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Changes in Spatial Distribution of Flexor Digitorum Superficialis Muscle Activity is Correlated to Finger's Action

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Abstract—**Multitendoned extrinsic muscles of the human hand can be divided into several neuromuscular compartments (NMCs), each of which contributes to the ability of human finger to produce independent finger movements or force. The aim of this study was to investigate the changes in the spatial activation of flexor digitorum superficialis (FDS) during the fingertip force production with non-invasive multichannel surface electromyography (sEMG) technique. 7 healthy Subjects were instructed to match the target force level for 5s using individual index finger (I), individual middle finger (M) and the combination of the index and middle finger (IM) respectively. Simultaneously, a 2×6 electrode array was employed to record multichannel sEMG from FDS as finger force was produced. The entropy and center of gravity of the sEMG root mean square (RMS) map were computed to assess the spatial inhomogeneity in muscle activation and the change in spatial distribution of EMG amplitude related to the force generation of specific task finger. The results showed that the area and intensity of high amplitude region increased with force production, and the entropy increased with force level under the same task finger. The findings indicate that the change of spatial distribution of multitendoned extrinsic hand muscle activation is correlated to specific biomechanical functions.**

I. INTRODUCTION

Individual finger movements allowing superior manual dexterity are produced by the co-contraction of extrinsic finger muscles and intrinsic hand muscles. Multitendoned extrinsic finger muscles, such as FDS, are anatomical heterogeneity with incompletely discrete neuromuscular compartments (NMCs), which have been discovered in animals [1] as well as in humans [2]-[5]. Knowledge of the NMCs-related activity pattern distributed in multitendoned hand muscles can open a new window to understand movement control of finger movement or force production, which could be potentially used for prosthetics control and neuromuscular rehabilitation evaluation [6].

An advantage of multichannel surface EMG (MCSEMG), compared to the frequently-used intramuscular electromyography, besides its non-invasive recording, lies in acquirement the spatial information of muscle activation during muscle contraction in a large spatial area. This makes the activated motor units located non-invasively on the skin surface possible [7]-[8].

The topographical representation of MCSEMG, especially the RMS topographical map, could be used to investigate the change of spatial activation pattern of motor units within the muscle related to force [8], muscle fatigue [9]-[10], local muscle pain [11], movements [12]-[13], and active biofeedback [14], thus it has been widely used in the research of clinical neurophysiology, rehabilitation and ergonomics. However, to the best of our knowledge, there is no report of using MCSEMG to investigate the relationship of spatial activation of multitendoned finger muscles and finger actions up to now. Therefore, this study utilizes RMS topographical map to quantify the degree of change in the spatial distribution of sEMG amplitude from FDS under different force levels and task fingers.

II. METHODS

A. Subjects

The volunteers had no previous history of neuropathies or any skeletal muscle injury on the upper limbs. There were not strenuous sporting activities in 24 hours before the experiment. The study was approved by ethics committee of Chongqing University. Seven subjects aged between 20 and 27 signed written informed consent forms before their participation in the experiment.

B. Experimental protocol

In order to provide a stable condition for fingertip force production, subjects were required to sit comfortably in a chair and horizontally place his/her right forearm on a shelf with the elbow flexed approximately 120° to the humerus. All fingers except the thumb were positioned on the force transducers (linear operation range 0-196N, JHBM, JinNuo Inc., China) for fingertip force measurement. Then subjects were required to produce press force with task fingertip(s) to match the pre-specified target force line as accurate as possible.

The experiment consisted of three sessions. In the first

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session, the task finger was index finger (I), and the target force levels were specified as 6N, 8N, 10N or 12N, respectively. The target finger used in the second session was the middle finger (M) with the same target force levels as the first session. In the third session, the subjects were asked to produce 8N, 12N or 16N with the combination of index finger and middle finger (IM).

In all trials, the target force followed a trapezoidal pattern which consisted of 0.5s-preparation phase, 1s-ramp phase, 5s-constant phase, and 1s-drop phase. The duration of each trial was 8s and the time interval between two successive trials was 60s to avoid muscle fatigue. For each force level, the subject performed a block of 5 trials. The order of the blocks was randomized across all target force levels. Several practice trials were given before the experiment.

