33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

Quantification of Isolated Muscle Compartment Activity in Extrinsic Finger Muscles for Potential Prosthesis Control Sites

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Abstract—**Prosthetic hands are becoming more advanced and gaining degrees-of-freedom similar to their human counterparts. However, the command interface enabling control of these prostheses needs to be improved for more intuitive functional use. One barrier to using electromyographic (EMG) signals as the command interface is measuring independent muscle control sites in the residual limb. Surface electrodes are commonly used to detect muscle activity in the forearm; however, the measured signals are often comprised of EMG signals from multiple muscles that are close together. This study investigated the suitability of the index and middle finger compartments of the extrinsic muscles as control sites for prostheses using a direct myocontrol interface. Fine-wire intramuscular electrodes were inserted into seven subjects and their ability to achieve isolated activations of each compartment was tested. The results showed five of the six compartments yield signals suitable for independent volitional control. The middle finger compartment of *extensor digitorum communis* was found to be incapable of isolated contractions and is therefore not recommended as a control site for direct myocontrol prostheses. A cross-correlation threshold was used to verify that simultaneously measured EMG signals were free from crosstalk and were therefore attributed to muscle co-activations.**

I. Introduction

EXTERNALLY powered hand prostheses traditionally use direct myoelectric control that uses electromyogram (EMG) signals from residual muscles to command the degrees of freedom (DoF) of the hand [1]. As technology advances, these robotic hands more closely mimic the form and function of human hands [2-5] providing several new DoFs including individual finger movements. However, novel control strategies must also be developed in order to fully utilize the capabilities of these hands.

For persons surviving a trans-radial amputation, extrinsic hand muscles that reside in the forearm provide potential EMG sites for controlling their prosthetic device. Surface EMG electrodes are commonly used to detect the activity of the underlying musculature [6], but because the muscles are small, close together, and sometimes deep within the forearm, these electrodes detect the summation of simultaneous activity from several muscles. The three extrinsic muscles of the fingers each have compartments with a tendon connecting each compartment to a finger. These compartments could provide additional control sites for a prosthetic hand if people are able to control individual compartments.

Anatomical studies have been performed that suggest best electrode placement for the extrinsic muscle compartments [7, 8] using surface EMG electrodes.

Implantable wireless EMG sensors [5, 9] have also been developed and are capable of providing EMG signal measurements from up to 16 muscle sites to a prosthetic device. However, there needs to be a better understanding of the independence of the extrinsic finger muscle compartments before they can be fully utilized as myoelectric control sites for a prosthetic hand.

II. Methods

A. Data Collection

The Institutional Review Board at Northwestern University approved all procedures and the protocol for this study. Seven healthy subjects were recruited for this study and bipolar fine-wire EMG electrodes were inserted into muscles of their right forearm. The muscle compartments associated with the index and middle fingers were targeted in *extensor digitorum communis* (EDC1, EDC2), *flexor digitorum profundus* (FDP1, FDP2), and *flexor digitorum superficialis* (FDS1, FDS2). The subjects were instructed to make appropriate test contractions during electrode insertion and the EMG signal was played through a speaker to locate the desired muscle and compartment. A constant current stimulator (Digitimer Ltd. Model DS7A, Hertfordshire, England) was used to verify electrode placement after insertion was complete.

Muscle activity was measured using a Delsys Bagnoli-16 system (Delsys Inc., Boston, MA) connected to a PC running LabVIEW and sampling at 3,000 Hz (National

Manuscript received March 28, 2011. This work was supported in part by the Daniel F. and Ada L. Rice Foundation, the Department of Veterans Affairs, Rehabilitation Research and Development Service, and is administered through the Jesse Brown VA Medical Center - Lakeside CBOC, Chicago, Illinois, and a Bioengineering Research Partnership (BRP: 1 R01EB01672-01 "Multifunction Prosthesis Control using Implanted Sensors") from the National Institutes of Health - NIBIB and NICHD.

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Instruments Inc., Dallas, TX). A LabVIEW program was written to filter the EMG signals (4th order Butterworth filters to band-pass 30-450 Hz and notch 59-61 Hz), compute the RMS using a 200 msec window, and record the raw and processed data.

