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NEUROMUSCULAR DETERMINANTS OF FORCE COORDINATION DURING MULTIDIGIT GRASPING

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Abstract

The biomechanical structure of the hand and its underlying neurophysiology contribute to the coordination of the kinematics and kinetics necessary for multidigit grasping. We recently examined the neural organization of inputs to different extrinsic finger flexors during multi-digit object hold and found moderate to strong motor unit short-term synchrony. This suggests a common neural input to the motoneurons innervating these different hand muscles/muscle compartments, which may in turn influence the coordination of grip forces.

To further characterize this common input to the hand muscles during multidigit grasping, we used the frequency-based measure of coherence. Motor unit coherence provides information with regards to the oscillatory frequency of a common input, as well as the coupling of the discharges of a motor unit pair at both short and long latencies.

Preliminary results indicate that a large proportion of trials are characterized by significant coherence in the 1–12 Hz frequency range, which is more pronounced in the within- than between-muscle/ muscle compartment analysis. This indicates a differential organization of common oscillatory inputs to pairs of motoneurons innervating the same vs. different muscles/ muscle compartments. The functional role of the 1–12 Hz oscillatory modulation of motor unit behavior is currently being investigated.

Keywords

EMG; grasping; hand

I. INTRODUCTION

The hand is one of the most complex and fascinating biological motor systems due to the large number of muscles and joints. Specifically, many muscles insert on individual digits, some of which cross more than one joint. Furthermore, the long flexor and extensor muscles of the digits insert on all fingers. The result of this complex architecture is that even the performance of a ‘simple’ movement of one digit (*‘individuated’* finger movement) requires complex patterns of muscle activation, as some muscles need to be activated to move only one digit while others are activated to prevent movement at other digits [1]. Furthermore, manual tasks often require fine coordination of motion and forces at multiple digits, i.e., unscrewing a lid or lifting a heavy object. It is clear that the control of such complex structure would require a very sophisticated ‘controller’. Hence, an important question arises: what are the strategies used by the Central Nervous System to effectively coordinate finger motion and forces?

Over the last few decades research on hand function has provided significant insight on the biomechanical and neural factors underlying hand function (for review see [2]). Tasks involving multiple digits such as piano playing [3], typing [4,5], grasping [6–11] and finger spelling [12–13] are characterized by a few and consistent kinematic coordination patterns that

effectively reduce the number of independent degrees of freedom to be controlled. Consistent coordination patterns have also been described in the kinetic domain, where normal forces exerted by pairs of digits tend to be synchronized across a variety of multidigit grasping tasks [for review see 14]. These patterns are the net result of the interaction between hand's biomechanics (see above) and neural factors such as broad coactivation of multiple hand muscles [1], motor units innervating more than one digit compartment of the digit flexors [15] and motor unit synchrony [16]. We focused our attention on the latter, motor unit synchrony, as it represents common input to motoneuron pools of hand muscles. As such, it might be one of several mechanisms capable to generate a synergistic control of finger motion and forces [17]. To better understand the neural control of hand muscles, we have measured synchrony of single motor unit activity of the thumb and finger flexor muscles as subjects held a device against gravity with five digits. We reported [18] moderate to high motor unit synchrony across digit compartments of the m. flexor digitorum profundus (FDP) as well as between the index finger FDP compartment and a thumb flexor muscle, flexor pollicis longus (FPL). To further characterize the organization of common input to hand muscles, we performed additional analysis of hand muscle motor unit activity in the frequency domain. The preliminary results of this analysis are described here.

II. METHODOLOGY

We recorded the normal force exerted by each digit and the electrical activity of single motor units from each of the four divisions of FDP and FPL during the hold phase (4 minutes) of a multidigit grasping task. To assess the natural modulation of motor unit activity and fingertip forces, we imposed no constraint on the amount of force to be exerted or the firing rate of the motor units. Our analysis focused on quantifying motor unit synchrony as an indirect measure of common input to hand muscle motor neurons. Single motor units were discriminated off-line from each channel before quantifying the synchrony between motor unit pairs. The strength of motor unit synchrony has already been quantified in the time domain [18] by the common input strength index (CIS; [19]). Briefly, this index quantifies the number of synchronous events (motor unit action potentials) above chance level within a ± 20 ms time period relative to the reference motor unit.

Here we present the preliminary results of coherence analysis in the frequency domain to determine the extent of common oscillatory modulation of motor unit firing times. After the discrimination of individual motor units, the motor unit data were downsampled to 200 Hz by binning the data into 5-ms segments and assigning a value of 1 if that segment contained a discharge and a 0 if it did not [20]. The mean offset of each data set was removed by subtracting the mean of each 1s segment from the data set [21]. Coherence was calculated based on the cross-spectra (f_{xy}) and auto-spectra (f_{xx} , f_{yy}) estimated from 1.28 s of non-overlapping segments of data resulting in a bin resolution of 0.78 Hz. The coherence, R_{xy} , was estimated from the combined spectra:

$$\left| R_{xy}(\lambda) \right|^2 = \left| f_{xy}(\lambda) \right|^2 / \left(f_{xx}(\lambda) f_{yy}(\lambda) \right) \quad (1)$$

where λ is the frequency at which coherence is computed. The significance of the coherence was computed using the test provided by [22]. The confidence limit for zero coherence at the $\alpha = 0.05$ and for the number of disjoint segments, L (i.e. total trial duration/data segment duration), was:

$$\text{sig}(\alpha) = 1 - (1 - \alpha)^{1/(L - 1)} \quad (2)$$

The hypothesis of non-correlated activity at each frequency is rejected if the estimated coherence at that frequency exceeds this value.

