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Impairment-Based 3-D Robotic Intervention Improves Upper Extremity Work Area in Chronic Stroke: Targeting Abnormal Joint Torque Coupling With Progressive Shoulder Abduction Loading

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Abstract

The implementation of a robotic system (ACT^{3D}) that allowed for a quantitative measurement of abnormal joint torque coupling in chronic stroke survivors and, most importantly, a quantitative means of initiating and progressing an impairment-based intervention, is described. Individuals with chronic moderate to severe stroke ($n = 8$) participated in this single-group pretest-posttest design study. Subjects were trained over eight weeks by progressively increasing the level of shoulder abduction loading experienced by the participant during reaching repetitions as performance improved. Reaching work area was evaluated pre- and postintervention for ten different shoulder abduction loading levels along with isometric single-joint strength and a qualitative clinical assessment of impairment. There was a significant effect of session (pre versus post) with an increase in reaching work area, despite no change in single-joint strength. This data suggests that specifically targeting the abnormal joint torque coupling impairment through progressive shoulder abduction loading is an effective strategy for improving reaching work area following hemiparetic stroke. Application of robotics, namely, the ACT^{3D}, allowed for quantitative control of the exercise parameters needed to directly target the synergistic coupling impairment. The targeted reduction of abnormal joint torque coupling is likely the key factor explaining the improvements in reaching range of motion achieved with this intervention.

Index Terms

Arm; kinematics; kinetics; rehabilitation robotics; stroke

I. Introduction

The field of rehabilitation robotics is relatively new and has shown significant promise [13], [19], [20]. Unfortunately, one of the difficulties in this fast growing field is determining how

robotics can best contribute to the rehabilitation of movement disorders resulting from brain injury such as that occurring following stroke. One possible way that robotics can become integrated in the rehabilitation process is by utilizing them in the quantification of impairments underlying movement disorders and then developing specific interventions that directly target these impairments in ways that otherwise would not be possible with currently existing therapeutic techniques. In a previous study, we have demonstrated the effect of shoulder abduction on upper extremity reaching range of motion (work area) in 18 individuals with chronic stroke using the arm coordination training 3-D robot (ACT^{3D}) [22]. This robotic system is capable of quantifying movement kinematics during reaching while simultaneously loading the paretic arm such that participants have to generate various levels of active shoulder abduction torque during reaching. This work confirmed findings obtained in earlier static and dynamic experiments [1], [4], [5], [7], [16] and demonstrated an incremental increase of abnormal coupling of elbow flexion for greater levels of shoulder abduction in the paretic limb that results in a progressive reduction in available work area and associated independent joint control [22]. This then made possible the development of an intervention based on the assertion that directly targeting abnormal joint torque coupling in a progressive and quantitative fashion would result in an increase in total reaching range of motion (work area) at and above limb weight. Utilizing the ACT^{3D}, we were able to progressively increase shoulder abduction loading of the paretic arm during reaching movements in a standardized manner over an eight-week, 24-session training period. Our results demonstrate not only the ability of chronic stroke survivors to regain functionally relevant reaching range of motion but the substantial role that robotics can play in upper extremity rehabilitation as well.

II. Methods

A. Participants

Eight individuals (five females and three males) ranging in age from 50 to 71 participated in the study. There was equal representation of both left- and right-side hemiparesis, and all participants except one was right handed. Baseline upper extremity Fugl-Meyer motor assessment (FMA) [10] scores were between 10 and 37. 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 and 50 out of a possible 66 in order 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], [22]. All participants were screened for inclusion in the study by a physical therapist. 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 [18]. Passive range of motion of the affected arm was measured to verify full passive extension of the elbow and at least 90° of passive shoulder motion in both the sagittal and coronal planes in order to participate in the study. Overpressure at the end of the range of motion was used as a medical screening procedure 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.

B. Arm Coordination Training 3-D Robot (ACT^{3D})

The arm coordination training 3-D robot (ACT^{3D}) comprises a modified force-controlled HapticMASTER (HM) robot (MOOG, The Netherlands) integrated with a Biodex experimental chair (Biodex Medical Systems, Shirley, NY) and represents the system and

