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Muscle Activation Patterns during Force Generation of the Index Finger

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***Abstract*—The article investigated whether joint postures affect index finger muscle activation patterns. Ten subjects attempted to produce submaximal isometric forces in six orthogonal directions (palmar, dorsal, abduction, adduction, distal and proximal) at each of 9 different joint postures. Activation patterns were recorded from intramuscular electrodes inserted into 6 of the index finger muscles. Post hoc statistical analysis revealed that joint angles significantly affected muscle activation levels for each of the force directions. Activation was especially sensitive to interphalangeal joint angles; changes in these angles led to not only changes in the magnitude of activation but to changes in patterns as well.**

I. Introduction

Understanding activation patterns of hand muscles can inform clinical decision making for the rehabilitation of hand impairment. For example, these patterns can serve as a template for functional electrical stimulation (FES) or can help guide tendon transfer surgeries. Additionally, this knowledge would aid in evaluating impairment mechanisms following neurological injuries, such as stroke.

In previous studies, we have found a postural dependence on index finger muscle moment arms [1]. In this study, our goal is to determine if this postural dependence translates into actual changes in activation patterns. Previous work looking at activation patterns did not explore this potential postural dependence [2, 3]. Potential implications of this research include further refinement of our understanding of hand function and an increase in the accuracy and success of interventions for people with disabilities.

II. Methods and Procedures

A. Subjects

Ten subjects (mean age: 38.1 years, range: 24-50 years) with no known impairment of the hand participated in this study. Subject pool included 9 males and 1 female. The dominant hand was tested in all subjects: one was left hand dominant, nine were right hand dominant. All subjects gave written informed consent to participate in the study, approved by the Institutional Review Board of Northwestern University.

B. Index Fingertip Force Generation and finger muscle activation patterns

Subjects participated in two separate sessions measuring force of the index finger and muscle activation patterns on two separate days.

The wrist and forearm were placed within a fiberglass cast secured to a tabletop with a magnetic clamp [8]. The cast maintained neutral wrist flexion/extension and forearm ulnar/radial deviation, while preventing hand displacement. The tip of the index finger was affixed to a six degree-of-freedom load cell (JR3, Inc., Woodland, CA) through a set of four set screws embedded in casting material placed around the fingertip (Figure 1). The other three fingers were allowed to rest against a post positioned so that contact with the load cell was prevented but a relaxed posture was maintained.

In the first session, subjects were instructed to generate maximal isometric force at the fingertip in each of six orthogonal directions with respect to the distal segment of the finger: dorsal/palmar, distal/proximal, abduction/adduction (Fig. 1). Subjects sustained an isometric force for an average of three seconds during the trial and rested for one minute between trials. This procedure was repeated for nine different joint postures. Three metacarpophalangeal (MCP) angles (0°, 30°, and 60°) were examined at each of three combinations of proximal interphalangeal (PIP) and distal interphalangeal (DIP) joints: {(0°,0°), (30°, 0°), (60°,30°)}.

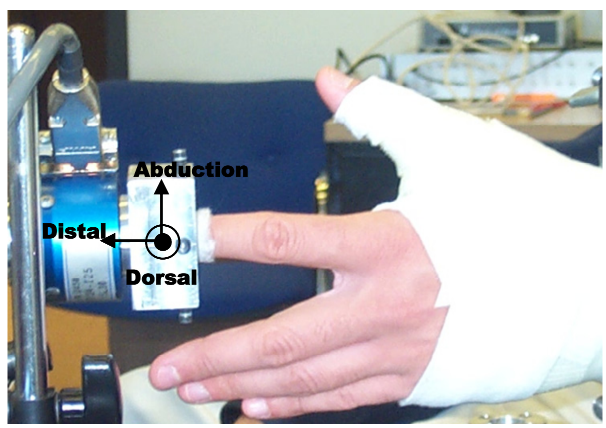

Fig.1. Jig used to connect the tip of the index finger to the load cell for recording force data. The six different force directions are labeled, referenced to the distal finger segment.