B. Experimental Setup

Subjects wore a ball splint once the electrodes locations were verified. The splint served to standardize hand posture for all subjects, allowed for isometric contractions, and minimized confounding motions from the wrist and digits. A maximum voluntary contraction (MVC) was recorded for each muscle compartment as it was contracted to its fullest. Each channel was normalized to its MVC signal in order to establish a reference for the activity level of each muscle compartment. The LabVIEW program displayed six vertical bars that represented the normalized real-time RMS signal for each electrode. The top and bottom of each bar corresponded to the RMS value for MVC and no activity of each muscle, respectively.

Subjects were instructed to activate a single muscle compartment (instructed muscle) to 20% MVC without activating other muscle compartments. The user was presented with a green 'target zone' in each bar. The target activation zone for the instructed muscle compartment was centered at 20%±2.5% MVC and target zones for the non-instructed compartments spanned from 0–5% MVC. This tested the subjects' ability to sustain a controlled level of activity in one compartment while maintaining the others in a non-active state (Figure 1). Subjects were given as much time as they desired to practice each task before data was collected, with most subjects feeling comfortable with their performance after 5-10 minutes. Each trial lasted three seconds and commenced after the subject's targeted muscle activity was in the 20±2.5% MVC green zone. The order of instructed target muscles was randomized for each subject. There were 10 trials for each of the six muscle compartments for a total of 60 trials per subject. Several trails were also recorded at rest for background noise measurements.

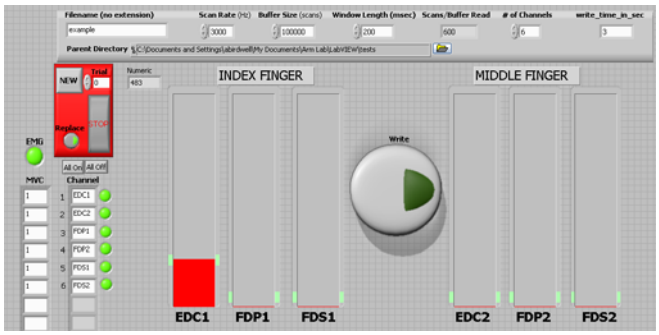

Fig. 1. Experiment display. Six vertical bars represent real-time normalized activity for each muscle compartment. The height of each bar depicts 100% MVC for that muscle compartment and the bottom of the bar is 0% activity. Target zones are shown in green for each channel. One compartment at a time was tested in its ability to sustain isolated activity, and subjects attempted to activate to 20% MVC.

C. Data Processing

Both the raw EMG data and filtered RMS data were recorded during the experiment. The mean noise from each channel was subtracted from the filtered RMS data and the middle two seconds of each trial was used for analysis. The first and last half seconds were removed from each trial to reduce transient activity and filtering artifacts. An ensemble average was calculated for each of the six channels using the 10 trials of each target muscle compartment.

III. Results

A. Co-Activation versus Crosstalk

A cross-correlation analysis was performed on the filtered EMG signals to confirm that measured signals were accurate representations of individual muscle compartment activity and not crosstalk between electrodes. For this analysis, fine-wire intramuscular EMG signals were recorded from EDC1and EDC2, which provided two sites in adjacent compartments of a single muscle, as well as a site in a neighboring muscle, FDP1. Figure 2 shows example activity detected in both FDP1 and EDC1 (top and middle signals, respectively) but minimal activity in EDC2 (bottom signal). Cross-correlation values less than 0.3 suggest that the signals contain little crosstalk [10-13]. The maximum cross-correlation found between any pair of the tested signals was less than 0.1.

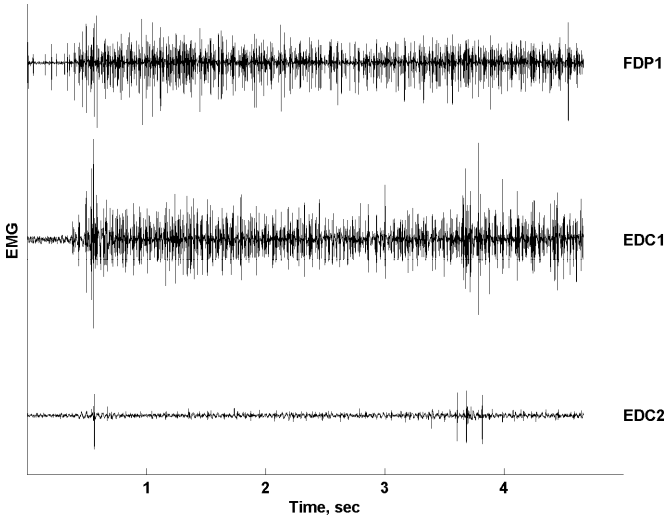

Fig. 2. Example of signals used in the cross correlation analysis. These three signals measured from FDP1, EDC1, and EDC2 (top to bottom) show activity on FDP1 and EDC1 but not EDC2. Cross-correlation values between any two signals were an order of magnitude lower than the 0.4 threshold, showing a lack of crosstalk between the electrodes.

