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Impaired Motor Unit Control in Paretic Muscle Post Stroke Assessed Using Surface Electromyography: A Preliminary Report*

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Abstract— **The objective of this preliminary study was to examine the possible contribution of disordered control of motor unit (MU) recruitment and firing patterns in muscle weakness post-stroke. A novel surface EMG (sEMG) recording and decomposition system was used to record sEMG signals and extract single MU activities from the first dorsal interosseous muscle (FDI) of two hemiparetic stroke survivors. To characterize MU reorganization, an estimate of the motor unit action potential (MUAP) amplitude was derived using spike triggered averaging of the sEMG signal. The MUs suitable for further analysis were selected using a set of statistical tests that assessed the variability of the morphological characteristics of the MUAPs. Our preliminary results suggest a disrupted orderly recruitment based on MUAP size, a compressed recruitment range, and reduced firing rates evident in the paretic muscle compared with the contralateral muscle of one subject with moderate impairment. In contrast, the MU organization was largely similar bilaterally for the subject with minor impairment. The preliminary results suggest that MU organizational changes with respect to recruitment and rate modulation can contribute to muscle weakness post-stroke. The contrasting results of the two subjects indicate that the degree of MU reorganization may be associated with the degree of the functional impairment, which reveals the differential diagnostic capability of the sEMG decomposition system.**

I. Introduction

Cerebral stroke is a leading cause of disability in the United States [1]. Despite functional recovery, many stroke survivors exhibit persistent motor impairments. Muscle weakness is one of the major impairments limiting motor function in stroke survivors [2-4]. Possible mechanisms of weakness include muscle atrophy, uncoordinated muscle activation (e.g., co-contraction), and disorganization of MU pool activation. The first two mechanisms have been studied extensively [5-10] and therapeutic approaches have been developed [11-14]. However, the choice as to which mechanisms should be targeted during therapeutic intervention is still unclear [15, 16].

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Only a few studies have investigated disturbances of MU pool activation (e.g., reduced MU firing rates and compressed recruitment threshold) in paretic muscles of stroke survivors e.g.[17]. A reduction in MU firing rate could result in inefficient activation of MUs; therefore, to achieve any desired muscle force, more MUs, possibly more fatigable, need to be activated. This recruitment compression and/or disordered recruitment can promote early muscle fatigue and ultimately weakness. Indeed, using a spinal hemisection cat model [18], an earlier study has observed that MNs with low recruitment threshold tend to show increased recruitment force post-lesion, and vice versa. This non-uniform change in recruitment threshold provides indirect evidence for disturbance of orderly recruitment, where larger MNs are recruited earlier than smaller MNs in opposition to the size principle [19]. Thus, a more direct and rigorous examination of MU reorganization post-stroke is necessary to extend our understanding of the neural mechanisms of muscle weakness.

Typically, MU recruitment and firing rate features are assessed using intramuscular EMG recordings. A novel sEMG electrode array recording and decomposition method has recently been developed [20, 21] and it yields a large number of MUs simultaneously over a relatively large force range. Using the results from this sEMG decomposition technique, we have developed an analytical method to examine MUAP properties in neurologically intact individuals. Using these novel techniques, the objective of this preliminary study was to examine the change in recruitment patterns and firing rates in contribution to muscle weakness during voluntary muscle activation post stroke.

II. Methods

A. Subjects

Two chronic hemiparetic stroke subjects one with mild and one with moderate weakness (see Table 1) of the extremities contralateral to the cerebral lesion were tested. All participants gave informed consent via protocols approved by the Institutional Review Board at Northwestern University.

TABLE I. Demographic Information of Stroke Subjects

ID	Sex	Age	Side	Time	Chedoke	FM	MVC
1	M	61	R	7	4	55	0.49
2	M	61	R	4	6	63	0.91

Note: Side: paretic side. Time: time after stroke in years. FM: Arm Motor Fugl-Meyer Motor assessment. MVC: MVC ratio between the paretic and contralateral sides

B. Experimental Setup

The participants were seated upright in a Biodex chair with their upper arm comfortably resting on a plastic support. To standardize hand position and to minimize activity of unrecorded muscles, the forearm was placed in a brace frame of a ring-mount interface that was mounted to the table. The index finger was placed in line with the long axis of the forearm (Fig. 1A). The proximal phalanx of the index finger was fixed to a ring-mount interface attached to a six degrees-of-freedom load cell (ATI, Inc.). The recorded forces from the x (abduction/adduction) direction was low passed (cutoff =200 Hz) and digitized at a sampling frequency of 1 kHz.