C. Multi-channel sEMG acquisition

Multi-channel sEMG signals were detected in single differential configuration from FDS with a semi-disposable 2D adhesive electrode array configured as a 6 by 2 arrays where 2 columns of 6 electrodes (Chongqing University, Chongqing, China) were evenly distributed along the muscle fiber direction (Fig. 1). The diameter of the electrode was 1.2 mm with a 3 mm inter-electrode distance in both directions. A 0.5 mm thick well was built for each electrode site to improve the quality of sEMG signals.

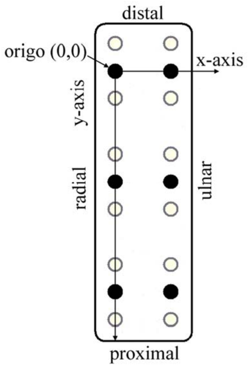

Fig. 1. Construction of the bipolar sEMG recordings with the electrode array, whose inter-electrode distances were 3 mm in both directions. The gray circles indicate the electrode location, and the black-filled circles indicate the virtual location of the constructed signals.

The adhesive electrode array was placed over the skin between the innervations zone and the tendon for sEMG recording, and the reference electrode at the dominant wrist. Bipolar signals were captured in the fiber direction and 6 channel bipolar sEMG signals in total were obtained by a multi-channel physiological recording system (RM6216, Chengdu Instrumentation Inc., China). The sEMG signals were sampled at a rate of 2000 samples per second and filtered with an 8-500Hz band-pass filter. The force signals of the task finger were recorded simultaneously with the sEMG signals and low-pass filtered with a cut-off frequency of 30 Hz.

D. Multi-channel sEMG processing and visualization

The 6-channel sEMG signals were band-pass filtered (elliptic filter, bandwidth 20-500Hz). Then the effective force epoch was specified as the segment containing more than 2048 sample points which were all within ±5% of target force level. The sEMG signals of FDS in 6 channels corresponding to the effective force epochs were extracted for each trial.

For each channel, the extracted sEMG segment was divided into eight sub-segments, each of which was used to calculate root mean square (RMS). Then the mean RMS value of eight sub-segments was calculated to characterize the sEMG amplitude in each channel. For each force level, the mean RMS values of five trials were averaged to reduce random factors existed in the experiments.

For visualization purpose, the RMS values of six channels were interpolated using a cubic spline interpolation. The interpolated values normalized by the maximum RMS value were used to construct the color topographical map with contour lines indicating the variation of myoelectric activities.

To characterize the spatial distribution of muscle activity, five parameters were extracted from the six bipolar signals: RMS averaged over the six channels (RMS_{mean}), the maximum RMS among six channels for each force level (RMS_{max}), the coordinates of the center of gravity of the RMS map (G_x and G_y for the radial-ulnar and distal-proximal directions, respectively) [11], and the entropy of the six RMS values [15].

E. Statistical analysis

Results are presented in the text as mean ± standard deviation and in the figures as mean ± standard error (SE). A wilcoxon matched pair test was applied to compare the two coordinates of the center of gravity for different force levels and task fingers. In all tests, $p<0.05$ was considered significant.

III. RESULTS

Fig. 2 shows the one subject's color RMS topographical maps which illustrate the spatial distribution of RMS values. It can be observed that the RMS topographical maps are unevenly distributed and change with force levels. The area and intensity of the high amplitude region in the topographical maps increased with the finger's force strength. Moreover, the topographical maps are more uniform manifested as the entropy of the maps slightly increased with force (Fig. 3).

The sEMG activity of FDS depends on the task finger. In this study, the sEMG amplitude of FDS for M tended to be larger than that of I and IM (Fig. 2 and Fig. 3). No significant difference was found for G_y of different task fingers ($p>0.05$). There was a tendency that G_x shifted towards the radial direction for I as force production increased, while a shift towards the ulnar direction was seen for G_x of M (Fig. 4).

