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Properties of Motor Units of Elbow and Ankle Muscles Decomposed Using High-Density Surface EMG

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Abstract

Analyses of motor unit activity provide a window to the neural control of motor output. In recent years, considerable advancements in surface EMG decomposition methods have allowed for the discrimination of dozens of individual motor units across a range of muscle forces. While these non-invasive methods show great potential as an emerging technology, they have difficulty

discriminating a representative sample of the motor pool. In the present study, we investigate the distribution of recruitment thresholds and motor unit action potential waveforms obtained from high density EMG across four muscles: soleus, tibialis anterior, biceps brachii, and triceps brachii. Ten young and healthy control subjects generated isometric torque ramps between 10–50% maximum voluntary torque during elbow or ankle flexion and extension. Hundreds of motor unit spike trains were decomposed for each muscle across all trials. For lower contraction levels and speeds, surface EMG decomposition discriminated a large number of low-threshold units. However, during contractions of greater speed and torque level the proportion of low threshold motor units decomposed was reduced, resulting in a relatively uniform distribution of recruitment thresholds. The number of motor units decomposed decreased as the contraction level and speed increased. The decomposed units showed a wide range of recruitment thresholds and motor unit action potential amplitudes. In conclusion, although surface EMG decomposition is a useful tool to study large populations of motor units, results of such methods should be interpreted in the context of limitations in sampling of the motor pool.

I. INTRODUCTION

Investigation of motor unit activity in humans affords a more comprehensive view of the neural drive underlying motor output. Traditionally, motor unit recordings were carried out with intramuscular concentric needle or fine wire electrodes. Though these invasive approaches are used in both clinical and research settings, they are usually only effective during low levels of muscle contraction due to the increased superimposition of motor unit action potentials (MUAPs) at higher forces. Further, these methods show high selectivity, can usually only detect a handful of motor units, and often require a trained operator to discriminate individual MUAPs. All of these factors have been a major hurdle in clarifying fundamental questions about the neural control of motor output [1]. In recent years, decomposition algorithms utilizing high-density surface EMG arrays have allowed for non-invasive recordings from a larger population of motor units, across a wider range of contraction levels, and with greater efficiency [2][3]. These advancements have made it possible to detect dozens of motor units during the same contraction.

Despite these obvious advantages, investigators using these methods must remain aware that surface EMG decomposition may not provide a representative sample of motor units from all muscles. When recording from the skin, the ability to decompose a motor unit is based on the statistical characteristics (spatial and temporal) [4] [5] and the surface energy of its action potentials [6]. This may impede identification of lower-amplitude smaller MUAPs, including those originating deeper within the muscle. Additionally, the number of active motor units comprising the EMG signals may reduce the capacity of the decomposition approaches to separate the contribution of individual units, though to a lesser degree than conventional intramuscular single motor unit analysis techniques.

The goal of the present study was to investigate the distribution of motor unit recruitment threshold and MUAP amplitude in a large sample of recordings from the soleus (SOL), the tibialis anterior (TA), the biceps brachii (BIC), and the triceps brachii (TRI), using an automatic high-density surface EMG decomposition approach [2][4]. According to

Hennemans size principle, smaller motor units are recruited before their larger counterparts due to the intrinsic electrophysiological properties of motor units [7]. Fine wire analysis has shown that the number of motor units recruited decreases exponentially as force increases, including muscles reported in this paper [8][9][10][11]. Similarly, Oya and colleagues discovered that in the SOL, the number of recruited units decreases as the torque level increases until about 50% MVT and increases afterward [12]. This is consistent with the notion of a relatively large number of slow motor units with fewer large motor units [13]. Our current results are contrary to this expectation. However, a moderate level of correlation between MUAP amplitude and force recruitment threshold has been shown previously [14] [15] and, as stated above, the decomposition algorithm may be biased by amplitude. For the higher contraction levels, the distribution of motor units recruitment threshold was relatively uniform. The number of motor units identified was muscle dependent and decreased considerably at higher torque levels. These factors should be considered in the interpretation of results discriminated from surface EMG decomposition methods

II. METHODS

A. Participants

The data shown in this paper is from two separate experiments, one in the upper limb and one in the lower limb. Ten healthy adults (aged 26.4 ± 3.6 , 40% female, 729 units from females, 2196 units from males) participated in these two experiments, with five participants in each. All participants reported having no known neurological or motor impairments. All participants provided informed consent prior to participation in these experiments, which were approved by the Institutional Review Board of Northwestern University (IRB Number: STU00202964 (lower limb); STU00084502 (upper limb)).