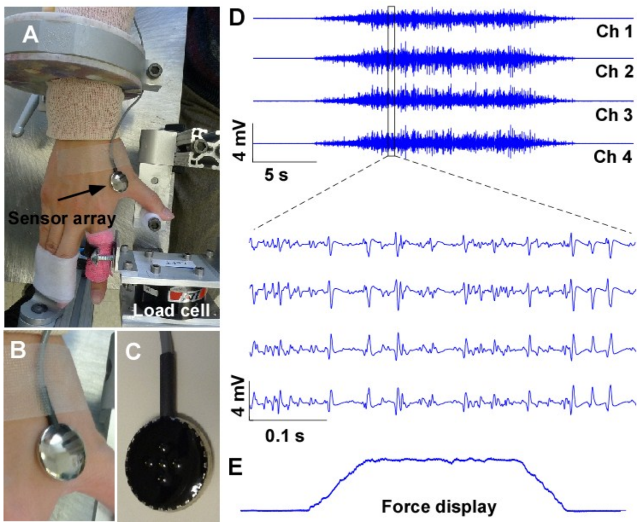

Fig. 1: Experimental setup, surface sensor array, sEMG signals, and force display.

sEMG were recorded from the first dorsal interosseous (FDI) muscle using a surface sensor array (Delsys, Inc.) as shown in Fig. 1B that consists of 5 slender cylindrical probes. The probes are located at the corners and at the center of a 5 × 5 mm square (Fig. 1C). Pairwise differentiation of the 5 electrodes yields 4 channels of sEMG signals (Fig. 1D). The sEMG sensor and a reference electrode were connected to 4 channels of a Delsys Bagnoli sEMG system. The signals were amplified and filtered with a bandwidth of 20 Hz to 2000 Hz. The signals were sampled at 20 kHz.

C. Procedures

Each of the subjects was tested at two separate sessions (one for each side) of the same protocols spaced less than a week apart. During each session, the first trial consisted of the assessment of the subject's maximal voluntary contractions (MVCs) for both arms. For fair comparison between the two sides, the MVC of the paretic side was used to determine the force level for the contralateral side.

Subsequent to MVC testing, the rest of the sessions consisted of a series of isometric force contractions during which the subject was asked to follow trapezoid force trajectories displayed on a computer screen, each at a different varying percentage of the MVC. The force output in one exemplar trial is shown in Fig. 1E. To ensure that the subjects could trace the trapezoid trajectory closely, they practiced 5 trials of 30% MVC constant force trapezoid before the main experiment. The subjects then performed 5 blocks of trials that with 4 repetitions of each block. Five constant force levels (20%, 30%, 40%, 50%, and 60% MVC) were tested and assigned to each block. The order of the force levels was randomized for each subject. A 1 min rest period between trials was provided to minimize fatigue. Upon request, additional resting time was provided.

D. Data Analysis

To ensure smooth force traces and good quality in the EMG signal, the sEMG and force trials were selected for further analysis based on the following criteria: (1) There was no sudden change (i.e., larger than 20% MVC/s) in the up-ramp force; (2) The force variability during the steady state force was low (mostly within ± 2 standard deviation (SD) of background force level); and (3) The sEMG signals had a P-P baseline noise < 20 µV and signal to noise ratio > 5.

For each subject, two trials at each force level were selected based on the preceding criteria for further analysis. Next, discriminable MUs were extracted using the decomposition system (version 1.0.0.28). For each identified MU, the output of the algorithm consisted of firing times and 4 MUAP waveforms (for the 4 recorded channels). Detailed information for the decomposition algorithms is described in [20].