IV. DISCUSSION

FDS can be divided into four neuromuscular compartments, which are thought to contribute to the ability of human finger to produce independent finger movements or force. Our results showed that the spatial activation of FDS vary with finger's force production and specific task finger(s).

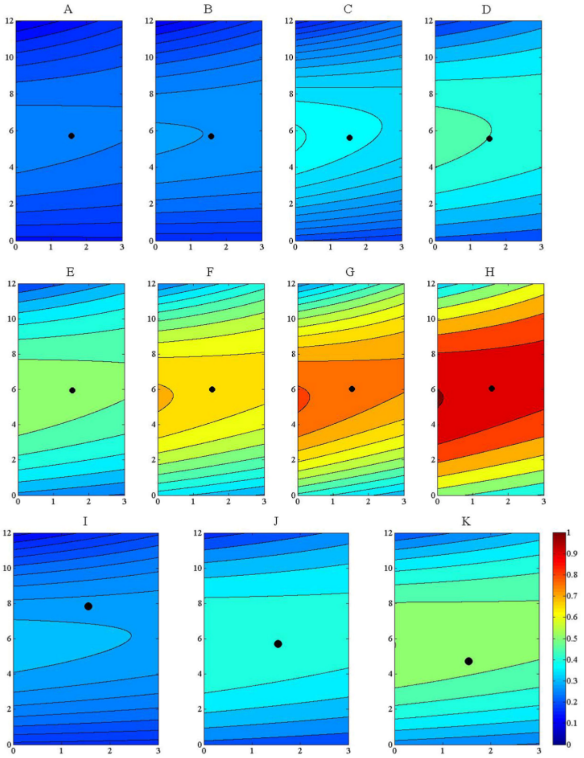

Fig. 2. Color RMS topographical maps for I (A-D) and M (E-H) at force levels of 6N, 8N, 10N, 12N, and IM (I-K) at force levels of 8N, 12N, 16N. The black dot represents the position of the centre of gravity. The color scale is the same for all maps.

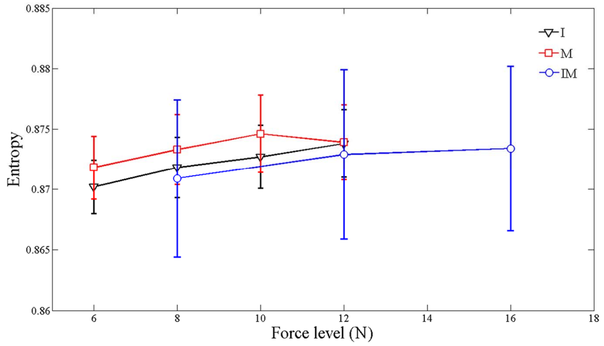

Fig. 3. Mean (±SE) of entropy for (a) I and M, and (b) IM.

Previous investigations involving multitendoned extrinsic finger muscles either from the view of motor unit force [2]-[4] or synaptic input to motor neuron [16]-[17] were commonly accomplished by the recording of the muscle's electrical activity with intramuscular needle EMG electrodes. Although this technique enables one to study the structure and of motor units and functional units in a muscle, the invasiveness and finite recording area hinder broad application for the whole muscle under the strong contraction. Furthermore, the application of conventional sEMG techniques comprising a single bipolar signal only supports the notion of NMCs [18], but couldn't gain a more comprehensive insight into spatial information of NMCs within the whole muscle. The RMS topographical map of MCSEMG, a graphic presentation of the muscle activation patterns in a large spatial area, provides non-invasively more information of anatomical and functional relevance related to force, muscle fatigue and specific task [9], implying the possibility of further understanding of NMCs of the multitendoned extrinsic finger muscles. The spatial distribution of activation motor units within FDS varies with force level of finger and specific task finger, as seen in Fig. 2, , which indicates that this method is reliable and valid, and can be used to investigate spatial distribution pattern of multitendoned hand muscles.