method outlined in United States Patent No. 7 252 644 B2 (Aug. 7, 2007). Participants are seated in the Biodex chair with straps across the shoulders and lap to restrict trunk and shoulder girdle movement (see Fig. 1). A rigid arm orthosis with Velcro straps is used to couple the arm directly to the HM without the need for external slings or other supports. The hand and wrist are placed in a neutral position in the orthosis to reduce spastic activity in hand and wrist flexors. The HM is connected to the same support track as the Biodex chair to allow relative and controlled movement and rotation with respect to one another. The ACT^{3D} allows for low inertia movements in three dimensions and can provide a virtual effect of gravity that can be enhanced or reduced by imposing forces along its vertical axis. The direction and magnitude of these forces dictate the vertical loading on the arm, ranging from fully supported where the arm weight is removed to an environment where the arm weight is doubled by requiring the participant to lift the weight of the limb while haptically adding 100% (or more) additional mass. This is done by first taking a baseline measure when the participant is fully relaxed at the “home” arm position while resting the arm on a horizontally oriented haptic surface. The haptic surface is rendered such that a 90° shoulder abduction angle is achieved. The robot provides an equal force in the positive Z-direction to create an “antigravity” environment, adds 100% of limb weight in the negative Z-direction to simulate double the limb weight, and creates seven additional intervals in between. In this way, the ACT^{3D} can simulate a total of nine levels of limb loading (0, 25, 50, 75, 100, 125, 150, 175, and 200% of arm weight). During all trials, the haptic horizontal surface is always present, allowing the participant to lower the arm to rest on the haptic surface between trials, and to provide a reference for the required degrees of shoulder abduction. Participants are cued via an audio signal if they are not providing enough abduction/external rotation torque to keep their limb off the table. This way, alterations in shoulder abduction loading are felt only when the participant lifts off the haptic table. Arm movements are constrained to a plane that is in line with the shoulder center of rotation, done via the haptically rendered table, and goniometric measures to place that table at 90° of shoulder abduction. Endpoint forces and torques are recorded during movement using a 6-degree of freedom (DOF) load cell (JR3 load cell, Woodland, CA) attached to the end effector of the robot arm. The HM endpoint is also instrumented with position sensors and potentiometers are used to measure the angle of the forearm relative to the shaft of the HM. At the onset of the experiment, limb measurements are taken to customize the display for the participant. Their arm is placed in a known configuration using a goniometer and the position of the shoulder is backcalculated using the joint angles and upper and forearm segment lengths. With this information and the position information provided by the HM, elbow and shoulder angles are calculated and saved to update the visual feedback display, as well as for subsequent analysis.

C. Protocol—Primary Measurement: Work Area

Quantitative kinematic measurements were performed for each participant in the laboratory following the exact protocol described previously [22]. These measurements included two baseline measurements and one postintervention measurement. In short, participants sat in an experimental chair with their arm resting in the forearm–hand orthosis attached to the ACT^{3D} (see Fig. 1). The participant's trunk was immobilized to prevent shoulder girdle movement by a set of straps attached to the experimental chair. The shoulder was positioned at 90° of abduction when the tested arm was resting on the haptically rendered table. Participants were manually placed in an initial position of 40° of shoulder flexion or horizontal adduction and 90° of elbow flexion using a goniometer. The ACT^{3D} software was used to calculate the position of the shoulder and a graphic representation of the arm was illustrated on a computer screen in front of the participant. Participants were asked to move their arm in a circular motion producing the largest hand path possible while it was fully supported by and gliding on the haptic table. The reaching work area task was performed slowly limited approximately to 5°/s of angular joint velocity to minimize the effects of

stretch reflexes or spasticity. Participants performed the task in both clockwise and counterclockwise directions, the order of which was randomized, in order to capture the full reaching work area upon superimposition of all trials (see Fig. 2). Rest was given between the two directions to eliminate fatigue, 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 in, and participants were required to actively lift their arm just above the haptic table resulting in 90° of shoulder abduction as it was when supported by the haptic table. The protocol was repeated while the ACT^{3D} provided forces along its vertical axis to alter the amount of shoulder abduction loading. A total of nine limb loading levels were randomized for testing. They ranged from 0% to 200% of limb weight, in increments of 25%. Kinematic data obtained by the ACT^{3D} was collected for all trials and saved for future analysis.

D. Protocol—Secondary Measurement; Strength and FMA

Isometric strength was also measured before and after the intervention following a previously documented procedure [9]. 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 aforementioned home position was used for isometric strength testing. The forearm, wrist, and hand were fixed to a 6-DOF load cell (JR3 Inc., Woodland, CA, Model #45E15A) 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 (verification of quiescent electromyography). Orthogonal forces and moments measured by the load cell were filtered and converted on-line to torques at the elbow and shoulder via methods described by Beer *et al.* [1]. 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 three random blocks consisting of shoulder abduction/adduction, flexion/extension, and elbow flexion/extension mirroring methods reported previously. Joint torque was concurrently measured at both the shoulder and elbow while the participant attempted to maximize the torque in the primary direction, which was shown in real-time on a computer monitor. Data obtained was stored offline for future analysis. Although the work area measurement has been cross validated with clinical evaluations of impairment and function [8], each participant was scored using the qualitative clinical measurement, FMA, due to its commonality in the rehabilitation field and to assist in future potential meta-analyses. Participants were scored prior to the onset of the intervention and immediately following the intervention by a physical therapist.