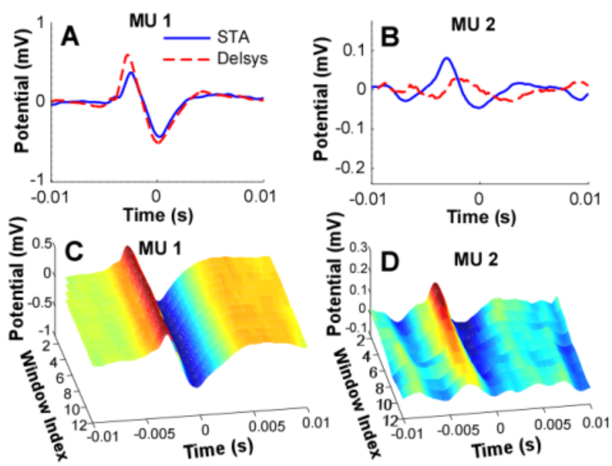

Fig. 2: Correlation between STA estimated and decomposition estimated MUAPs of exemplar MUs and variation of STA estimated MUAP shape across a moving time window. Window index denotes the time location of the window over the sEMG signal. STA waveform of MU 1 showed good fit with the decomposed MUAP, and the waveform shape was stable over the trial duration (window index). STA waveform estimate of MU 2 showed poor fit with the decomposed MUAP, and the waveform shape was unstable over the trial duration.

Spike triggered averaging (STA) of the sEMG was then performed to characterize the MU waveform recorded from the surface electrodes. STA is a type of waveform average where multiple segments of the recorded signal were time aligned based on an event (a MU firing in this case) and averaged to attenuate the interference of other MUs and recording noise. A STA was performed on each of the 4 channels of the sEMG signals resulting in 4 representative STA MUAP estimates for each MU. The identified firing times for each MU were used as triggers for the STA calculation. The time interval used to derive the template estimate was set at 10 ms prior to and after the firing time, and the firing time was placed at the algebraic center of the time window. To ensure reliable estimate of MUAP P-P amplitude, two separate tests was performed to determine which MUAP estimates would be retained for further analysis:

First, the variation of the STA MUAP over time was calculated based on a window length of 8 s which yielded approximately 100-200 firing events in each window, and the window was shifted using a step size of 1 s on the sEMG. The coefficient of variation (CV) of the MUAP P-P amplitude was calculated as a measure of the reliability of the MUAP estimates. The MUAPs estimated at different windows (labeled as Window Index) are shown in Fig. 2C and 2D.

Second, the STA estimated MUAP was compared with the decomposition MUAP estimates. The correlation between STA estimate and the decomposition estimated MUAP was calculated over the entire trial duration as a second measure of the reliability of the waveform average (Fig. 2A and 2B). The STA MUAP was shifted 10 ms backward and forward relative to the decomposition estimation to find the maximum correlation coefficient.

Based on our earlier study (Hu et al. In preparation), identified MUs with a CV < 0.3 and a correlation coefficient > 0.7 were retained and used for further analysis. To avoid possible bias of the results from one particular channel, the average CV of P-P amplitude and average correlation coefficient derived from each of the 4 channels were used to select MUAPs for further analysis.

The computed MUAP P-P amplitude was used as an estimate of the MU size. To estimate the recruitment threshold, the threshold force was calculated from the averaged force over an interval (-50 to 100 ms relative to the first firing event). The relation between the MUAP P-P amplitude and the recruitment threshold force of the MU was examined. In addition, distribution of the recruitment threshold and the mean firing rate (at steady state force) of the MUs were compared between the paretic and contralateral sides of the 2 stroke subjects, respectively.

III. Results

Using the decomposition method [20], we analyzed sEMG data of the FDI muscles of two hemiparetic stroke subjects

A total of 85 MUs from the affected side and 112 MUs from the contralateral side were extracted from 7 contraction trials in each side of subject 1 (Chedoke score = 4). A total of 181 MUs from the affected side and 209 MUs from the contralateral side were extracted from 10 contraction trials on each side of subject 2 (Chedoke score = 6). Fig. 3 displays the comparison of MU recruitment organizational properties between the contralateral and affected sides. For subject 1, MUs with larger P-P amplitude (STA estimate over the entire trial duration) were recruited at higher force in the contralateral side (Fig. 3A), supporting the size principle. However, this orderly recruitment was disrupted on the affected side. The threshold force at recruitment (Fig. 3B) in the affected side was also compressed compared with the contralateral side. In contrast, the examined parameters (the size principle in Fig. 3C and the threshold force distribution in Fig. 3D) of subject 2 were largely the same between the affected and contralateral sides.

