Assessment of Impaired Finger Independence of Stroke Survivors: A Preliminary study

Jiahao Fan, Henry Shin, and Xiaogang Hu

Abstract— **Hand impairment is prevalent in individuals after stroke. Regaining independent finger control is especially challenging. An objective and continuous assessment of finger impairment could inform clinicians and allow them to prescribe targeted therapies. The objective of this preliminary work was to quantify the neuromuscular factors that contribute to impairment in independent finger control in chronic stroke survivors. We obtained high-density electromyographic (HD-EMG) signals of extrinsic finger muscles and fingertip forces, while stroke or control participants were instructed to produce independent finger forces. We observed an impaired ability to isolate individual muscle compartment activation (i.e., co-activation of muscle compartment). This muscle co-activation pattern correlated with finger independence as well as clinical assessment scales on hand impairment. Our preliminary work showed that HD-EMG recordings can be used to continuously monitor activation abnormalities of small finger muscles in contribution to impaired finger independence. With further development, the outcomes can provide a basis for clinical decision making to reduce hand impairments of stroke survivors.**

I. INTRODUCTION

In the United States, there are about 800,000 people each year who suffer from a cerebral stroke. Approximately two-thirds of these individuals tend to show persistent deficits in hand functions [1, 2], and functional recovery of hand dexterity is most challenging among different functions [3-6], despite extensive therapy.

Accurate and continuous assessment of functional outcomes is critical to prescribe targeted therapies. Although hand functional outcomes are assessed using standardized clinical assessments during routine clinic visits, we are unclear to what extent these clinical scores translate to actual hand functions in daily activities. The evaluated tasks in the clinic typically do not account for the variation of activities in a home environment with unpredictable environmental barriers and distractions. In addition, the discrete assessments in the clinic do not capture the frequency and quality of hand usage in daily life, which requires continuous monitoring. Understandably, such information is critical for assessing the therapeutic effect of rehabilitation strategies in real-world environments, and for clinicians prescribing more targeted therapy and making timely adjustments to better implement optimized strategies.

Anatomically, each digit is actuated by sets of extrinsic flexor, extrinsic extensor, and intrinsic muscles. Although identified separately anatomically, many of the extrinsic muscles are comprised of multiple distinct compartments, each driving a different digit. In neurologically intact individuals, these separate compartments are controlled by different sub-populations of motoneurons, but with some degree of synchronized activation [7, 8]. However, human stroke survivors and non-human primates with a cortical lesion have difficulty selectively activating particular muscle compartments to generate individuated finger motion [4, 6, 9]. Coupled activation of finger muscle groups can also limit finger independence when muscles are activated in a coupled manner despite the intention of moving a single finger [10, 11]. The neuromuscular control of extrinsic finger muscles has been studied using invasive techniques [12], largely because the muscle compartments overlap, are organized obliquely, and are located at different depths relative to the skin surface [13, 14]. These factors largely preclude the capture of individual compartment activation with traditional surface electrodes due to inevitable cross-talk [14]. Accordingly, the objective of the current preliminary study was to evaluate inappropriate muscle activation patterns in association with impaired finger independence in stroke survivors.

II. METHODS

A. Subjects

We recruited 5 neurologically intact subjects and 5 chronic stroke survivors. Each subject gave informed consent via protocols approved by the Institutional Review Board of the University of North Carolina at Chapel Hill.

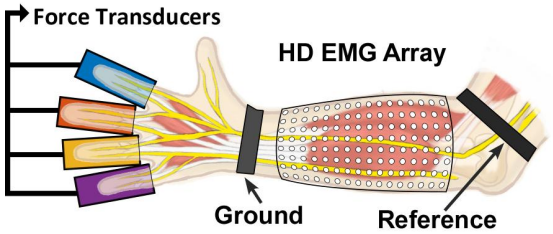

Figure 1. Diagram illustrating the experimental setup. High-density electromyography (HD EMG) array recorded finger flexor and extensor activities, and the load cells recorded individual fingertip forces.

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B. Experimental Design

Participants were seated upright in a chair with their forearm in a neutral position resting on a table and wrist in 0° (radial/ ulnar) deviation (**Fig.1**). The distal and intermediate phalanges of individual fingers were attached to load cells (SM-100, Interface, Inc) through a finger strap The load cells, measuring each finger flexion/extension forces, were attached to a custom-made holder fixed to the table. A U-shaped wooden block fixed to the table was placed to the palmer and dorsal sides of the hand with form padding to reduce force contamination from the wrist. The force signals were amplified and sampled at 1 kHz. HD-EMG grid (OT Bioelettronica, Inc) (8x16 channel, with 3 mm diameter recording electrodes and a 10 mm inter-electrode spacing) was placed over the ventral and dorsal sides of the forearm to acquire EMG signals from both flexors and extensor (Fig. 1). The monopolar signals were amplified with a gain of 1000 at a bandwidth of 10-900 Hz, and were sampled at 2048 Hz using the EMG-USB2+ acquisition system (OT Bioelettronica)

The stroke subjects performed the same protocol twice (once for each upper limb) in two lab visits occurring within a week. The neurologically intact control subjects also performed the protocol twice, once with the dominant hand and once with the non-dominant hand. Hand testing order was randomized across subjects. Prior to the testing, subjects performed maximal voluntary contractions (MVCs) for 3 s by flexing or extending one or all their fingers isometrically. As the MVC of individual fingers tends to be lower when all fingers are activated concurrently [15, 16], the MVC was calculated either from a single load cell in the case of individual finger flexion/extension conditions, or from the sum of all 4-finger flexion/extension forces.

