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Quantifying Loss of Independent Joint Control in Acute Stroke with a Robotic Evaluation of Reaching Workspace

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***Abstract*—Early recovery after stroke is significant for slow emergence of volitional movement. Initial movements are constrained by stereotypical co-activation of muscle groups such as shoulder abductors and distal limb flexors resulting in the loss of independent joint control. The objective of this study was to utilize new quantitative methods to evaluate the emergence and progression of the loss of independent joint control in the acute phase of recovery from stroke. Fifteen participants have been followed a maximum range of 2 to 32 weeks post-stroke. Participants underwent weekly and monthly robotic evaluations of horizontal plane reaching workspace as a function of abduction loading (0%-200% of limb weight). The magnitude of loss of independent joint control, indicated by the rate of work area reduction as a function of abduction loading, was evident even as early as 2 weeks post-stroke. Group analysis indicated that individuals with mild stroke show immediate presence of the impairment with an exponential rate of recovery over time while individuals with severe stroke show persistent impairment. Early detection and quantification of reaching impairments, such as the loss of independent joint control, will allow clinicians to more efficiently identify patients who would benefit from impairment-based targeted interventions. For example, patients with severe loss of independent joint control will likely benefit from early administration of an intervention attempting to reduce abnormal shoulder abductor/distal limb flexor co-activations during reaching. The field of rehabilitation robotics has demonstrated such interventions to be promising in the chronic severe stroke population.**

I. Introduction

It is estimated that 6.4 million Americans over the age of 20 have had a stroke [1]. Each year another 795,000 people have a stroke making it the third ranking cause of death and a leading cause of disability in adults [1]. Some level of hemiparesis affecting the arm and/or leg is present in 50% of individuals with chronic stroke (greater than 6 months) [1]. Robotic investigations of arm function in individuals with chronic stroke have shown a severe reduction in reaching workspace when actively supporting the affected arm against gravity [2, 3]. These studies attributed reductions in reaching workspace to the abnormal co-activation of shoulder abductors with distal flexors (referred to as flexion synergy or loss of independent joint control) that occurs following stroke [4-6] and demonstrated the relationship of this impairment to more global activity and participation limitations [2]. Whereas impairments in chronic stroke have been studied at length, very little is known about the onset and progression of the loss of independent joint control in the acute and subacute phases of recovery. It is hypothesized that the loss of independent joint control emerges very early on in recovery based on mid-twentieth century observations describing slow emergence of volitional movement that were stereotypical in nature (referred to as flexion and extension synergy) [7, 8]. The objective of this study was therefore to employ the robotic device, ACT^{3D} (Department of Physical Therapy and Human Movement Sciences, Northwestern University, Chicago), to quantitatively describe the onset and progression of loss of independent joint control immediately following stroke.

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II. Methods

A. Subjects

Fifteen individuals with acute stroke were recruited from inpatient services of The Roessingh Center for Rehabilitation, Enschede, The Netherlands. All participants provided informed consent that was approved by the local investigational review board. All participants were deemed medically stable and safe to participate in the study by a physician.

B. Protocol- Design

The measurement of total reaching work area was performed at Roessingh Research and Development, Enschede, The Netherlands, using the robotic device, ACT^{3D}. Work area evaluation was performed following previously published procedure [3] on a weekly basis for 12 weeks followed by monthly for 3 months post-stroke onset.

Figure 1. Set-up for assessment of total reaching work area with the ACT^{3D}.

C. Protocol- Data Acquisition

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 a horizontal haptic surface or "table." The task was performed slowly limited approximately to 5º/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 during two separate trials, the order of which was randomized. Since the work area measurement attempts to capture the total available reaching range of motion, envelopes generated from all trials were superimposed and the area of the combined envelope was calculated. Rest was given between each trial to eliminate fatigue, and verbal feedback was given to encourage the participant to achieve the maximum movement excursion while moving slowly. Following completion of the work area performed while supported by the haptic table, the experimental chair was elevated by approximately two inches, and participants were required to actively support their arm just above the horizontal haptic table resulting in 90º of shoulder abduction as it was when supported by the haptic table. Participants were then instructed to lift the arm with the hand maintained close to the center of their body. 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 of 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 abduction loading that the participant was required to support. A total of 10 abduction loading levels (0%-200% of limb weight), including on the haptic table, were randomized for testing. Data acquired by the ACT^{3D} were stored offline for future analysis (see Fig. 2 for an example of work area taken with permission from [9]).

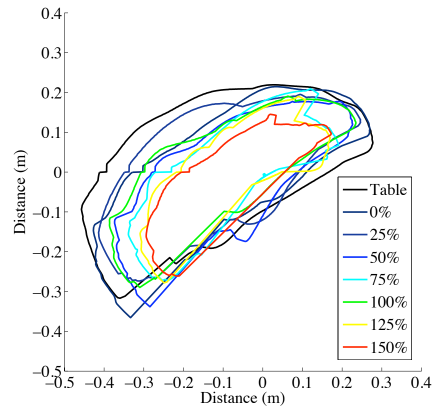

Figure 2. Example of a top-down view of calculated work areas for movement while fully supported by the horizontal haptic surface (Table) and 7 abduction loading levels equivalent to 0% to 150% of limb weight.

