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Using spike-triggered averaging to characterize motor unit twitch vectors in the first dorsal interosseous

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Abstract- Earlier studies in multifunctional muscles such as the first dorsal interosseous (FDI) have demonstrated that the selection and control of motor units (MUs) can vary as a function of generated force direction. While directionally dependent motor unit recruitment and rate properties imply that there may also be differential mechanical action, this has yet to be directly demonstrated. Our objective was to determine whether there exists a range of force vectors from different motor units in the FDI muscle within individual subjects. We utilized the spike-triggered averaging (STA) method to derive force twitch estimates from single motor units. We derived MU twitch direction from the ratio of individual twitch estimates recorded concurrently from the load cell. Fifteen units from 2 subjects were used to determine MU force vectors. We were able to estimate force twitch vectors from 7-8 different MUs in each subject. The results of our study suggest that there is varied mechanical action of motor units in the FDI. It is thus possible that differential activation of individual MUs in the FDI is a function of varied mechanical action.

Key words: motor unit, spike-triggered averaging, motor unit twitch, first dorsal interosseous, twitch force

I. INTRODUCTION

The selection and control of motor units (MUs) for a given motor task is assumed to depend primarily on the level of muscle force generation required for the task. Thus during isometric force production, motor units are believed to be recruited on a graded basis, generally according to motor unit size [1], which also corresponds to the magnitude of force output. However, there exist muscles that act to generate multi-directional forces across a joint. The system governing motor unit activation in such muscles remains incompletely understood.

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Earlier studies in muscles such as the biceps, deltoid and first dorsal interosseous (FDI) have demonstrated that the selection of motor units in these multifunctional muscles, can vary as a function of generated force direction [2-4].What remains to be shown is that spatial selectivity of motor unit activation by the nervous system is linked in a functionally useful way to the actual pattern of force generated by the motor unit. While directionally dependent motor unit recruitment and rate properties are suggestive of differential mechanical action, the existence of varying directional force output from a muscle's motor unit pool has yet to be directly demonstrated.

Previous studies on motor unit force output in the first dorsal interosseous [4, 5] focused on assessing changes in twitch force parameters, such as twitch magnitude and time course as a function of direction. They utilized the spike-triggered averaging method to quantify motor unit twitch forces, mainly in the two primary directions, abduction and flexion in which the muscle is known to be active. Twitch direction for individual motor units was not described and there was no (published) assessment of twitch direction range.

Our focus in this study is to characterize force twitch vector output, that is, force twitch magnitude *and* direction, of individual motor units in the first dorsal interosseous in neurologically intact subjects. We utilize the spike-triggered averaging method to derive force twitch vector estimates from single motor units. The spike-triggered averaging method is based on the ability to extract individual motor unit force twitches by averaging the force trace subsequent to the activation of a motor unit and is the only analytical method consistently utilized to calculate motor unit force output in intact preparations [5-7]. We derive motor unit twitch direction from the ratio of individual twitch estimates recorded concurrently from a six-degree of freedom load cell.

Our main objective in this study was to determine whether there was a range of force vectors from different motor units in the first dorsal interosseus muscle in individual subjects. If differential mechanical action does exist and is the basis for differential activation of single motor units(SMU), this would suggest that there are novel neural control strategies required to control activation of multifunctional muscles.

II. METHODS

A. Subjects

Data were collected from the dominant hand of 2 neurologically intact adult human subjects. All participants reported no history of neuromuscular impairments, and gave informed consent via protocols approved by the Institutional Review Board under the Office for the Protection of Human Subjects at Northwestern University.

B. Experimental Setup

Subjects were seated upright in a mobile Biodex Chair. The upper arm was placed on a plastic support and the forearm was cast 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 (JR3 Inc) (Figure 1). This standardized position served to reduce activity of non-tested muscles. The force recording of the JR3 load cell was from 1 mN to 9N. The recordings from x,y and z (outside the task plane) coordinates of the force generated at the meta-carpo phalangeal (MCP) joint were band pass filtered (DC-200 Hz) and digitized at a sampling rate of 1kHz. Motor unit activity of the first dorsal interosseous was recorded using fine-wire intramuscular electrodes. The electrode combination was inserted in two maximally separate locations in the FDI. Single differential surface EMG electrodes were placed over the fine wires in order to record both surface and SMU EMG signals. The intramuscular electromyograph(EMG) signal was band passed from 100-2000 Hz and digitized at a rate of 10 kHz.