The experimental task consisted of a series of isometric voluntary contractions, during which the subject tracked trapezoidal force trajectories displayed on a computer screen. Peak force amplitude for the trapezoid was set to a particular percentage of the MVC. The forces on the instructed fingers were displayed, but all the four finger forces were recorded for later analysis. Two steady state force levels (20% and 50% MVC) were tested in random order. A steady state contraction of 8 s was used. During the experiment, subjects flexed or extended their individual finger isometrically against the load cells, while minimizing the forces of other fingers. The subjects were asked to activate all their four fingers simultaneously. The subjects repeated the same task five times with a 60-s rest period between contractions, and if necessary, longer resting time was provided to minimize fatigue.

. The functional assessment (Action Research Arm Test (ARAR) and motor impairment (the Chedoke-McMaster Assessment) were performed prior to the first session.

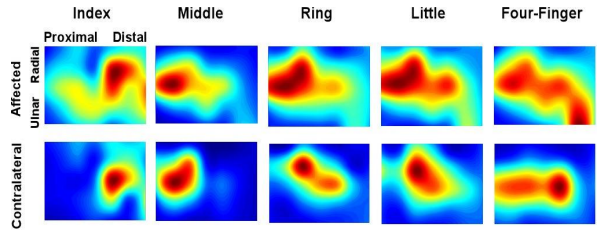

Figure 2. Normalized extrinsic extensor muscle activation from a stroke subject during individual finger and four-finger extensions. Warmer color means more EMG activity.

C. Data Analysis

The EMG signals during the 8 s steady-state hold period were analyzed. Prior to the analysis, potential motion artifacts and power line noise were removed with minimal distortion to the EMG signals [17]. The sum-of-squared values of the EMG of each channel were calculated as the energy of the EMG [18-20]. The average of the five repetitions was calculated for each channel. Then, the 2D energy map was calculated across channels to capture the spatial patterns of muscle activation.

Muscle compartment co-activation: Each constructed map was normalized such that the values at each map ranged from 0 to 1 (**Fig. 2**). The 2D cross-correlation coefficient of the energy maps between the individual finger tasks and the four-finger task was calculated for each individual muscle, in order to quantify the degree of muscle co-activation patterns. A higher correlation signifies that there is substantial muscle co-activation in single-finger force tasks, similar to that in the four-finger force task, thus indicating reduced finger individualization. Different finger tasks were averaged for a global estimation of the degree of muscle compartment co-activation.

To identify potential associations between the muscle co-activation patterns and the force deficits and/or clinical outcomes, the altered activation patterns of each muscle were quantified by the asymmetry of correlation measurement between the affected and contralateral sides of each stroke subject, defined as:

$$Correlation\ Asymmetry = \frac{Corr_{contra} - Corr_{affect}}{Corr_{contra} + Corr_{affect}} \quad (1)$$

The $Corr_{contra}$ and $Corr_{affect}$ are the correlation coefficients of the contralateral and affected sides, respectively.

Finger force independence: The degree of independent finger force signifying hand dexterity was evaluated by calculating the dimensionality of the extension/flexion forces during the ramp-up and ramp-down phases, based on principal component analysis (PCA) [21]. We expected that the impaired hand would have a low dimensionality, i.e., a highly correlated finger force output with limited hand dexterity. The difference in variance accounted for between the first PC (with the highest variance accounted for) and the remaining three PCs was calculated. The average of the difference was used as an index of finger independence. A higher difference indicates a smaller degree of finger independence (i.e., more deficits).

We performed a correlation between the force independence deficits and the abnormal muscle co-activation patterns of different muscles, as well as a correlation between the clinical assessment scores and the abnormal muscle co-

activation patterns, which provided information regarding the contribution of muscle impairment to reduced hand dexterity.

III. Results

A. Muscle Compartment Co-Activation Sample

Fig. 2 shows a representative sample of 2D energy maps of the extrinsic extensor finger muscles in a stroke survivor with moderate hand impairment (hand component of Chedoke = 4 out of 7). The activation patterns on the contralateral side (bottom row) exhibited distinct localized activation across different tasks (i.e., movement using different fingers). In contrast, the activation patterns on the affected side (top row) tended to show widespread activation with less differentiation between patterns of different tasks. The 2D cross-correlation coefficient of the energy maps between the individual finger tasks and the four-finger task was calculated for each individual contraction task to quantify the degree of muscle co-activation patterns in the single finger tasks. A high 2D correlation coefficient indicated high muscle co-activation.