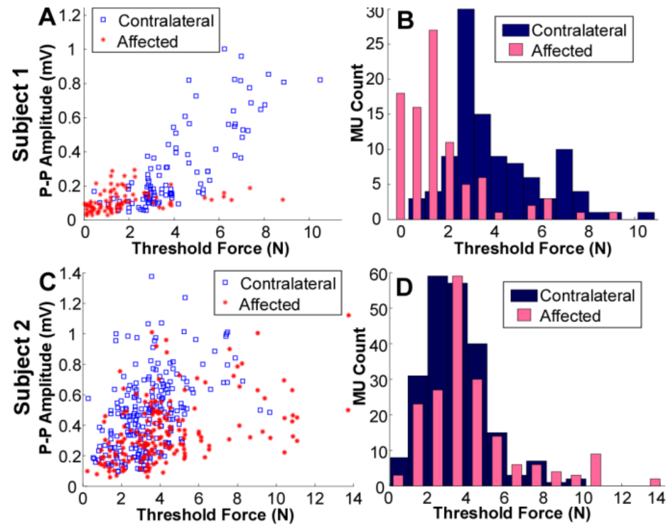

Fig. 3: MU recruitment organization: bilateral comparison of orderly recruitment (A) and recruitment range (B) of subject 1 (Chedoke score = 4); orderly recruitment (C) and recruitment range (D) of subject 2 (Chedoke score = 6).

Fig. 4 illustrates the mean firing rate histogram distribution contrasted between the affected and contralateral sides. The mean firing rate at steady force (Fig. 4A) was also lower in the affected side than in the contralateral side of subject 1. Subject 2 showed a similar, though a less degree, shift of the mean firing rate in the paretic side (Fig. 4B).

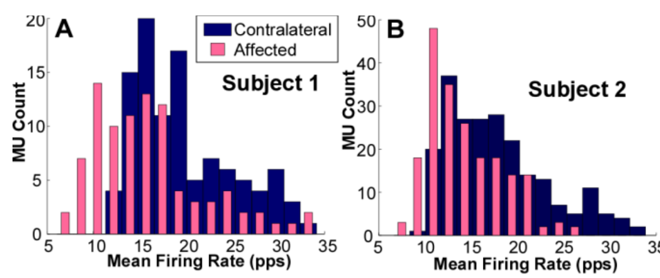

Fig. 4: MU firing rate organization of the 2 subjects.

IV. Discussion

This preliminary study examines the possible contributions of changes in MU recruitment and firing to muscle weakness post-stroke by analyzing sEMG data from both sides of two stroke subjects. A novel sEMG recording and decomposition system was used to record sEMG signals and decompose single MU activities. The system is non-invasive and yields a large number of MUs simultaneously over a large force range [20, 22]. A spike triggered averaging of sEMG was used as a second level of analysis to extract reliable estimate of MUAPs.

The preliminary results reveal a disrupted recruitment order, a compressed recruitment threshold range, and a reduced firing rate in the subject with moderate impairment.

The results support earlier findings [17] that show that MU organizational changes in recruitment and rate modulation can contribute to muscle weakness following a stroke. The MU activation of the subject with minor impairment showed similar MU organizational patterns between the affected and contralateral sides. The contrasting results of the two subjects indicate that the degree of MU reorganization may be associated with the degree of the functional impairment, which reveals the differential diagnostic capability of the sEMG decomposition system. The analytical STA method combined with the sEMG decomposition system will potentially provide an efficient way to identify a large number of MUs that can be used to systematically examine the MU pool reorganizational properties in stroke survivors. From a clinical perspective, the noninvasive nature and efficiency of the methods afford us the ability to develop a diagnostic tool for muscle weakness post stroke.

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