C. Procedures

To aid participants control the isometric forces they exerted, we displayed the vertical and horizontal forces on an oscilloscope placed before them. Participants were instructed to generate force, using the index finger, in four pure directions in x (abduction and adduction) and in y (flexion and extension) as well as in intermediary directions; thereby generating a variety of planar radial forces (Figure 2).

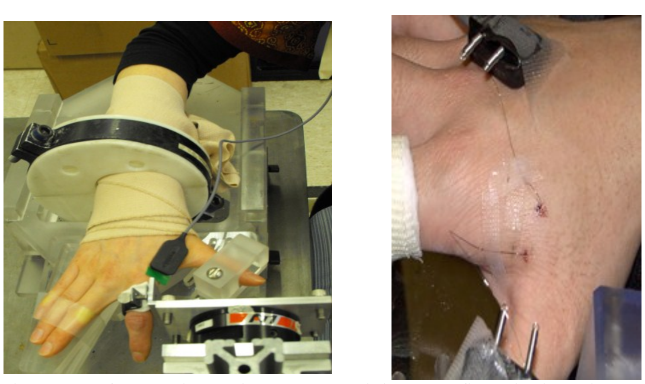

Figure 1 Left: Experimental setup in the FDI muscle. Right: Two fine wire insertions

Participants generated forces in at least 8 radial directions, distributed over all four quadrants of the movement plane. Force directions were generated in quasi-random order, at the discretion of the participant. and each force direction was tested a minimum of two times.

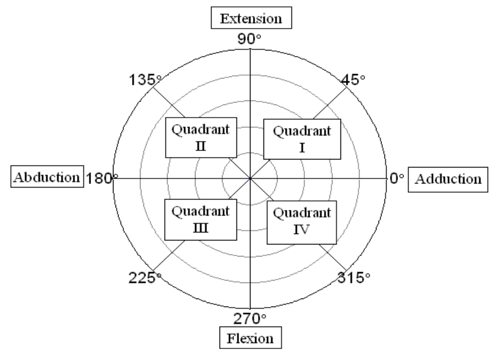

Figure 2: Diagram of isometric force plane showing force angles and force tasks.

The motor unit firing rate and force magnitude were monitored on a computer screen to guide the subject in maintaining the force level and firing rates at a relatively steady value. The firing rate of the targeted motor unit was monitored, to ensure that it was between 5 pulses per second (pps) and 12 (pps) [5, 6] in order to minimize the error in the force twitch calculation and that a steady rate was maintained. The subject was asked to hold the force steady for a minimum period of 50 seconds to a maximum period of 300 seconds, the length often determined by the steadiness and acceptability of the force and firing rate signals. Figure 2 shows raw data from one subject over a 40 second period.

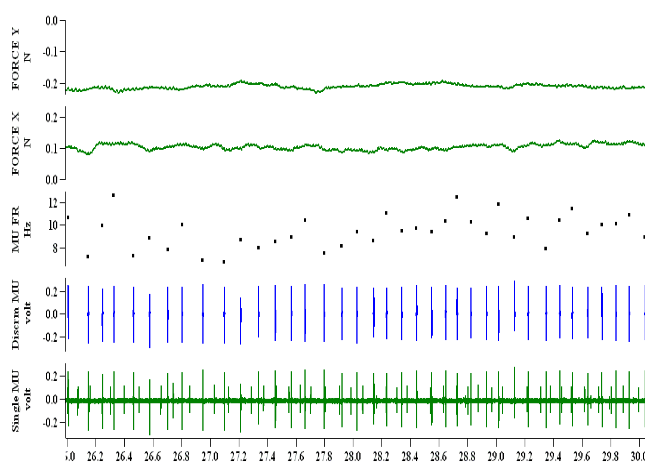

Figure 3: Exemplar raw signal trace (from top to bottom): 1. Force generated in extension/flexion 2. Force generated in adduction/abduction 3. Instantaneous MU firing rate 4. Discriminated spikes, 5. Raw single motor unit trace

In subsequent trials, the motor unit was tested in a full range of force directions. This allowed for multiple estimates of a motor unit's force twitch vector. Once a motor unit was tested adequately, the process was repeated to test another motor unit.

