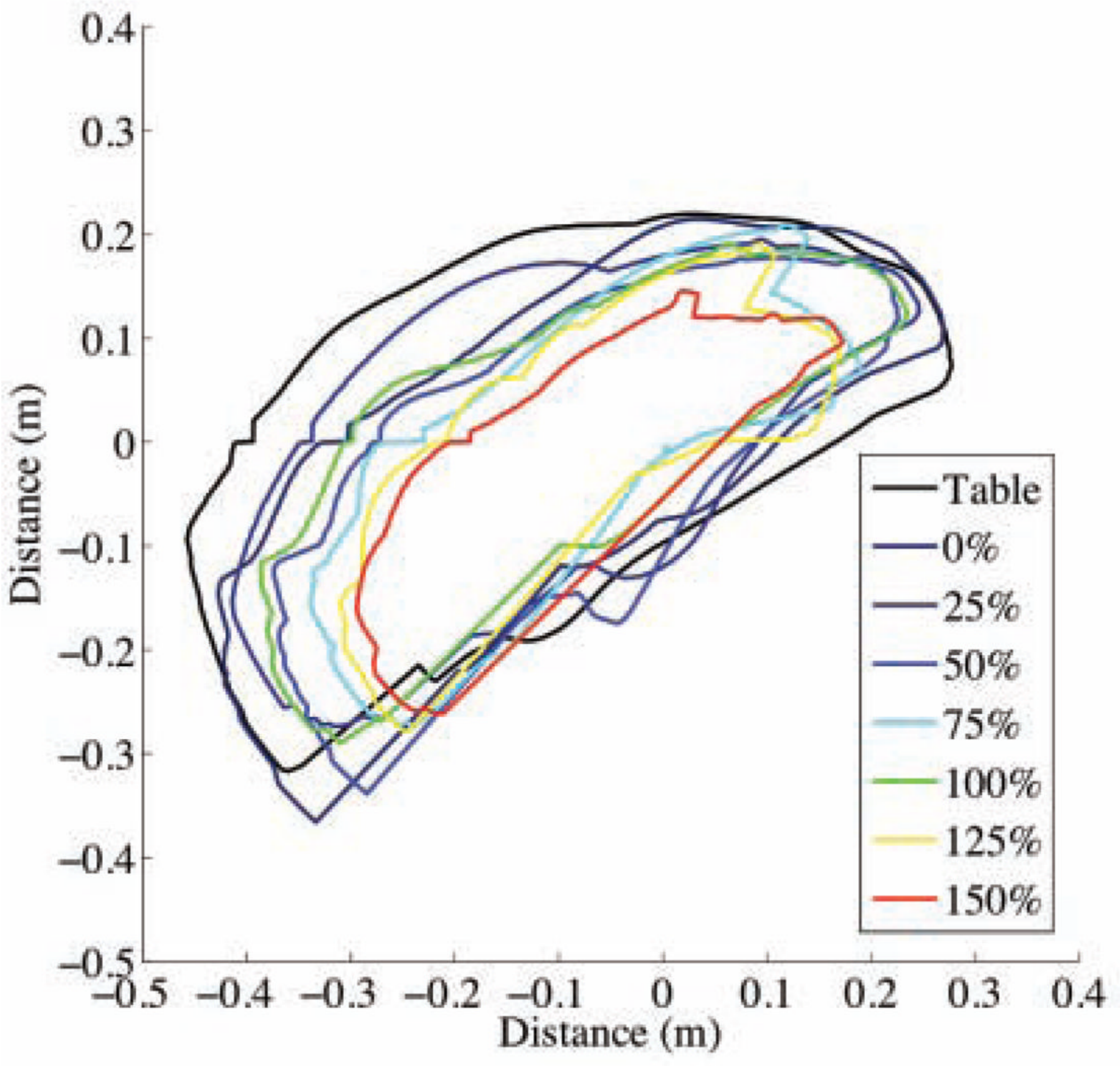

Figure 2.
Example of a Top-Down View of Calculated Work Areas for Movement While Fully Supported by the Horizontal Haptic Surface (Table) and 7 Shoulder Abduction Loading Levels (0%-150% of Limb Weight)
Note: Work area reduces as a function of increasing shoulder abduction loading where the 100% level is equivalent to reaching under normal gravitational loading conditions.