D. Protocol- Data and Statistical Analysis

For the investigation of onset of loss of independent joint control, work area was calculated as a function of abduction loading level on the first session for all 15 participants. Work areas for all abduction loading levels were normalized to the area produced while supported by the haptic table to account for differences in limb length amongst participants. The participants were separated into two groups based on severity of stroke. Individuals who could lift their arm against gravity to 90º of shoulder abduction were classified as "Mild" and individuals who could not were classified as "Severe." This classification produced 10 mild stroke and 5 severe stroke participants. A two factor (group, loading level) repeated measures analysis of variance (RMANOVA) was performed to determine the effect of group and loading level on work area. *A priori* between-subjects comparisons were also performed for the 0% and 25% loading levels (only levels completed by severe group) using an independent samples t-test.

For the investigation of progression of loss of independent joint control each work area measurement session was consolidated into a single value representing the expression of loss of independent joint control. This was easily completed by fitting a trendline to the work area values across all loading levels within a single session (Fig. 3). A two factor (group, session) RMANOVA was then completed to determine the effect of group and session on the loss of independent joint control (slope). Five work area sessions were utilized for this analysis as it represented the largest common number of completed sessions of all subjects. For various reasons, 3 of the 5 severe participants only completed 5 sessions. Additionally, 2 of the 10 mild participants completed 1 and 3 sessions. These participants were excluded from progression analysis. As a group, the average time post-stroke that the first session occurred on was 5.3±0.6 weeks. On average, the fifth session occurred

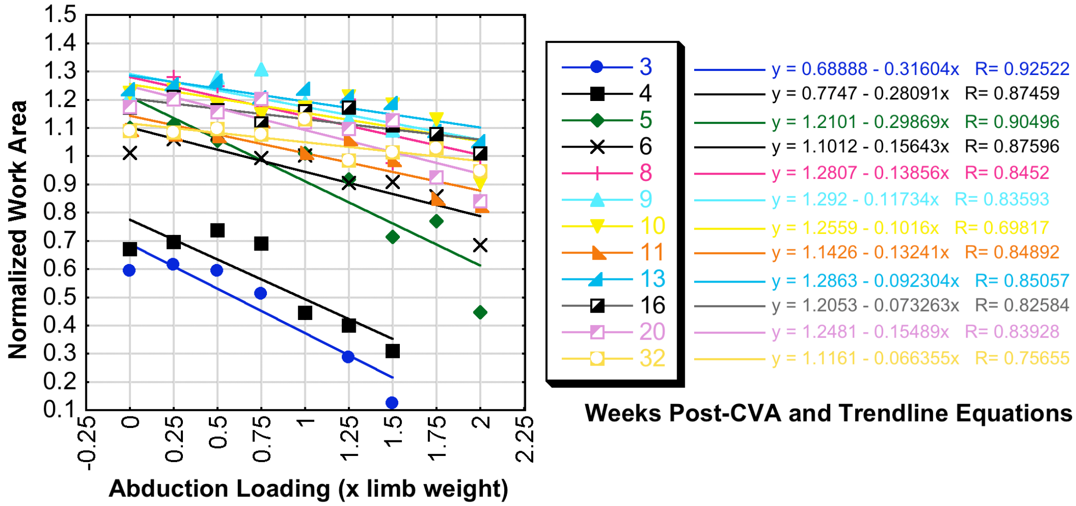

Figure 3. Example of the expression of loss of independent joint control as a rate of reduction of work area as a function of abduction loading level (slope of the trendline). Trendlines were calculated for all sessions of all participants for analysis of progression of the loss of independent joint control over time.

10.5±1.2 weeks post-stroke. In order to analyze progression out to a longer period of time post-stroke, a separate RMANOVA was completed for only mild participants. Five of the 10 mild participants completed 9 sessions allowing for analysis to be carried out from an average first session of 4.0±0.3 weeks to 15.2±1.0 weeks post stroke.

III. Results

For the investigation of the onset of loss of independent joint control, the RMANOVA found a significant effect of group (p = 0.00) and level (p = 0.00) and a significant interaction effect of group * level (p = 0.00) (Fig. 4). Trend analysis indicated a linear reduction in work area as a function of abduction loading for both groups similar to previous work [3]. *A priori* comparisons, demonstrated that work areas were not significantly different at the 0% loading condition (p = 0.49) but were significantly less at the 25% loading condition (p = 0.00) for individuals with severe stroke indicating a more severe expression of loss of independent joint control.

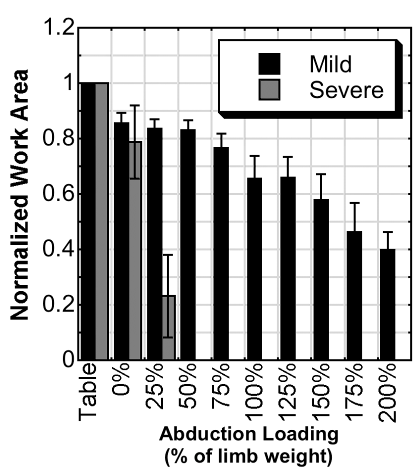

Figure 4. Mean normalized work area and standard errors on the first session for mild (n=10) and severe (n=5) participants. There is a significant reduction in work area as a function of abduction loading and a significant difference between groups.

