

Examination of Motor Unit Control Properties in Stroke Survivors Using Surface EMG Decomposition: A Preliminary Report

Nina Suresh, Xiaoyan Li, Ping Zhou, William Zev Rymer, *Senior Member, IEEE*

Abstract- The objective of this pilot study was to examine alterations in motor unit (MU) control properties, (i.e. MU recruitment and firing rate) after stroke utilizing a recently developed high-yield surface electromyogram (EMG) decomposition technique. Two stroke subjects participated in this study. A sensor array was used to record surface EMG signals from the first dorsal interosseous (FDI) muscle during voluntary isometric contraction at varying force levels. The recording was performed in both paretic and contralateral muscles using a matched force protocol. Single motor unit activity was extracted using the surface EMG decomposition software from Delsys Inc. The results from the two stroke subjects indicate a reduction in the mean motor unit firing rate and a compression of motor unit recruitment range in paretic muscle as compared with the contralateral muscles. These findings provide further evidence of spinal motoneuron involvement after a hemispheric brain lesion, and help us to understand the complex origins of stroke induced muscle weakness.

Key words: motor unit, motor unit recruitment, firing rate, surface EMG, stroke

I. INTRODUCTION

Hemispheric brain injury resulting from a stroke is often accompanied by weakness of voluntary movement in upper and lower limbs on the side contralateral to the lesion. There are three mechanisms that could contribute to poststroke weakness: 1) muscle fiber atrophy and contracture; 2) changes in the spatial and/or temporal patterns of muscle activation; and 3) disorganization of motor unit recruitment and rate modulation patterns.

It has been reported that the motor unit discharge rates are abnormally low in paretic muscles of stroke subjects and in spinal cord injury subjects [1-2]. Direct measurement of the rate and recruitment patterns of single motor unit discharge was further confirmed through intramuscular electromyography (EMG) decomposition.

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Nina Suresh is with the Sensory Motor Performance Program (SMPP) of the RIC, 345 East Superior Street, Chicago, IL, USA, 60611 (phone: 312-238-1279, email: n-suresh@northwestern.edu)

Xiaoyan Li is with the SMPP of the Rehabilitation Institute of Chicago (RIC), (email: xiaoyan-li-1@northwestern.edu)

Ping Zhou is with the SMPP of the RIC and Department of Physical Medicine and Rehabilitation of Northwestern University (email: p-zhou@northwestern.edu)

William Zev Rymer is with the RIC and Departments of Physical Medicine and Rehabilitation, Physiology, and Biomedical Engineering of Northwestern University (email: w-rymer@northwestern.edu)

Relying on intramuscular EMG recordings, Gemperline et al. reported that in 50% (3 of 6) of their hemiparetic subjects, there were significant reductions in motor unit mean discharge rate in the paretic muscle, when compared to the contralateral muscle [3]. In the paretic muscles, all subjects showed compression of motoneuron recruitment forces and failure to increase motor unit discharge rate during voluntary force increments. Due to the difficulty in carrying out intramuscular EMG recording, it is not practical to perform this study on a large group of stroke subjects. In addition, the role of alterations in motor unit control properties has not been systematically studied in paretic hand muscles.

The objective of the current study was to examine the associations between muscle weakness and motor unit control properties including firing rate and recruitment pattern in the first dorsal interosseous (FDI) based on recent advances in surface EMG decomposition. Compared with selective intramuscular needle recording, the non-invasive surface EMG technique can yield significant scientific and diagnostic information without medical supervision or discomfort to patients.

II. METHODS

A. Subjects

Two stroke subjects with hemiparesis participated in the study. They were recruited from the Clinical Neuroscience Research Registry at the Rehabilitation Institute of Chicago (Chicago, IL, USA). The study was approved by the Institutional Review Board of Northwestern University (Chicago, IL, USA). Written consent was obtained before the experiment. Clinical assessments included spasticity measures at the elbow and assessment of upper arm or hand impairment using the Fugl-Meyer test and the Chedoke-McMaster assessment. Table 1 summarizes the demographic and clinical information of the 2 stroke subjects.

Table 1. Demographic information of stroke subjects.