B. Experimental Apparatuses

Upper limb.—Participants were seated in a Biodex experimental chair (Biodex Medical Systems, Shirley, NY) and secured with shoulder and waist straps to minimize trunk movement. In order to measure isometric shoulder and elbow torques, the participants dominant forearm was placed in a fiberglass cast and rigidly fixed to a six degrees-of-freedom load cell (JR3, Inc, Woodland, CA). The arm was positioned at a shoulder abduction (SABD) angle of 75° and an elbow flexion (EF) angle of 90° . The fingers were placed on a custom hand piece at 0° wrist and finger (metacarpophalangeal) flexion/extension.

Lower limb.—Participants were seated in a Biodex experimental chair and secured with shoulder and thigh straps to minimize change in position. Each participants dominant foot was strapped to an ankle attachment, which was attached to Systems 2 Dynanometer (Biodex Medical Systems, Shirley, NY) to measure the torque. Unless participant expressed discomfort, the ankle was positioned at an angle of 100° and the knee were positioned at an angle of 160° .

Bipolar surface EMG recordings were collected from the biceps brachii (BIC), the triceps brachii (TRI), the soleus (SOL), and the tibialis anterior (TA) using grids of 64 electrodes,

with 8mm inter-electrode distance. The signals were amplified (x150), band-pass filtered (10–500Hz) and sampled at 2048 Hz (EMG-USB2 for 2 lower limb subjects and Quattrocento for rest, OT Bioelettronica, Turin, IT).

C. Protocol

Participants were asked to generate maximum voluntary torques (MVTs) during elbow flexion (EF) and elbow extension (EE), in the upper limb, and ankle dorsiflexion (DF) and plantarflexion (PF), in the lower limb. Trials within a direction were repeated until three trials with peaks within 10% of the maximum torque were collected. Participants were provided with enthusiastic vocal encouragement, as well as real time visual feedback during MVT trials.

Upper limb.—Experimental trials entailed the generation of triangular isometric torque ramps. Participants were instructed to gradually increase their EF/EE torque to 20% MVT over 10 seconds, followed by gradually relaxing back to baseline over 10 seconds. Trials consisted of either two or three ramps with ten seconds between ramps and five seconds of baseline at the beginning and end of each trial.

Lower limb.—In this experiment, data were collected at varying contraction speed and level; participants were instructed to gradually increase their DF/PF to 10%, 30%, or 50% MVT over 10 seconds, followed by gradual relaxation over 10 seconds. Trials consisted of two ramps with ten seconds between ramps and five seconds of baseline at the beginning and end of each trial.

D. Data Analysis

All surface EMG channels were visually inspected and those with substantial artifacts or noise were removed. The remaining surface EMG channels were analyzed based on convolutive blind source separation to provide motor unit spike trains [2]. The silhouette threshold for decomposition was 0.85 for upper limb trials and 0.87 for lower limb trials. All motor units were manually inspected by experienced investigators and only reliable discharge patterns with physiological variability were considered for the analysis. Throughout the decomposition process duplicate motor units were detected and removed if its crosscorrelation with an existing unit was greater than 0.3.

MUAPs were reconstructed based on spike-triggered averaging of each of the surface EMG channels in the high-density surface array grid. The root mean square (RMS) amplitude of the MUAP was calculated over a 25 ms window within each channel. In order to reduce inter-subject variance, the RMS amplitudes of the reconstructed MUAPs were all normalized to the maximum RMS MUAP amplitude seen during the highest contraction level trials, within each subject.

E. Statistical Analysis

Values are presented as means $\pm$ standard deviation (SD). For all distributions shown, normality was assessed using the Kolmogorov-Smirnov. Kurtosis and skewness were used to quantify the tailedness and asymmetry, respectively, of the distributions. Wilcoxon rank-sum

was performed to compare MUAP RMS values between contraction levels within the SOL and the TA, because data were non-normal. A confidence level of $p < 0.05$ was considered statistically significant.

III. RESULTS

Number of decomposed motor units.