Trials and sub-sections of trials in which 1) the average firing rate was within the 5-12 (pps) range 2) and a minimum of 100 spikes were available during the trial were included for further analysis.

D. Data Analysis

Motor unit spike discrimination was accomplished using software from Spike2 (CED, Inc.). For each selected motor unit data record, a waveform average of the force signal was computed over an interval 50 ms prior to the SMU spike occurrences and 150 ms after the spike occurrences. This spike-triggered average was computed for the forces in the x direction as well as for the force signal in the y direction. The average number of sweeps that were used to compute motor unit force twitches ranged from a minimum of 121 to a maximum of 926 with an average of 460 sweeps

The resultant waveform average is representative of the force twitch produced by the single motor unit in the respective direction.

In order to determine the magnitude and direction of the force twitch corresponding to each motor unit, the angle and magnitude of the motor unit force vector were computed from the peak-to-peak values obtained from the x and y force twitches separately. If P_x represents the peak-to-peak value of the x force twitch and P_y represents the peak-to-peak value of the y force twitch. Then the $\arctan(P_y/P_x)$ is equal to the angle of the twitch force vector and the magnitude of the force vector is square root $((P_y^2 + P_x^2))$. This method is widely accepted and almost universally been used in the estimation of force twitch vectors [4-6].

III. RESULTS

We analyzed a total of 15 motor units drawn from 2 neurologically intact subjects.

Force twitch estimates were derived from force tasks generated in radial directions that ranged from 108 degrees to 303 degrees. The force magnitude during these tasks ranged from a minimum of 0.407 N to a maximum of 4.44 N with an average force magnitude of 1.23 N. The firing rates of the motor units that were included in the computation of force twitches ranged from a minimum of 4.5 pps to a maximum of 12.4 pps with an average of 6.9 pps.

To determine the range of measurable mechanical action in an individual subject, we were able to estimate 8 MU force twitch vectors from Subject#1 and 7 MU force twitch vectors from Subject#2. The range of mechanical action for tested motor units was 51.6 degrees for Subject#1 and 47.2 degrees for Subject#2. These ranges were significantly different ($P < .001$) from the angle range derived from repeated force vector estimates (derived from a single motor unit).

In Figure 4A are the twitch forces recorded for all tested MUs for Subject#1, in the y (flexion/extension direction and in Figure 4B shows the respective MU twitch forces recorded for Subject#1 in the x direction.

A plot of the motor unit twitch in the x direction against the motor unit twitch in the y direction (for each individual MU) is a graphical representation of the motor unit twitch vector. Note this plot is different from those in Figure 4 as information regarding the time course of the individual twitch force is not shown. In Figure 5 are the force twitch vectors for the MUs for Subject#1. The angles that these force vectors represent ranges from 185-270 degrees and the force magnitudes range from 20-40 mN. In Figure 6 are the force twitch vectors for the analyzed MUs for Subject#2, the angles represented by these force vectors ranges from 191-238 degrees and the force magnitude ranges from 10-20 mN.