ID	Sex	Age	A	FT	C	Duration (years)	Paretic side	MVC Ratio
1	F	58	1+	29/66	3	9	L	0.375
2	M	48	1+	24/30(h)	5	1.5	R	0.675

A: Ashworth test (biceps), FT: Fugl-Meyer test, C: Chedoke-McMaster test, h: hand only, MVC Ratio: ratio of MVC force between paretic muscle and contralateral side

B. Experiments

Subjects were seated upright in a mobile Biodex Chair. Their shoulder and waist were tightly strapped to the chair to minimize unnecessary trunk and shoulder movements. The upper arm was placed on a plastic support and the forearm was casted and strapped in a ring-mount interface. The proximal phalanx of the index finger was casted and fixed to a small ring-mount interface attached to a six degree-of-freedom load cell (ATI, Apex, NC). This standardized position served to reduce activity of non-tested muscles.

Surface EMG signals were recorded from the first dorsal interosseus (FDI) muscle using a surface sensor array (Delsys, Boston, MA). The output signals were differentially amplified and filtered between 20Hz and 2000Hz. The forces and surface EMG signals were sampled at 20 kHz using EMGWorks® (Delsys, Boston, MA).

At the beginning of the experiment, subjects performed three trials of isometric maximum voluntary contraction (MVC) using the paretic index finger for abduction. The MVC from paretic hand was used as a standard to calculate the target forces. The target force trajectory and visual feedback of the contraction force were displayed on a computer monitor. Subjects were instructed to match the trapezoidal target force trajectory which included holding the force for 10 s. The target force was set from 20% to 80% of the paretic MVC at 10% MVC increments. Depending on the amplitude of the target force, the duration of each trial varied from 20 to 29 s. Each target force was performed at least twice and the order of target forces was randomized. Practice trials and substantial rest period between trials were provided. Each subject was scheduled for two visits, one for the paretic hand and the other for the contralateral hand.

C. Data Analysis

The advanced EMG decomposition techniques were applied to separate superimposed action potentials and extract the firing event of single motor units from four-channel surface EMG signal [4-7]. Subsequently, a reconstruction accuracy test was performed to further verify the accuracy of the decomposed results. Those motor units which had less than 95% accuracy on the reconstruction test were excluded from ongoing analysis.

Motor unit recruitment characteristics were tested when slow contractions were developed in the FDI muscle. The recruitment threshold of each motor unit was measured in absolute force, at the instance when the first firing of the motor unit occurred. The initial firing rate and recruitment threshold from the paretic hand and contralateral sides were compared across all force level for each individual.

At each contraction level, the mean firing rate was calculated using the firing rate curve of the motor unit. The firing rate curve was computed from the inter pulse intervals and filtered with a Hanning window of 1-s duration. The averaged value of the curve at the sustained

force level was recorded as the mean firing rate of the motor unit. Therefore, we calculated the mean firing rate for each active motor unit and the mean contraction force for each trial. By matching motor units across these trials, we were able to estimate the firing rate of the motor unit as a function of steady-force.

For each subject, the Mann-Whitney U test was used to compare the distributions of mean firing rate at matched force, the recruitment threshold, and the initial firing rate of the paretic muscle versus contralateral side. A stringent alpha value ($p < 0.01$) was selected considering the number of comparisons computed in some trials [8].

III. RESULTS

For each subject, we collected at least two trials per force level for all target forces ranging from 20% to 80% (at 10% increment) of the subject's maximum force of the paretic hand. The force range used for the contralateral side was matched to that used in the paretic side.

The surface EMG decomposition algorithm was used to decompose the four-channel raw EMG signals. Here we present an example of force, raw surface EMG data and decomposed results from the paretic first dorsal interosseus (FDI) muscle of one stroke subject in Figure 1. The force trajectory traced by the subject depicts the process when the subject slowly increased the contraction and maintained at 40% maximal voluntary contraction (MVC) for about 10 s and then slowly decreased the force (Fig 1, top left). Here one of the four-channel EMG signals is presented (Fig 1, top right). The decomposed data (bottom of Fig 1) shows the individual inter pulse intervals of 7 active motor units.