Figure 2 shows firing patterns of motor units during a typical trial. Shown here are 14 units from the TRI with wide range of recruitment thresholds that were collected and decomposed. The black line represents the torque generated by the subject under 20% MVT condition. A total of 730 and 960 motor unit spike trains were decomposed and analyzed for the SOL and TA, respectively. For 10% MVT, 286 and 338 motor unit spike trains were analyzed; for 30% MVT, 253 and 355 motor unit spike trains were analyzed; and for 50% MVT, 191 and 267 motor unit spike trains were analyzed, for the SOL and TA respectively. A total of 445 motor unit spike trains were analyzed for the BIC and 930 for the TRI.

Recruitment threshold.

Figure 3 shows the distributions of %MVT at motor unit recruitment from all four muscles during different %MVT ramps. The average recruitment threshold for 10% MVT per subject is $4.4 \pm 3\%$ MVT for the SOL and $2.7 \pm 3.3\%$ MVT for the TA. The average recruitment threshold for 30% MVT per subject is $16.9 \pm 8.3\%$ MVT for the SOL and $10.2 \pm 10.6\%$ MVT for the TA. Finally, the average recruitment threshold for 50% MVT per subject is $28.5 \pm 12.8\%$ MVT for the SOL and $17.9 \pm 17.6\%$ MVT for the TA. In the upper limb, the average recruitment threshold for the BIC and TRI is $12.6 \pm 4.1\%$ MVT and $10.0 \pm 4.2\%$ MVT respectively, measured at 20% MVT. The skewness and kurtosis for these distributions is showed in Table II.

MUAP Amplitude.

Figure 4 shows the normalized root-mean-squared amplitudes of MUAPs from all four muscles. There is no unit because all the values are normalized. The average MUAP RMS amplitude at 10% MVT for the SOL and TA are 0.35 ± 0.25 and 0.21 ± 0.16 , respectively. The same measurement for 30% MVT is 0.36 ± 0.21 in the SOL and 0.29 ± 0.19 in the TA. For 50% MVT, the average distributions of MUAP RMS amplitude are 0.43 ± 0.20 in the TA and 0.41 ± 0.24 in the SOL. For the muscles in the upper limb, the average distributions of MUAP RMS amplitude is 0.47 ± 0.15 in the BIC and 0.47 ± 0.23 in the TRI at 20% MVT. For the TA and SOL the distribution of MUAP amplitudes is skewed to the right, across all contraction levels and speeds. The median MUAP amplitudes for the SOL are 0.28, 0.33, and 0.39 at 10%, 30%, and 50%. The median MUAP amplitudes for the TA are 0.17, 0.27, and 0.43 at 10%, 30%, and 50%. The median MUAP amplitude for the BIC and TRI are 0.45 and 0.38, respectively. The skewness and kurtosis for these distributions is listed in Table III. In the SOL, there is a significant increase in the median MUAP amplitude between 10% and 50% ($p < 0.001$) and 30% and 50% contraction levels ($p < 0.001$). The median MUAP amplitude for the TA also increases from 10% to 30% ($p < 0.001$), from 10% to 50% ($p < 0.001$), and from 30% to 50% ($p < 0.001$). However, the large sample size and number of degrees of freedom may play a role in the strength of significance seen.

IV. DISCUSSION

By comparing the number of motor units decomposed in various muscles and different effort levels and contraction speeds, this study highlights some of the protocol dependent limitations inherent in the current implementation of high-density surface EMG decomposition. In particular, the action potentials of lower-threshold motor units seem more difficult to discriminate during relatively fast ramp contractions at high contraction levels.

Based on the current understanding of motor unit properties and previous fine wire findings, we would expect that the number of units recruited would be skewed toward lower threshold units for all four muscles [8] [9] [10] [11] [12]. However, as seen in Figure 3 our results show that low threshold motor units can be decomposed well during slower contractions at lower effort levels, but, as the contraction speed and effort level increase the number of low threshold motor units decomposed was reduced. Instead, at higher contraction speeds and torque levels we see broader distributions of recruitment thresholds. Recruitment threshold distributions (Table II) show that except for the TA at 10% MVT, every MVT level for the SOL and TA show broad distribution (Kurtosis < 3.0).

The results in Figure 4 show that surface decomposition produced a wide range of MUAP amplitudes. A larger number of smaller amplitude units were decomposed in the SOL and TA, when compared with the BIC and the TRI, evidenced by skewness to the right (Table III). As muscle contraction level increases, larger units are recruited [7]. Additionally, it has been shown that later recruited units have larger MUAP amplitudes [14] [15]. Our results show that in both the SOL and TA, MUAP amplitudes significantly increase during contractions of higher effort level and speed.