E. Protocol—Arm Intervention

The intervention protocol consisted of reaching movements in five directions while lifting a percentage of the weight of the arm during the execution of the movement. The five movement directions are simultaneously displayed in Fig. 1 for illustrative purposes. The initial limb loading level was determined from the preintervention laboratory testing. The initial level of shoulder abduction loading for each target direction was the level at which the participant could reach to a distance halfway between the starting position and the target. Participants were trained at this limb loading level until they could reach a position 10% (or less) from the target in eight out of ten repetitions. The limb-loading level was then increased to a new level, where again, participants could only reach to within 50% of the distance between the starting position and the target. The limb-loading levels were increased in intervals equal to 25% of limb weight as participants improved over the eight-week period. Random or occasional verbal feedback of movement performance was provided to the participants by the first author during the initial sessions until the subject was familiar with the exercise. Each intervention session consisted of three sets of ten repetitions for each of the five movement directions totaling 150 repetitions. Rest periods of up to 10 s between

repetitions and a fixed 1-min rest between sets were provided to avoid fatigue. The order of the 15 sets was randomized for each session. A total of three sessions a week were implemented over an eight-week period with the goal being to progressively increase shoulder abduction loading for each target.

F. Data Analysis

The total work area for each shoulder abduction loading level was calculated offline using customized software in the MATLAB environment (Mathworks, Inc.). Work area was defined as the total area in square meters contained within the perimeter of the superimposed clockwise and counterclockwise hand paths. Statistical analyses were performed using Data Desk (Ithaca, NY).

A two-factor repeated measures ANOVA was used to determine the effect of session (*repeat; baseline 1 vs. baseline 2*) and level (0%, 25%...200%) on work area (dependent variable) 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 of ≤ 0.05 .

A second two-factor ANOVA was used to determine the effect of session (*pretest versus posttest*) and level (0%, 25%...200%) on normalized work area to determine the impact of the intervention on reaching ability. 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 limb length. 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 of ≤ 0.05 .

A two-tailed paired t -test was used to test the difference between sessions in MVTs for each of the six torque directions. The Wilcoxon paired sample sign rank test was used when data were not normally distributed as found by the Kolmogorov–Smirnov test. A significant difference was defined as a p -value of ≤ 0.05 .

A Wilcoxon paired sample sign rank test was used to test the difference between sessions for the FMA. A significant difference was defined as a p -value of ≤ 0.05 .

III. Results

A. Primary Measurements

The statistical analysis of work area indicated no effect of repeated session ($p > 0.05$) and no interaction effect of repeated session and level ($p > 0.05$). This analysis demonstrated that the evaluation was repeatable and stable, which was consistent with previous reports of this outcome measure in individuals with chronic stroke [22].

Analysis of the primary measurement of normalized work area indicated that there was an effect of session ($p < 0.05$) and an interaction effect of session and level ($p < 0.05$). Post hoc analysis indicated that there was a significant increase in work area at the limb loading levels of 100% ($p = 0.01$), 125% ($p = 0.001$), 150% ($p = 0.02$), and 175% ($p = 0.04$). Significant differences at these levels represented work-area improvements of 42%, 60%, 59%, and 71%, respectively. While average work areas at all other limb loading levels increased, they did not reach statistical significance during post hoc testing with Scheffe's test. Pre- and post-test normalized work areas and standard errors for each level are illustrated in Fig. 3.

B. Secondary Measurements

Analysis of the secondary measurement of isometric strength (MVTs) indicated that there was no difference between sessions for isometric strength at either the shoulder or the elbow (see Fig. 4).

Analysis of the secondary measurement of qualitative impairment score on the FMA indicated that participants improved by an average of three points (19 ± 4 to 22 ± 4) although they did not reach statistical significance ($p = 0.07$) likely due to the qualitative nature of the assessment and the small sample size of the study.