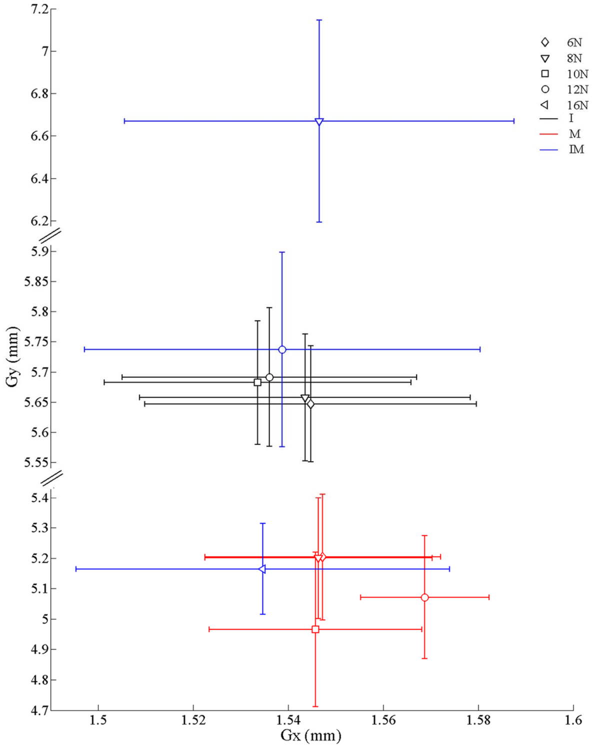

Fig. 4. Mean (±SE) of (a) G_x (b) G_y for I and M, and (c) mean (±SE) of G_x and G_y for IM.

As illustrated in Fig. 2, the spatial distribution of FDS activities has been affected by the force level produced by different task fingers. For muscle isometric contraction, stronger force production accompanied with increased muscle fiber conduction velocity (MFCV) of action potentials and decreased motor unit inter-pulse intervals [9]. Therefore, larger amplitude of sEMG signal will be observed (see Fig. 2). On the other hand, higher force produced by isometric contraction of FDS largely attribute to the increase of motor unit discharge rates and the number of recruited motor units [19]-[20], which resulted in more stochastic interferences in sEMG signals [21] and manifested as the increased entropy in the topographical map of sEMG.

Spatial activation patterns of FDS are impacted by the task fingers. The center of the gravity tends to shift towards radial direction for I, while the shift towards the opposite direction shift was observed for M, indicating the heterogeneity of muscle activation within FDS. These observations in our study is in agreement with previous study which had shown the differentially activated parts within triceps surae muscle related to specific biomechanical functions [22]. Moreover, Falla et al. reported that the neural drive received by the upper trapezius depended on the muscle region [10] which might conform to our hypothesis to some extent. For FDS, anatomical heterogeneity was indeed shown to correspond to its functional heterogeneity by EMG signals [5]. Therefore it might be reasonable to assume that when the motor unit recruitment and the adaption of discharge rate of active motor units within different regions of FDS would be different for different task fingers, which forms the basis for analyzing functional heterogeneity of FDS by using RMS topographical map.

There are some limitations in this study. We assumed that the placement of the electrode array was parallel to muscle fiber direction, thus the shift of the center of gravity in the proximal-distal direction may be negligible compared with the ulnar-radial shift. However, spatial heterogeneity may simply result from the anatomical factor. In this case, the varying of the degree of the anatomical heterogeneity within FDS has to be more considered. Slight misalignment of the electrode array with respect to the fiber orientation could be another reason. However, both the absolute and relative changes were used in this study. Thus, above reasons do not affect the main conclusion of this study. Other factors should be improved in our future study include the use of absolute force levels of FDS contraction, lower electrode density in the radius-ulnar direction, and small number of subjects.

V. CONCLUSION

In this study, we observed that the center of gravity tended to shift with the increment of force level towards regions of the NMCs within FDS serving task finger. These results indicate that changes of sEMG spatial distribution within FDS is related to specific biomechanical functions of finger. Our study demonstrates that the RMS topographical map based on high-density sEMG technique is a reliable and valid method to investigate the spatial muscle activation of the complex multitendoned extrinsic hand muscles.

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