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Thus, each subject completed 54 trials (6 directions, 9 joint postures). The force data measured by the load cell were filtered with a 4th-order low-pass Butterworth at 125 Hz, and then sampled at 2 kHz.

In the second session, the subject was asked to generate 25% of maximal force at the fingertip in the same six orthogonal directions, while keeping off-axis forces within ±10% of intended force. Desired and actual force levels were displayed on a computer monitor to provide feedback for the user (Fig. 2). Subjects sustained the isometric force for an average of three seconds during the trial and rested for one minute between trials. Multiple trials were sometimes needed to accomplish the task.

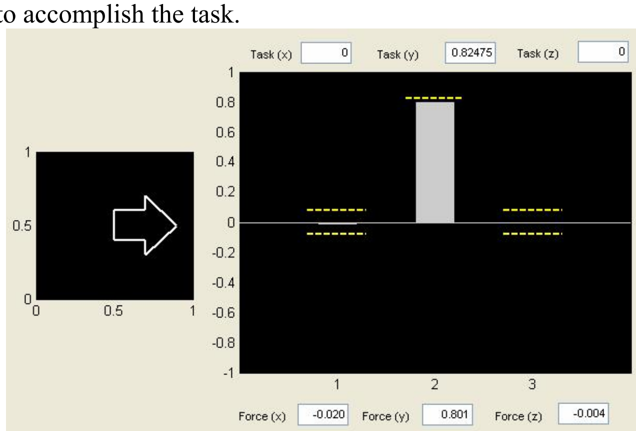


Fig. 2. MATLAB GUI on computer screen instructs subject to generate 25% of their maximum force in the desired direction. Three columns indicate the force magnitude for the x, y and z axes with respect to the distal finger segment. Arrow on the left indicates desired force direction from the subject's perspective.

Electromyographic (EMG) signals were recorded throughout the trials. Fine wire electrodes, consisting of two 55-µm stainless steel intramuscular electrodes threaded through hypodermic needles [6], were inserted into 6 of the 7 muscles of the index finger: first compartment of flexor digitorum profundus (FDP), first compartment of flexor digitorum superficialis (FDS), first palmar interroseous (FPI), first dorsal interrosseous (FDI), first compartment of extensor digitorum communis (EDC), and Extensor Indicus (EI). The lumbrical was not targeted due to its relatively small size and concerns that the associated pain would interfere with task performance. Ultrasound, palpation, and recommendations from the literature were used to guide electrode placement [4-5]. Audial cues were used to guide proper insertion of the fine wire electrodes into each muscle. Electrical stimulation was applied to ensure accurate placement of the electrodes following insertion. EMG signals were sampled at 2 kHz.

In order to scale EMG amplitude with muscle activation, maximum voluntary contractions were performed both at the beginning and end of the experiment at specific postures. Subjects were instructed to produce maximal force in each of the 6 directions.

C. Data analysis

The first session of the experiment was conducted to determine maximum isometric force capacity at the fingertip. Maximum force in the intended direction was determined for each of the 6 directions at each of the 9 postures using a custom MATLAB GUI.

These maximum forces were then used in the second session. Force data collected in the second session were analyzed to find the one-second window during which the force profile was closest to optimal (25% of maximum force in the intended direction and minimal force along the other axes). EMG amplitudes were then computed across these windows.