IV. Discussion

This study has demonstrated that 3-D robotics can be employed to regain functionally relevant reaching range of motion (work area) in individuals with chronic hemiparetic stroke. The implementation of the proposed robotic approach allowed not only for a quantitative measurement of work area but, most importantly, for a quantitative means of initiating and progressing an impairment-based intervention that targets abnormal joint torque coupling by requiring subjects to reach outward while actively lifting the arm at an operationally defined percentage of limb weight as well. Considering related previous work [9], increases in work area may be attributed to a reduction in shoulder–elbow discoordination or improvements in independent joint control that are specific to functional arm loads (submaximal shoulder abduction) and explained by neural adaptation of the motor system.

A. Strengthening and Multijoint Coordination Exercise in Stroke

Increases in work area cannot be explained by gains in single-joint strength at either the shoulder or the elbow (see Fig. 4). This is inconsistent with our previous study that demonstrated gains in isometric single-joint strength following an isometric exercise protocol designed to train individuals with stroke to produce multijoint torque patterns (shoulder abduction, flexion, and elbow extension) away from the flexion synergy [9]. Considering our current results, it is likely that strength gains previously reported were due to the resistive nature of the intervention. Participants were routinely pushing against a rigid object (i.e., the 6-DOF load cell) as they attempted to generate multijoint torque patterns. In the current dynamic intervention, participants never pushed against resistance but instead always attempted to reach outward while maintaining a certain level of shoulder abduction. This highlights the possibility that resistance may not be a key factor in ameliorating abnormal joint torque coupling. Strength changes may have been a byproduct of the previous study with the key factor being the attempt itself to move outside of the synergy.

Similarly, increases in work area cannot be explained by changes in passive properties of the upper limb. By comparing total work area while supported on the haptic table before and after the intervention, 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. In fact, similar to our previous dynamic work, reaching range of motion while on the haptic table remained fairly unaffected [2], [3]. Therefore, any increases in normalized work area while actively lifting the arm were not due to factors such as tissue extensibility, length, or tonicity that can impact passive range of motion.

B. 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. A previous study has reported that abnormal joint torque coupling, or, specifically, the amount of spontaneous elbow flexion that occurs when an

individual with stroke attempts to abduct the arm *maximally*, can be reduced with a physical intervention [9]. We suggest that during reaching at *submaximal* shoulder abduction levels, as implemented in the current study, there may have been an intervention-induced reduction in abnormal coactivation with elbow flexors and a concurrent reduction of the inhibition of elbow extensors. The lack of neural data, and specifically neural imaging data, precludes this study from more than speculation about the underlying neural mechanism explaining the positive response to the intervention. Therefore, this line of investigation would greatly benefit from future mechanistic approaches utilizing brain-imaging techniques as an outcome measure especially considering that previous work has illustrated that cortical reorganization occurs following an intervention and is related to improvements in impairment and function [11], [14], [15], [21], [23]. Furthermore, while abnormal abduction/elbow flexion coupling is hypothesized to be attributed to increased bulbospinal system influence [3], [4], [7], cortical reorganization, including a reallocation of unaffected corticofugal fiber bundles, may explain increased upper extremity control following the ACT^{3D} intervention [24].

C. Implications for Future Research

There are other upper extremity robotic devices currently being used for the rehabilitation of reaching that are not altering the vertical loading forces on the arm. Devices such as the MIT MANUS [6], the MIME [17] and the ARM Guide [12] support the full weight of the limb while measuring kinematic variables of reaching. Similarly, additional rehabilitation experiments in our laboratory are attempting to study the affects of reaching practice while fully supporting the arm and then compare results with those obtained during progressively increasing shoulder abduction loading such as presented in the current study. This additional work attempts to identify whether progressive shoulder abduction loading is a crucial factor in the rehabilitation of functional reaching in chronic stroke survivors and should, therefore, be incorporated into existing rehabilitation techniques including other robotic devices. Future research should also seek to identify the neural substrate responsible for reduced abnormal joint torque coupling and the subsequent improvements in reaching work area and clinically measured impairment. The application of rehabilitation robotics in the current study allowed for quantitative measurement of the effects of abnormal joint torque coupling on reaching range of motion. This technology in combination with both electromyography and neural imaging techniques should be employed to identify the neural substrates responsible for this specific stroke impairment. This will offer an additional means for future attempts to reduce physical impairment and improve function in individuals following stroke.

V. Conclusion

Application of rehabilitation robotics like the ACT^{3D} offers rehabilitation specialists new tools for quantifying movement impairments and implementing targeted interventions. The next steps in advancing stroke rehabilitation will be to better identify and measure impairments underlying dysfunction so that they can be directly targeted during interventions. Devices like the ACT^{3D} provide the quantitative and reproducible control of exercise parameters, such as progressive shoulder abduction loading, that are required for direct targeting of specific movement impairments that are likely necessary for continued refinement of existing therapeutic approaches in stroke rehabilitation.