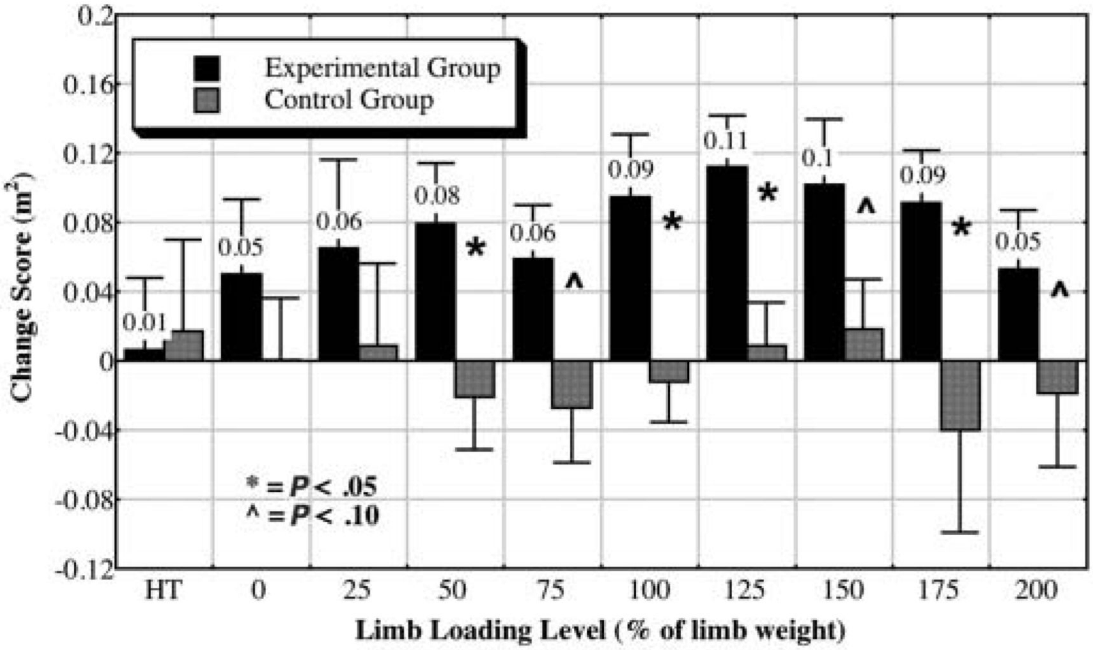

Figure 3.

Work Area Change Scores (m^2) for Both the Experimental and Control Groups Following the Intervention Period

Note: Change scores in the experimental group are positive indicating improvement and are significantly greater than the control group at shoulder abduction levels experienced during everyday reaching and retrieval tasks. Change scores at 100% to 175% are clinically meaningful* in that they equate to improvements of >20% of work area while supported on the haptic table or >60% of the work area at the respective loading level. *A 0.10 m^2 (1000 cm^2) change score is equivalent to the average length of the upper limb segment squared (32 cm × 32 cm).

Table 1

General Demographic Table for the Participant Pool

Group	Race	Age	Gender	Affected	Dominant	Lesion Location	FMA
Experimental							
	W	55	M	L	R	IC, BG, CL	10
	AA	59	M	R	R	BG, IC, TH	14
	W	64	M	L	R	BG, IC, TH	37
	W	50	F	R	L	IC, TH, BG	18
	W	71	F	L	R	BG	34
	AA	60	F	R	R	TH, IC, BG, CF/PL	14
	W	55	F	R	R	BG, TH, IC, CFL, SF/PL	12
Control							
	W	60	M	L	R	CF/PL, BG, TH, IC, CR	25
	W	54	M	L	R	IC, TH	17
	A	61	M	L	R	CR	43
	W	60	M	L	R	TH, IC, BG	24
	W	78	M	L	R	IC, TH	35
	W	52	M	R	R	CF/PL, SF/PL SOL, TH, IC, CR, BG	, 15
	W	70	F	L	R	CR, IC, BG, TH	10

Abbreviations: FMA, arm motor portion of the Fugl-Meyer Motor Assessment, 66 point maximum; W, white; AA, African American; A, Asian; M, male; F, female; L, left; R, right; IC, internal capsule; BG, basal ganglia; CL, claustrum; TH, thalamus; CF/PL, cortical frontal and parietal lobe; SF/PL, subcortical frontal and parietal lobe; CR, corona radiata; SOL, subcortical occipital lobe.