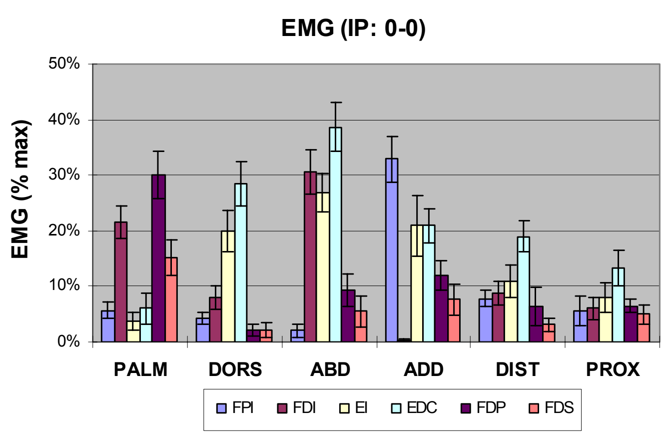
First, raw EMG data were filtered with a high-pass Butterworth filter (cutoff frequency of 80Hz) to reduce the effects of 60 Hz noise. EMG magnitude was estimated by computing the RMS (Root Mean Square) value across the chosen one-second time window. This RMS value was normalized by maximum RMS found during trials of maximum voluntary contraction performed during each session.

These EMG values were analyzed using repeated measures MANOVA with the statistical software SPSS. Force directions (6 levels), Muscles (6 levels), MCP joint angles (3 levels), and interphalangeal (IP) joint postures (3 levels) served as the with-in subject variables. Findings of significance for all of these variables led to subsequent repeated measures ANOVAs run for each direction independently.

III. RESULTS

Results of the multivariate analysis with Wilks' Lambda revealed that muscle activation varied significantly with force direction ($p < 0.001$) and IP posture ($p < 0.001$). Across most directions, there was a significant effect of IP angle on muscle activation. Not only the magnitude of activation changed, but the pattern of activation changed with some muscles increasing activation and others decreasing activation as the IP joints were flexed (see Fig. 3).

a)



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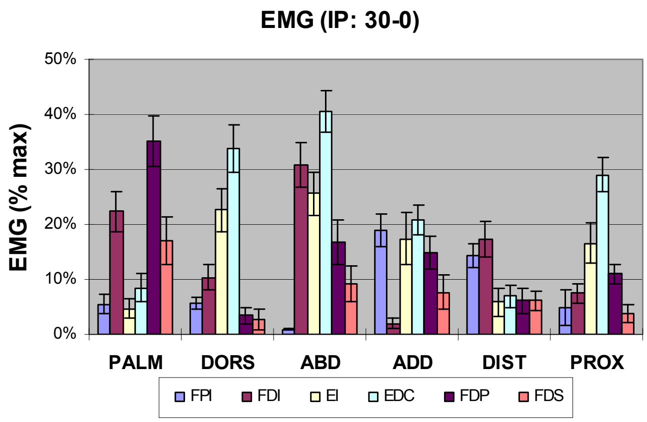

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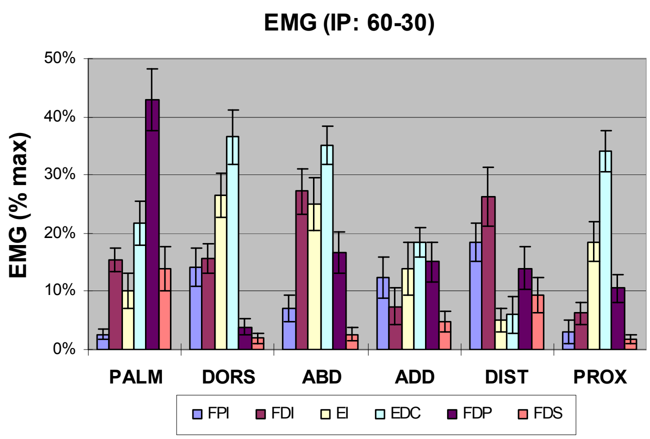


Fig. 3. EMG activation normalized as a percent of maximum voluntary contraction for all force directions. Data shown for each muscle averaged across MCP angles at each IP posture. (a) IP at (0°, 0°), (b) IP at (30°, 0°), (c) IP at (60°,30°). PALM: palmar; DORS: dorsal; ABD: abduction; ADD: adduction; DIST: distal; PROX: proximal

Separate repeated measure ANOVAs were then performed for each direction. For the palmar direction, a significant effect was observed for IP ($p = 0.016$). Interestingly, there was a significant interaction term MUS×IP. At IP 0-0, FDS, FDP, and FDI were primarily active, while at IP 60-30, FDP and EDC had the greatest mean activation. FDP and EDC activations rise from 30% and 6.1%, respectively, at IP 0-0 to 42.9% and 21.8% at IP 60-30. In contrast, FDI and FDS activations slightly decrease (see Fig. 4). The ratio of FDS/FDP decreases from 0.50 to 0.32.