This study shows that surface EMG decomposition is capable of recording a wide range of motor units across multiple muscles, and across several different levels of contraction. These results confirm that although surface EMG decomposition is an improved method to decompose larger number of motor units than more traditional methods such as fine wire electrodes, there are still limitations. These data demonstrate higher contraction speeds and/or intensities will bias the detection towards units with larger MUAP amplitudes. It is possible that interference from the number of motor units active may be playing a large role in preventing the decomposition of as many low threshold units, and previous work has shown that small deep units may not decompose as well [6]. It is also possible that the speed of contraction has affected the decomposition algorithms ability to capture smaller units during high contraction levels. Because the duration of ramps stayed constant for all the contraction levels, the speed of contraction varied from 1% to 5% MVT per second. During high contraction speed, the muscle length changes more rapidly and it has been shown that shortening of muscle length during dynamic contractions changes MUAP shapes, introducing a non-stationarity into the decomposition [2]. These changes can negatively affect decomposition algorithms ability to discriminate motor units. To achieve better stability during high speed contractions, the algorithm can be modified to follow changes in MUAP shapes [16].

In conclusion, surface EMG decomposition is a useful tool to examine large number of motor units simultaneously across varying contraction levels and muscles. The current protocol compares recruitment thresholds and MUAP amplitudes from different contraction levels, but the results cannot be generalized due to varying speed of contraction. However, these results provide evidence that investigators should be aware that protocols involving high contraction speed may limit the capability of decomposition algorithm to discriminate the activity of motor units with smaller MUAP amplitudes. Future work will aim to improving the algorithm to increase the number of units with smaller MUAP amplitudes detected at high contraction levels. Additionally, further experiments will focus on decomposed units collected during varying contraction levels at a fixed, slower contraction speed.

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Fig. 1.

A: Isometric joint torque recording device with high-density surface EMG grids on the biceps brachii and triceps brachii. B: Lower limb isometric joint torque recording device with high-density surface EMG grids on the soleus and tibialis anterior.

Fig. 2.

The firing patterns of 14 motor units decomposed from the triceps of one subject during a single elbow extension trial (color), along with the torque trace (black). For scale, the ticks on the left y-axis are spaced at 50 pps apart.

Fig. 3. Motor unit recruitment thresholds during 10%, 30%, and 50% MVC for soleus (A) and TA (B). Motor unit recruitment thresholds for biceps (C) and triceps (D) during 20% MVC.

Fig. 4. Distribution of MUAP RMS amplitude for the soleus (A), TA (B), biceps (C), and triceps (D) collected during 10%, 30%, and 50% MVC for soleus and TA and 20% for biceps and triceps.

TABLE I**PARTICIPANTS**

Subject	Limb	Age	Gender	Units Decomposed
1	Lower	23	F	SOL: 161 TA: 81
2	Lower	26	M	SOL: 108 TA: 195
3	Lower	31	F	SOL: 130 TA: 57
4	Lower	23	M	SOL: 155 TA: 314
5	Lower	25	M	SOL: 176 TA: 313
6	Upper	33	F	BIC: 42 TRI: 69
7	Upper	27	M	BIC: 120 TRI: 131
8	Upper	25	M	TRI: 252
9	Upper	29	M	BIC: 179 TRI: 253
10	Upper	22	F	BIC: 84 TRI: 105

TABLE II**RECRUITMENT THRESHOLD DISTRIBUTIONS**

Muscle	%MVT	Skewness	Kurtosis
Biceps	20	-0.50	3.3
Triceps	20	-0.02	2.3
Soleus	10	0.41	2.1
	30	-0.21	1.9
	50	-0.26	2.1
TA	10	1.1	3.4
	30	0.44	1.7
	50	0.31	1.6

TABLE III**MUAP RMS AMPLITUDE DISTRIBUTIONS**

Muscle	%MVT	Skewness	Kurtosis
Biceps	20	0.90	4.11
Triceps	20	0.60	2.12
Soleus	10	1.70	6.76
	30	1.91	9.40
	50	0.82	3.26
TA	10	1.14	3.54
	30	1.14	5.18
	50	0.43	2.38