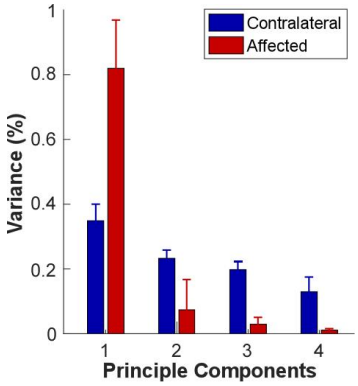

Figure 3. The PC in descending order of individual finger forces for one stroke subject. Four PCs are needed to capture 95% of variance in contralateral hand, and a single PC is sufficient to cover 95% variance in affected hand. The PCs were averaged across tasks and the error bars indicate standard errors

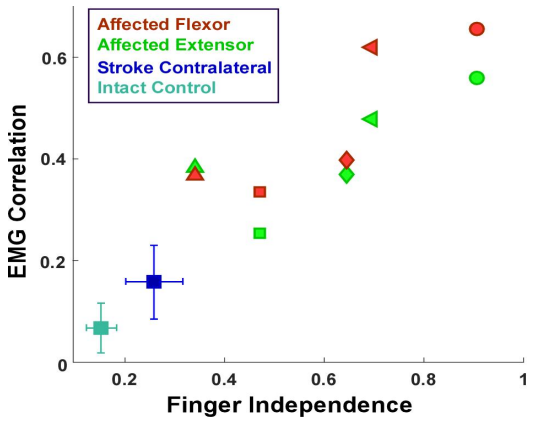

Figure 4. Muscle co-activation in relation with finger independence. Different symbol shapes represent different subjects, different colors in the affected side represent different muscles. The average values of the contralateral side of stroke subjects and both sides of control subjects are shown with error bars as standard errors.

B. Finger Independence Sample

PCA was used to quantify the degree of independent finger movement as a proxy for hand dexterity. Figure 3 shows that four PCs were required to capture the majority of the variance in the individuated finger tasks of the contralateral hand. In contrast, a single PC was sufficient to capture the majority of the variance in the affected hand. From these PCs, the average difference of variance accounted for between the first PC and the remaining three PCs was calculated as an index of finger independence.

C. Across Subject Association of Muscle Co-Activation, Finger Independence, and Clinical Assessments

Figure 4 summarizes the relation between these two quantitative metrics across all subjects. The muscle co-activation (EMG 2D cross-correlation coefficient between single-finger and four-finger tasks) is illustrated with the finger independence (average difference of variance between the first and the remaining PCs) for each of the affected side of the 5 stroke subjects. The averaged values of the contralateral side of 5 stroke survivors, and both sides of 5 control subjects are also shown in Fig. 4 as a comparison. We did not observe differences between the dominant and non-dominant hands in controls, and therefore the average across hands were calculated and plotted. These preliminary results show that the affected muscles, especially the flexor, tend to exhibit a higher level of co-activation. Additionally, these preliminary findings also suggest that excessive muscle co-activation plays a role in impairment of finger independence, which limits daily hand use.

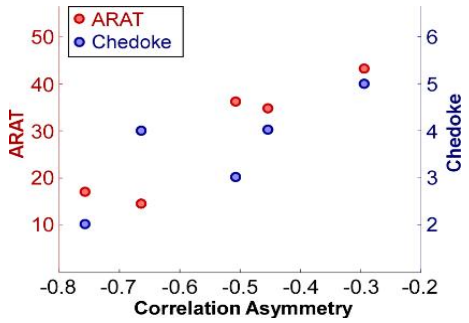

Figure 5. Association between clinical assessments and correlation asymmetry (i.e., degree of altered muscle activation).

We also identified associations between the abnormal muscle co-activation (correlation asymmetry) and the clinical assessments of hand function and hand impairment of stroke survivors. The preliminary results of 5 stroke survivors (Fig. 5) reveal a clear association between the abnormal muscle co-activation and clinical assessment outcomes (ARAT and hand section of Chedoke-McMaster scores).

IV. Discussion

This preliminary work demonstrated that the spatial patterns of muscle activation based on HD-EMG can provide information regarding the quality of finger control, with distinct localized patterns representing independent muscle control and widespread co-activation patterns representing

limited independent finger control. This information can provide a theoretical basis for the development of intervention strategies that can potentially reduce these maladaptive changes after stroke. In particular, aside from strength training or exercising finger range of motion, strategies that can enhance finger independence or dexterity should be emphasized. For example, exoskeleton gloves [22, 23] or electrical nerve stimulation [24, 25] techniques have been developed to specifically target hand dexterity.

Because of the small sample size, no statistical evaluations were performed to quantify the strength of association between abnormal muscle co-activation and finger independence, for example, using regression analyses. Recruitment of a larger sample of stroke survivors is needed.

With the advancement of wearable sensing and power-efficient electronics, HD-EMG recording has the potential to be implemented as a technique for continuous assessment of hand impairment in stroke survivors or individuals with other brain injuries.

V. Conclusion

Using HD-EMG recording arrays, we identified the abnormalities in finger muscle activation (i.e., muscle co-activation) and how they are associated with impaired finger independence and clinical outcomes. With further development, our preliminary work can provide a further understanding of the pathophysiology of hand dexterity deficits of stroke survivors.

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