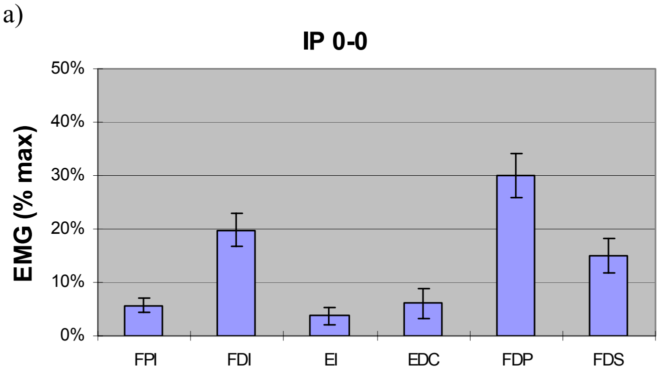
For the dorsal direction, EI and EDC were activated to the greatest extent. EI activity averages 23.1% and EDC activity averages 32.9% across all postures. Mean FDS and FDP activations are less than 4%. There was no significant effect of MCP, MCP×MUS, or MUS×IP, though IP was significant ($p = 0.033$)

In the abduction direction, FDI activation remains fairly constant across postures at 26.8%, but FPI activity increases as the IP joints become increasingly flexed. FPI excitation rises from 2.0% at IP 0-0 to 7.1% at IP 60-30. Thus, the MUS×IP interaction was significant ($p = 0.001$).

In contrast, FPI activation during production of adduction force dropped dramatically as IP flexion increased (32.9%, 18.9%, 12.3%). FDI increased slightly (0.4%, 1.8%, 6.7%) slightly. FPI activation was replaced by that of EI, EDC and FDP, each of which had greater mean activation at IP 60-30 than FPI. Not surprisingly, the MUS×IP interaction had a significant impact on EMG magnitude ($p = 0.001$).

For the distal direction, FPI and FDI are most active for the more flexed IP postures (16.4% and 19.6%, respectively). At the near singularity of IP 0-0, EDC and EI are used to a greater extent, with their activations increasing to 10.9% and 19.0%, respectively, from 5.1% and 6.0% at IP 60-30. Both MUS×IP interaction ($p < 0.001$) and IP ($p = 0.006$) had a significant effect on EMG magnitude.

a)



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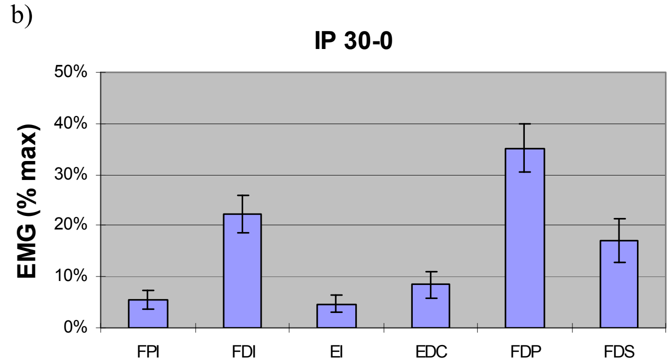

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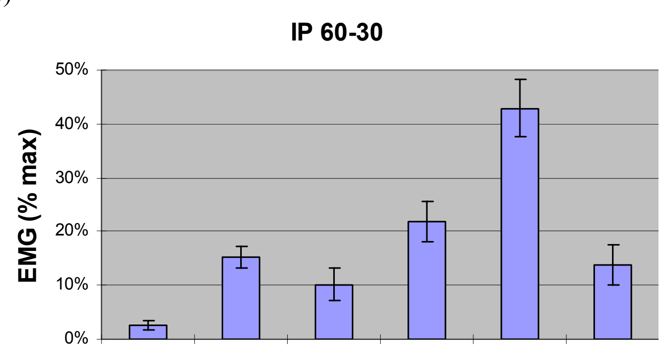

Fig. 4. Normalized EMG activation in the palmar direction, averaged across 10 subjects and 3 MCP angles. (a) IP at (0°, 0°), (b) IP at (30°, 0°), (c) IP at (60°,30°).