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Biographies

Michael D. Ellis received the B.Sc. degree (with honors) in exercise science from the University of Iowa, Ames, in 1997, and the Master's and Doctor of Physical Therapy degrees from Emory University, Atlanta, GA, in 2000 and 2003, respectively.

From 2001 to 2003, he was a Predoctoral Research Physical Therapist at the Rehabilitation Institute of Chicago, Chicago, IL. From 2003 to 2008, he was a Postdoctoral Research Physical Therapist with the Department of Physical Therapy and Human Movement Sciences (PTHMS), Northwestern University, Evanston, IL, where he became a Faculty Instructor in 2008. He is a Co-Investigator on three National Institutes of Health (NIH)-funded grants and one National Institute on Disability and Rehabilitation Research (NIDRR) grant, and studies discoordination in individuals with stroke and the development of novel therapeutic interventions. He has 13 peer-reviewed publications, and has received funding through an American Heart Association supported postdoctoral fellowship in clinical research. His current research interests in movement science and rehabilitation research include the elucidation of the neurological underpinnings responsible for movement discoordination and through the subsequent development of more effective rehabilitation therapies for individuals with functionally debilitating movement impairments.

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Theresa M. Sukal-Moulton (S'04) received the Bachelor of Biomedical Engineering degree from The Catholic University of America, Washington, DC, in 2003, and the Doctor of Physical Therapy degree from Northwestern University, Evanston, IL, as part of the joint DPT/Ph.D. Program, in 2008.

She is a Graduate Student of biomedical engineering at the Department of Physical Therapy and Human Movement Sciences, Northwestern University. She has six peer-reviewed publications and is supported by a National Science Foundation Graduate Research Fellowship. Her current research interests include using robotics and engineering techniques to study independent joint control in children and adults with neurological injury.

Julius P. A. Dewald (M'03) received the B.Sc. degree in physical therapy and rehabilitation medicine and the M.Sc. degree in neurophysiology and rehabilitation medicine from Vrije Universiteit Brussel, Brussels, Belgium, in 1978 and 1980, respectively, and the Ph.D. degree in neurophysiology from Loma Linda University, Loma Linda, CA, in 1992.

From 1988 to 2001, he was a Predoctoral Investigator, a Postdoctoral Researcher, a Clinical Assistant Professor, and finally a Senior Clinical Research Scientist at the Rehabilitation Institute of Chicago, Chicago, IL. From 2001 to 2005, he was a Tenure-Track Assistant Professor in the Departments of Physical Therapy and Human Movement Sciences (PTHMS), Biomedical Engineering (BME), and Physical Medicine and Rehabilitation (PM&R), Northwestern University, Evanston, IL, where he became the Chairperson and an Associate Professor at PTHMS and an Associate Professor in BME and PM&R in 2006, and is also the Director of the Neuroimaging and Motor Control Laboratories. His research is funded by the National Institutes of Health, the Department of Education, the National Science Foundation, and the American Heart Association. His current research interests include understanding movement discoordination of the upper limb in individuals with stroke, cerebral palsy, and brain injury, and the development of novel therapeutic interventions. He is also involved in combined applications of brain imaging (MRI, functional MRI (fMRI), and high-density EEG), rehabilitation robotics, and pharmacologic manipulations of the motor system.

Fig. 1. Example of a research participant positioned with the ACT^{3D}. The visual display pictured is showing all five of the targets practiced during the intervention sessions for illustrative purposes only.

Fig. 2.

Example of a top-down view of calculated work areas for movement while fully supported by the horizontal haptic surface (Table) and two arm loading levels (50% and 100% of weight). Work area reduces as a function of increasing arm loading, where the greater loading level of “100%” is equivalent to reaching under normal gravitational loading conditions.

Fig. 3.

Pretest and posttest normalized work areas. The significant difference between pre- and posttest measurement indicates improvement notably at arm-loading levels experienced during everyday reaching and retrieval tasks. Improvements at 100%–175% are *clinically meaningful** in that they equate to improvements of 42%, 60%, 59%, and 71% of the respective loading level.

Fig. 4.

Pretest and posttest mean joint torques and standard errors for elbow flexion (EF), elbow extension (EE), coronal plane shoulder abduction (AB and AD), and horizontal plane shoulder flexion and extension (SF and SE). There was no difference ($p > 0.05$) between pre- and posttesting sessions for all joint torques.