Coherence between motor unit pairs was calculated for each trial. For every trial, each 0.78 Hz bin was assigned a 1 if the coherence surpassed the confidence limit and a zero otherwise. These values were combined across trials and across subjects then divided by the total number of trials to create a histogram of the percentage of significant trials [20,23]. Coherence histograms were computed for motor unit pairs in each of the 10 across digit-pair combinations as well as those within the 5 individual digits. Two summary histograms illustrating the coherence of all the within digit motor unit pairs combined and all the between digit-pairs combined were also computed.

III. RESULTS

Results of the coherence analysis suggests a common oscillatory modulation of motor unit firing rates within the 1–12 Hz frequency range found both between and within the examined hand muscles and muscle compartments. This oscillatory modulation is more evident in motor units from within- than between-muscle/muscle compartments.

Intramuscular EMG was recorded from within the FPL muscle or muscle compartments of the FDP, as well as, between the two muscles (FPL-FDP) or two different compartments of the FDP (see Methods). Fig. 1A shows a typical 10 s recording of raw EMG activity from the FDP2 (index finger) compartment and FPL (thumb) muscle. Single motor units were reliably discriminated from the raw EMG (see Methods) and, as can be seen by Fig. 1B, the discriminated motor units were tonically active and had fairly stable firing rates. The coherence spectrum calculated for this motor unit pair is shown in Fig. 1C.

Within-muscle motor unit coherence

Significant motor unit coherence at a particular frequency indicates the presence of a common oscillatory presynaptic input to the motoneurons occurring at that frequency of oscillation. Fig. 2 shows the incidence of significant coherence for all the motor unit pairs within a muscle or muscle compartment ($n = 123$). There is a greater incidence of significant coherence within the frequency range of 1–12 Hz (59% of the frequency spectrum from 1–50 Hz), while much less coherence is observed at the higher frequency range (i.e. 16–32 Hz, 26%).

Between-muscle motor unit coherence

Fig. 3 shows the incidence of significant coherence for all the motor unit pairs between-muscles or muscle compartments ($n = 237$). Again, there is a greater incidence of significant coherence within the frequency range of 1–12 Hz (43% of the frequency spectrum from 1–50 Hz), while much less coherence is observed at the higher frequency range (20%). In fact, the incidence of significant coherence occurring at frequencies greater than 16 Hz barely surpassed the 5% that may be due to chance (with the exception of 32 Hz at 9%) [23].

A considerably higher incidence of significant coherence is observed in motor units within- compared to between-muscles/muscle compartments. The greatest incidence of coherence occurred at 2 Hz in 73/123 (60%) of the motor unit pairs recorded within- muscle/muscle compartment, and at 1 Hz in 46/237 (20%) for between-muscles/muscle compartments.

IV. DISCUSSION

When holding an object against gravity using a whole hand grasp, firing rates of motor units belonging to the same and different muscles/muscle compartments exhibit significant coherence primarily in the 1–12 Hz frequency range. This suggests that the common neural input to the muscles during multi-digit grasping involves oscillatory modulation of synaptic input. On average, though, the incidence of motor unit coherence between muscles/muscle

compartments is low (up to 20%) as compared to within-muscle motor unit coherence (up to 60%). This indicates that neural input to hand muscles is organized such as to produce oscillatory modulation of common input primarily within – rather than between - hand muscles/ muscle compartments.

In contrast to previous work examining between-muscle motor unit coherence [23], our data reveal only a small incidence of motor unit coherence between-muscles/muscle compartments within the frequency range of 16–32 Hz. This may be related to differences in task (coordination of multiple forces vs. independent force production), methodologies (constrained motor unit firing rate and/or force amplitude vs. our unconstrained task) and/or muscles examined (intrinsic vs. extrinsic hand muscles).

V. CONCLUSION

The neural inputs to extrinsic finger flexors during multi-digit object hold include a 1–12 Hz oscillatory input to pairs of motor units innervating both within and between muscles/muscle compartments. Work in progress is focusing on determining the relative contribution of short-term motor unit synchrony and the oscillatory modulation of motor unit firing times to the coordination of grip forces.

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Fig 1.

Raw EMG signal (A), discriminated units with their firing rates (B), and coherence (C) between the FPL (thumb) and FDP2 (index finger). Horizontal line in the coherence plot indicates the 95% significance level.

Fig 2.
Distribution of significant coherence for all within-muscle/muscle compartment motor unit pairs.

Fig 3.
Distribution of significant coherence for all between-muscle/muscle compartment motor unit pairs.