In the proximal direction, EI and EDC activations are 8.0% and 13.4% of maximum at the near singularity IP 0-0 but increase to the much higher levels of 16.6% and 29.0% at IP 30-0 and even higher to 18.5% and 34.1% at IP 60-30. FDI, FPI and FDS are activated less than 10%. Both IP ($p = 0.002$) and MUS×IP significantly impact activation.

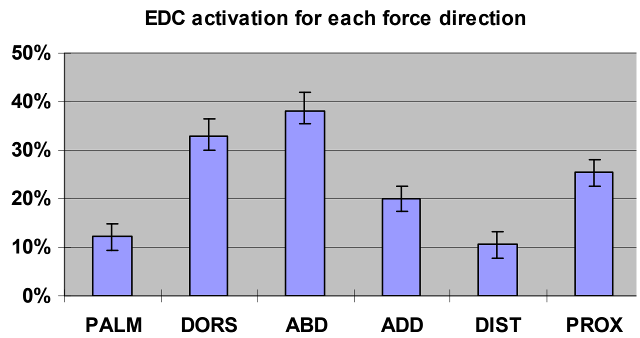

Fig. 5. EDC normalized EMG activation for each direction, averaged across subjects, MCP and IP postures. Columns from left to right are: PALM: palmar; DORS: dorsal; ABD: abduction; ADD: adduction; DIST: distal; PROX: proximal

One especially striking feature was the prevalence of EDC activation (see Fig.5). In the dorsal and abduction directions, EDC was activated 32.9% and 38.1%, respectively. EDC reached its peak RMS value of 42.6% in the abduction direction at a posture with MCP flexed to 30° and PIP and DIP both extended to 0°. EDC was activated least in the distal direction, but still averaged 10.3%. EDC was the only muscle to have a mean activation of greater than 10% for every force direction.

IV. Discussion

Joint posture had a profound impact on muscle activation patterns. This was especially true for the IP angles. In the statistical analyses the interaction terms between muscle and IP posture was significant for a number of the directions, thereby indicating that the IP dependence did not consist of a uniform scaling of EMG amplitude but rather impacted different muscles in different ways.

For example, we observed that during production of a palmar-directed force, activation of FDI decreased with greater IP flexion even as activation of FDP increased. From a biomechanical perspective this seems expedient as FDI flexes the MCP joint while extending PIP and DIP. Thus, with IP at 0-0, FDI would be expected to produce fingertip force in the palmar direction, but at greater IP flexion, such as at IP 60-30, the force from FDI excitation would not be directed in the desired direction.

Some of the variance was dictated by finger geometry. At the edge of the finger workspace (IP 0-0, when the PIP and DIP joints are fully extended), it is difficult to create force in the distal direction, aside from hyperextension of the PIP joint. Thus, EI and EDC activity were relatively high at this posture for the distal force direction (10.9% and 19.0%), but were much lower for fingertip positions in the interior of the workspace. Conversely, EI and EDC excitations at the edge of the workspace were relatively small for producing force in the proximal direction (8.0% and 13.4%), but increased for interior points, such as with IP 60-30 (18.5% and 34.1%).

The ubiquity of substantial EDC activity across directions was an interesting finding which suggests the importance of EDC to force production at the fingertip for many tasks. Hence, the observed impairment of EDC in stroke survivors [6-7] may profoundly affect hand function. This muscle appears to be an especially important target for intervention.

Acknowledgment

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