B. Co-Activation Patterns

All six muscle compartments tested were able to achieve and hold the target activation level of 20 ± 2.5% MVC. However, co-activity was frequently observed from the non-targeted muscle compartments. The relative amounts of co-activity varied greatly depending on the subject and the tested muscle compartment. Figure 3 shows an example of a

well-isolated activation of the target muscle, EDC1, (Figure 3A) and an example of a target muscle that was not capable of isolated activity, FDP2 (Figure 3B).

Each graph shows the median and interquartile ranges of normalized activity of the six muscle compartments across all trials for the target muscle (shaded). Each bar represents the activity for a muscle compartment normalized to its MVC value.

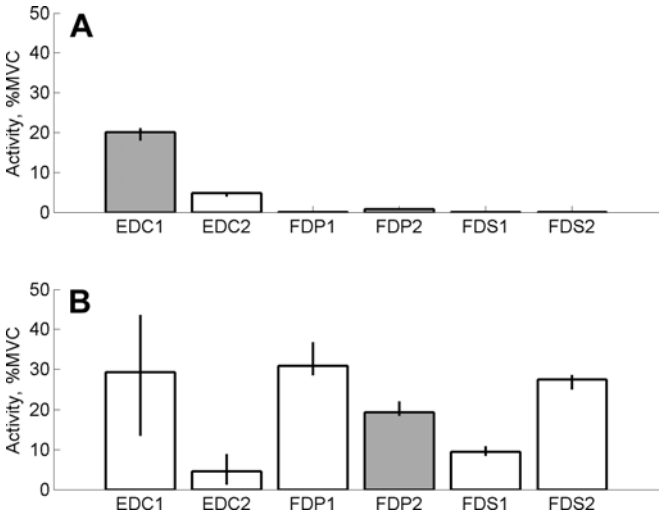

Fig. 3. Examples of a well-isolated (EDC1) and not well-isolated (FDP2) target muscle activations, A and B respectively. The target muscle compartment (shaded) maintained 20% target activity level and even though subjects attempted to minimize all other muscle activity, varying amounts of co-activations were measured. Normalized median activity for each muscle compartment is shown and error bars represent the inter-quartile range.

C. *Relative Mean Activity to Target Muscle*

For direct myocontrol, the relative amount of activity of non-targeted muscles with respect to the target muscle activity is more important than the absolute amount of activation in each muscle. This is because signal thresholds and differential measurements are commonly used by prosthetists to compensate for co-activity when setting up direct myocontrol devices.

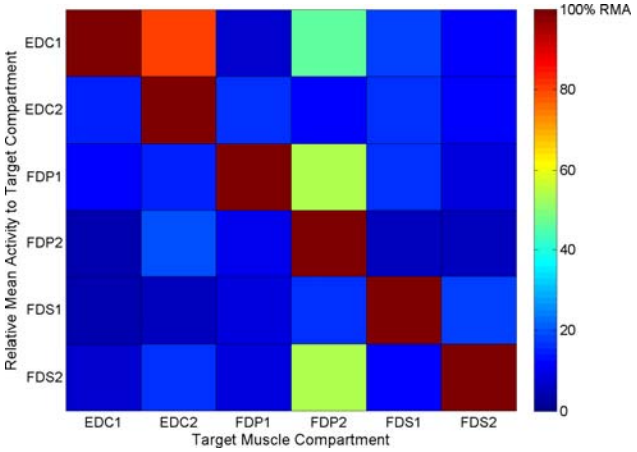

Fig. 4. Relative Mean Activity of each muscle (vertical axis) with respect to the target muscle for that set of trials (horizontal axis). Values are percent of target muscle activity. This figure shows data average across all seven subjects.

The relative mean activity (RMA) was calculated for each muscle in each trial. This was done by dividing the mean activity of each muscle by the mean activity of the target muscle for that trial. Figure 4 shows the RMA of the six muscle compartments (vertical axis) for a given target muscle compartment (horizontal axis). The diagonal displays the RMA of a target muscle with respect to itself, giving a value of 100% (dark red). If a muscle activated completely in isolation then the off-diagonal, non-targeted muscles would be at 0% RMA (blue). EDC2 and FDP2 showed noticeable co-activity when they were the target muscles. When EDC2 was the target muscle (second column from left) there was 85% relative co-activity from EDC1. When FDP2 was the target muscle (fourth column from left) there was roughly 50% relative co-activity seen in EDC1, FDP1, and FDS2.