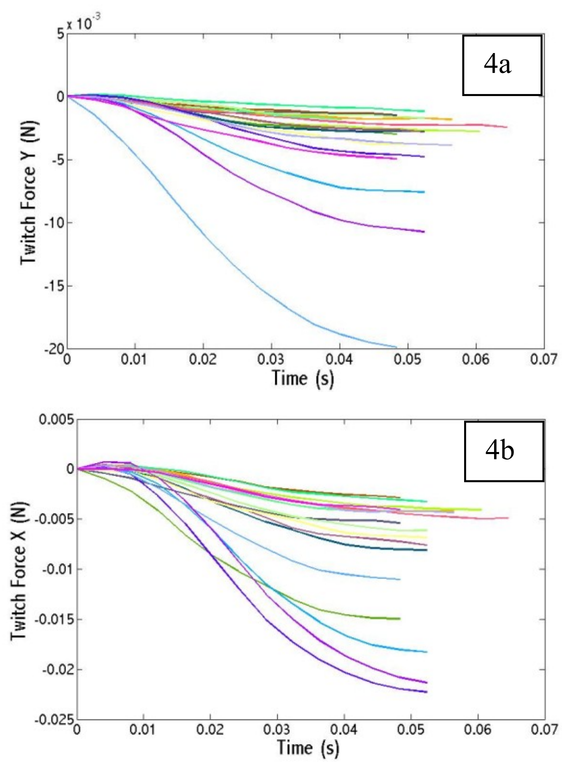

Figure 4: Top (4a): Motor unit twitch forces recorded in the x direction of the force plane. Each color represents the twitch force for an individual motor unit recorded in the x direction. Bottom (4b): Motor unit twitch forces recorded in the y direction of the force plane. Each color represents the twitch force for an individual motor unit recorded in the y direction.

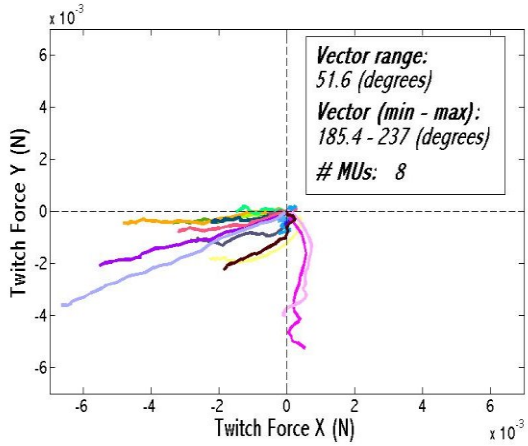

Figure 5: Estimated MU twitch force vectors for Subject#1.

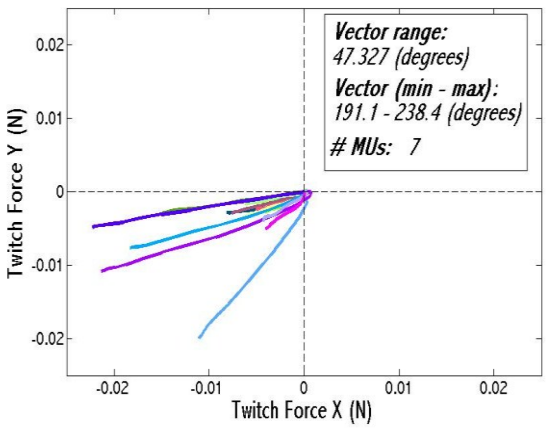

Figure 6: Estimated MU twitch force vectors for Subject#2.

IV. DISCUSSION

This study presents a preliminary examination of two neurologically intact subjects in order to assess the directional force output of individual motor units in the first dorsal interosseous muscle, using intramuscular recordings. Our preliminary results suggest that amongst a random group of tested FDI motor units, there is a range of twitch force vectors which is greater than the variability that exists in repeated measures of the fore twitch vector for the a given MU. This would suggest that a multi-functional muscle such as the FDI has the capacity to produce varied mechanical action and that directional force output can be generated without a complicated pattern of multiple muscles. The STA method of MU force twitch estimation can result in erroneous estimates due to sporadic or systematic synchronization with the activation of other motor units from the FDI motoneuron pool. However, computational model results [7] suggest that MU synchronization within the FDI would compress the measurable vector range, not enlarge it. Therefore the range of directions obtained in our results for MU twitch forces would still represent the ability to generate multidirectional force output from individual motor units that are consistent with the overall (isometric) force directions generated by the FDI about the MCP joint.

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