For the investigation of progression of loss of independent joint control over time, the RMANOVA found a significant effect of group (p = 0.00) but not for session (p = 0.19) or the interaction of group * session (p = 0.10) indicating significantly greater but persistent slopes or expression of loss of independent joint control in individuals with severe stroke. The second RMANOA of only mild participants over 9 sessions found a significant effect of session (p = 0.00). Furthermore, trend analysis indicated a linear reduction of slope over time indicating amelioration of loss of independent joint control in individuals with mild stroke (Fig. 5).

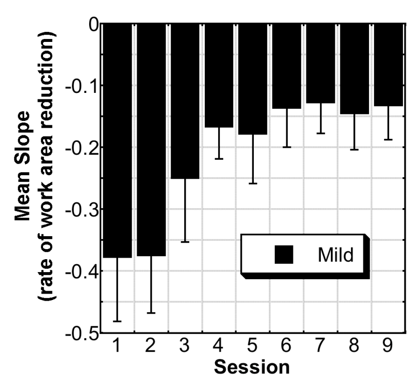

Figure 5. Mean slope and standard error across 9 sessions for participants with mild stroke. Trend analysis identified a significant quadratic/exponential reduction in slope or expression of loss of independent joint control from session 1 (4.0±0.3 weeks post-stroke) to 9 (15.2±1.0 weeks post stroke).

IV. Discussion

Results from this study indicate that the onset of expression of loss of independent joint control occurs as early as 4 to 5 weeks post-stroke. Despite classification of "mild" or "severe," all participants showed a linear reduction in reaching work area as a function of abduction loading similar to individuals with chronic stroke [3]. These results are consistent with a previous report of impaired isolated single joint motion, described as an "individuation index" in individuals at 1 to 2 weeks post stroke [10]. While our initial measurement didn't occur until 4 weeks post stroke, it is important to recognize that even individuals with mild stroke had a detectable loss of independent joint control at 4 weeks. Considering the well reported exponential decline in recovery over the first 4 weeks [11-13], one would expect that the mildly impaired individuals in the present study may have expressed an even greater loss of independent joint control in the earlier weeks post stroke as observed by Wagner et al [10]. This point can be illustrated on an individual case basis of a mildly impaired individual (Fig. 6). This patient had the work area measurement at 3 weeks post stroke. The linear relationship of declining work area as a function of abduction loading is evident in the first session indicating immediate expression of loss of independent joint control. Additionally, the exponential recovery over time demonstrates a rapid recovery.

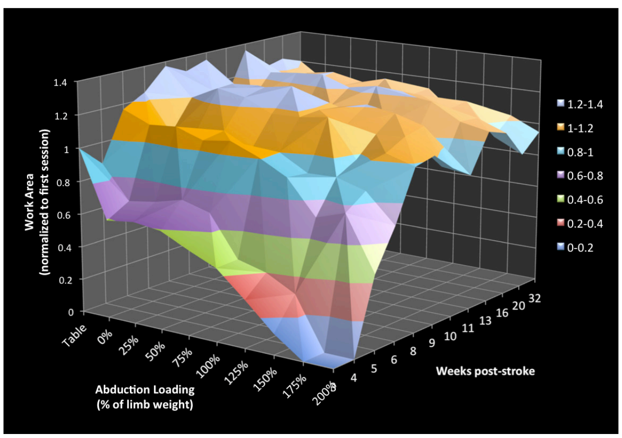

Figure 6. Illustrative example demonstrating rapid onset and amelioration of loss of independent joint control in an individual with mild stroke.

Group data in the present study reflects the exponential recovery process in the mild group but not in the severe group. In fact, the severe group showed persistent loss of independent joint control over time. This is inconsistent with others who have reported an exponential recovery from 1 to 12 months in individuals with severe stroke [14]. However, Mirbagheri et al. utilized the Fugl-Meyer Motor Assessment to track recovery. Although the Fugl-Meyer shares a similar construct to the measurement of work area [2, 15], it is qualitative in nature and is also influenced by changes in strength, reflexes, and fine motor function. For example, the persistent loss of independent joint control found in the present study may not have been detected by Mirbagheri et al. with the Fugl-Meyer Motor Assessment due to concurrent recovery of gross strength, fine motor control, or even reflex excitability that influence the total score of the qualitative assessment. This exemplifies the importance of impairment quantification, not only in clinical research, but in practice.

Accurate quantification of loss of independent joint control over time is critical to clinical decision making. This is especially important in the context of independent joint control since it is the impairment that most accurately predicts reaching performance in chronic stroke [16]. Results from this study suggest that individuals with severe stroke who may have persistent loss of independent joint control may require more appropriate interventions directly targeting this impairment. While these interventions are being developed in chronic stroke [9, 17], application in the acute setting may be warranted and should be investigated.

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