IV. Discussion

The cross-correlation analysis performed on the data validated that the EMG measurements of each electrode were representative of individual muscle compartments and were not corrupted by signal crosstalk. This was an important distinction to make because electrodes were in adjacent muscle compartments separated by only a few centimeters. Due to the results of this analysis, any simultaneous activity measured during these experiments are believed to be neurological co-activations of muscle compartments and not signal crosstalk between electrodes.

The middle finger extensor compartment, EDC2, was unable to activate without significant co-activity from EDC1 (Figure 4, second column from left, top row). However, when EDC1 was the target muscle, subjects were able to activate it without co-activity from other muscles, specifically EDC2 (Figure 4, left most column, second row). This means that, on average, subjects could extend their index finger alone but when they tried to extend their middle finger they also extended the index finger. **For this reason EDC2 is not recommended as a control site for direct myocontrol of a prosthetic hand.**

Targeted activation of the middle finger compartment of FDP (Figure 4, FDP2 column) resulted in co-activity from the middle finger compartment of FDS and index finger compartments of EDC and FDP (FDS2, EDC1, and FDP1 rows, respectively). The relative mean activity in these muscles was roughly 50%, meaning that their activity was roughly half of that of the target muscle, FDP2. All other muscle compartments were able to activate with minimal co-activity from the other compartments (light and dark blue squares). **If FDP2 were to be a control site for direct myocontrol, thresholds or other customizations would need to be used in order to accommodate for the co-activity from EDC1, FDP1, and FDS2.**

It was interesting to note which muscle compartments co-

activated with EDC2 and FDP2 and not just that there was co-activity. *Extensor digitorum* inserts just distal to the metacarpophalangeal (MCP) joint in the fingers and primarily causes extension in that joint. Extending your fingers against load is not a common task, and it is even less common to extend the middle finger by itself. The index finger is used more frequently by itself so it stands to reason that we observed isolated activations of EDC1 but not of EDC2. Also of note was the large amount of co-activity from EDC1 during attempted isolated activation of EDC2.

Flexor digitorum profundus tendons run across all the joints in the fingers and inserts on the palmar side of the distal phalanx. When subjects attempted to activate this muscle in the middle finger we observed co-activity in the other flexor muscle for that finger (FDS2) as well as an extensor and flexor (EDC1 and FDP1) in the index finger. This implies that while both flexor muscles are working to essentially curl the middle finger, the index finger has "stiffened" by co-activating both a flexor and an extensor.

Regardless of which finger muscles were contracting, this experiment necessitated the use of intramuscular fine-wire electrodes in order to measure those activations. The individual muscle compartments are very small, close together, and reside deep within the forearm. Traditional surface EMG electrodes are not able to separate the activity from individual muscle compartments from that of surrounding musculature. Fine-wire electrodes have a much small detection volume and are therefore ideally suited for this study. However, their small size makes them more sensitive to electrode movement during the experiment. This sensitivity coupled with some discomfort due to the invasiveness of the electrodes caused some recording complications.

Every electrode location was verified with electrical stimulation during electrode placement and at the conclusion of the experiment. If an electrode was found to have moved outside of its muscle compartment during the experiment, the data associated with that electrode was not used in our analysis. This occurred in only four out of 42 electrodes.

V. Conclusion

As stated above, the activations do not need to be completely isolated from one another for the application of using these muscles as potential control inputs for direct myocontrol prostheses. Rather, there needs to be a consistent difference between the activations of the muscle of interest and the other muscles being used as control sites. The index and middle finger compartments of the three extrinsic hand muscles tests could all serve as control sites for myoelectric devices, with the exception of the extensor of the middle finger, EDC2. Each digit would have two command inputs for flexion and both digits would share a common input for extension. This potentially allows each finger to have two degrees of freedom in flexion, which would allow for more functionality and dexterity in a prosthetic hand.

Acknowledgment

The authors would like to acknowledge Todd Kuiken, MD, PhD, for his support and guidance, the subjects who participated in this study, and all the graduate students, post-docs, researchers, and staff who contributed time, effort, encouragement, and advice.

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