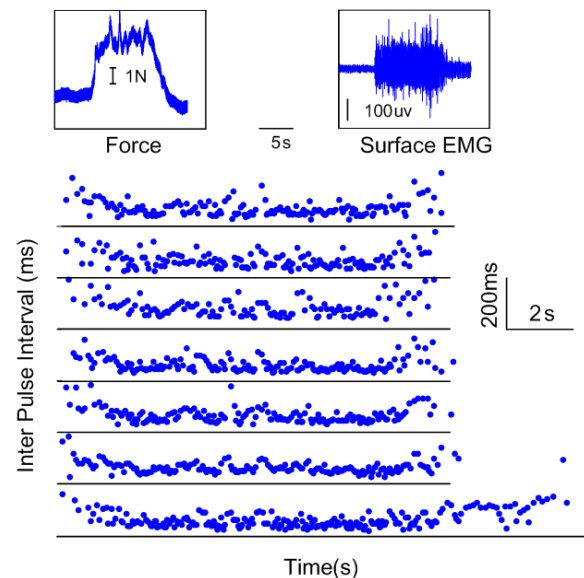


Fig 1. Force, raw EMG signal and decomposed data from the paretic first dorsal interosseus (FDI) muscle. Top: left: Force trajectory; right: one-channel of surface EMG data collected by the sensor. Bottom: example of the inter pulse intervals of 7 active motor units.

Motor unit firing rates at constant force

For each period of sustained voluntary contraction, we calculated the averaged force and firing rate of each active motor unit. Because of the relatively small amount of data collected from the two stroke subjects for preliminary analysis, we pooled the mean firing rates of all active motor units at the same averaged force. Distribution of mean MU firing rates of the paretic FDI muscle was compared with that of the contralateral side.

Table 2. Comparisons of averaged firing rate at matched force

Force (N)	Median firing rate for paretic side (pulses per second)	Median firing rate for contra. side (pulses per second)	Mann-Whitney U
4	9.32	12.3	U=62, d.f.=10,25; p<0.022
6	15.47	19.78	U=208.5, d.f.=33,35; p<0.0001

Figure 2 depicts the distributions of mean firing behavior of active motor units from the paretic FDI (red columns) muscle and contralateral side (yellow columns). The mean firing rates of the paretic FDI muscle range from 6.7 pulses per second (pps) to 11.2 pps with a median value at 9.3 pps when maintaining a 4 N force (Table 2). The mean firing rate of the contralateral side ranges from 7.7 pps to 21.7 pps, with a median of 12.3 pps at the same force level, indicating higher firing rates in the contralateral hand. The difference in averaged firing rate of paretic hand versus contralateral side approaches significance, under our stringent alpha level (U(10,25)=62, p<0.022).

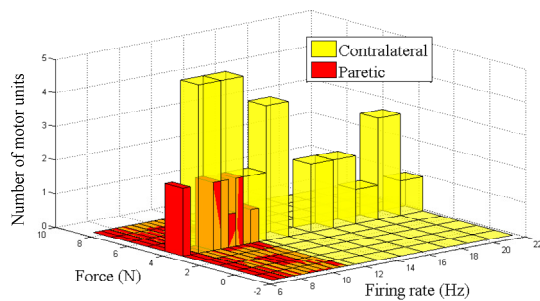


Fig 2. Distribution of mean motor unit firing rates at 4N.

Figure 3 presents a histogram of the mean firing rate at 6 N. The mean firing rates of the paretic FDI muscle range from 10.4 pps to 20.9 pps with a median value at 15.5 pps. Similarly, the mean firing rates of the contralateral side range from 11.6 pps to 34.4 pps with a median of 19.8 pps at the same force level. For both paretic and contralateral muscles, there is an increase of mean firing rate corresponding to a larger force. A significant relative reduction of mean firing was observed at the paretic hand (U(33,35)=208.5, p<0.001).

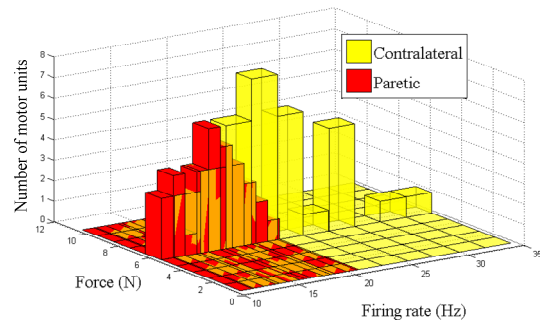


Fig 3. Distribution of mean motor unit firing rates at 6 N.

Recruitment characteristics: initial firing rate at recruitment

We calculated the initial firing rate for each active motor unit and the recruitment force. Figure 4 shows the relation between motor unit initial firing rate and recruitment force for subject 2. Comparisons of the initial firing rate demonstrate a lower firing rate on the paretic side. The difference approaches significance (p<0.015). The recruitment rates also spanned a smaller force range on the involved than the contralateral side.

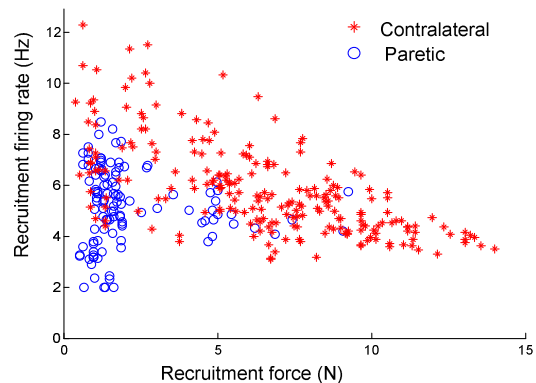


Fig 4. Motor unit recruitment firing rate as a function of isometric force for subject 2

Recruitment characteristics: force threshold

The recruitment forces for individual motor units were compared between paretic and contralateral hands to determine if there was a compression of recruitment force thresholds. Table 3 presents the median recruitment force for each subject across all force levels, and the Mann-Whitney U values comparing paretic and contralateral distributions. Both subjects show significantly lower recruitment force in the involved than in the contralateral side (Table 3).

Subject	median for paretic side (N)	median for contralateral side (N)	Mann-Whitney U
1	1.17	2.11	U=5248, d.f.=101,186; p<0.00001
2	1.46	6.6	U=3675, d.f.=115,225; p<0.00001

The compression of recruitment threshold is evident when the force is expressed in absolute units (Figure 5). The recruitment force of subject 1's paretic FDI muscle ranges from 0.27N to 6.27N with a median force at 1.17N, while that of the contralateral side ranges from 0.314N to 10.5N with a median recruitment force at 2.11N. Similar observations can be found in subject 2 whose paretic hand shows a smaller range of recruitment force ([0.49N - 9.26N], median: 1.45N) than the contralateral side ([0.375N - 14.025N], median: 6.6N). Both subjects show that the highest recruitment force is greater for the contralateral side than the impaired side. In sum, on the involved side, the motor units are recruited systematically at lower levels of absolute force.

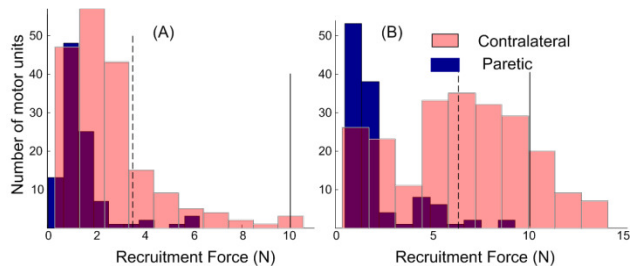


Figure 5. Histogram of recruitment force for two subjects. Solid vertical line in the plot is 25% MVC for contralateral side. Dashed vertical line is 25%MVC for paretic FDI muscle. (A): subject 1; (B) subject 2.

IV. DISCUSSION

This study presents a preliminary examination of 2 stroke subjects using the most recent advances in surface EMG decomposition. We used non-invasive surface electrode arrays and state-of-the-art surface EMG decomposition techniques to explore the role of disorganized motor unit recruitment and firing patterns in the paretic muscle (FDI) of two stroke subjects. The high-yield surface EMG decomposition technique enables us to build up a large pool of motor units to observe consistent changes in the discharge characteristics of single motor units [4].

In this pilot study, we found reductions in the mean firing rate of active motor units in the paretic hand muscles during the isometric constant contractions compared with the contralateral muscles. In addition, the paretic hand showed significant lower recruitment forces of motor units than the contralateral side and the range of recruitment threshold was compressed. This observation was consistent with previous findings from intramuscular EMG decomposition [3]. The evidence of segmental disorganization in the form of abnormal motor unit firing rates for a given muscle following a stroke has accumulated for some time [1, 9]. The cumulative effects of decreased recruitment threshold and firing rate are likely to induce an inefficiency of muscle activation. Such inefficient activation of motor units will result in

recruitment of more motor units to produce a given force, which is also reflected as abnormal high EMG amplitude [10]. For long-lasting contractions, a greater effort would be needed and ultimately fatigue and weakness would develop.

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