Activation of individual extrinsic thumb muscles and compartments of extrinsic finger muscles

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1Center for Bionic Medicine, Rehabilitation Institute of Chicago, Chicago, Illinois; 2Department of Mechanical Engineering, Northwestern University, Evanston, Illinois; 3Department of Physical Medicine and Rehabilitation, Northwestern University, Chicago, Illinois; 4Department of Biomedical Engineering, Northwestern University, Evanston, Illinois; 5Department of Bioengineering, University of Colorado Denver, Aurora, Colorado; and 6Veterans Affairs Eastern Colorado Healthcare System, Denver, Colorado

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Birdwell JA, Hargrove LJ, Kuiken TA, Weir RF. Activation of individual extrinsic thumb muscles and compartments of extrinsic finger muscles. J Neurophysiol 110: 1385–1392, 2013. First published June 26, 2013; doi:10.1152/jn.00748.2012.—Mechanical and neurological couplings exist between musculotendon units of the human hand and digits. Studies have begun to understand how these muscles interact when accomplishing everyday tasks, but there are still unanswered questions regarding the control limitations of individual muscles. Using intramuscular electromyographic (EMG) electrodes, this study examined subjects’ ability to individually initiate and sustain three levels of normalized muscular activity in the index and middle finger muscle compartments of extensor digitorum communis (EDC), flexor digitorum profundus (FDP), and flexor digitorum superficialis (FDS), as well as the extrinsic thumb muscles abductor pollicis longus (APL), extensor pollicis brevis (EPB), extensor pollicis longus (EPL), and flexor pollicis longus (FPL). The index and middle finger compartments each sustained activations with significantly different levels of coactivity from the other finger muscle compartments. The middle finger compartment of EDC was the exception. Only two extrinsic thumb muscles, EPL and FPL, were capable of sustaining individual activations from the other thumb muscles, at all tested activity levels. Activation of APL was achieved at 20 and 30% MVC activity levels with significantly different levels of coactivity. Activation of EPB elicited coactivity levels from EPL and APL that were not significantly different. These results suggest that most finger muscle compartments receive unique motor commands, but of the four thumb muscles, EPL and FPL, were capable of sustaining individual activations while multiple compartments were capable of limited independence from one another. However, it has yet to be conclusively determined if the individual muscle compartments of the multitendon muscles are capable of individual activation while multiple compartments within the same muscle and in other muscles are being observed.

“Force enslavement” describes the inadvertent force generation in adjacent digits that occurs when subjects attempted to generate force in a single digit (Zatsiorsky et al. 1998, 2000; Kibreath and Gandevia 1994, as well as others (Reilly and Hammond 2000; Reilly and Schieber 2003; and Gandevia 2011; van Duinen et al. 2009), have also noted similar effects in adjacent muscle compartments’ activity (spillover recruitment) during single-digit force generation tasks.

Reilly and colleagues found synchronizations between motor unit pairs within and across compartments of the multitendon finger muscle flexor digitorum profundus (FDP) during the central nervous system (CNS). This control mechanism is extremely complex and not yet fully comprehended.

Muscles that control the fingers and thumb reside within both the hand (intrinsic) and the forearm (extrinsic). Three of the extrinsic finger muscles have a compartment and tendon for each of the four fingers. Leijnse and colleagues have identified these individual muscle compartments and potential locations for surface sensors to measure their electromyographic (EMG) activity (Leijnse 1997a; Leijnse et al. 1997, 2008a, 2008b). However, the action of each compartment can have an effect on more than one digit, and the relationship is only partially understood.

Studies of these multitendon muscles have shown that they can be somewhat physically (anatomically) and functionally (able to activate independently) distinct (Keen and Fuglevand 2003, 2004a, 2004b; Kilbreath and Gandevia 1994; Reilly and Schieber 2003; Schieber 1995). Furthermore, independent digit motions are possible (Hager-Ross and Schieber 2000; Lang and Schieber 2004) despite being inhibited by mechanical connections between the tendons and fascia of the hand and finger muscles (Leijnse 1997b; Malerich et al. 1987; Vonschoorod et al. 1990). Butler et al. (2005) examined single-motor unit activity in the compartments of the flexor digitorum superficialis (FDS) muscle during single-digit flexion and stated that “FDS components can be selectively activated by volition” at higher activation levels (~50% MVC). In another study looking solely at the extensor digitorum communis (EDC) muscle, van Duinen et al. (2009) found that its compartments were capable of limited independence from one another. However, it has yet to be conclusively determined if the individual muscle compartments of the multitendon muscles are capable of individual activation while multiple compartments within the same muscle and in other muscles are being observed.

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The subjects’ ability to initiate and sustain muscle activity in a single muscle, or muscle compartment, was quantified at three normalized activity levels to evaluate subjects’ ability to maintain activation across a range of activity levels.

Methods. Intramuscular EMG electrodes were inserted into six finger muscle compartments, the first two compartments (associated with the index and middle fingers, respectively) of the extrinsic finger muscles of the right forearm: extensor digitorum communis of fingers 1 and 2 (EDC1, EDC2), flexor digitorum profundus of fingers 1 and 2 (FDP1, FDP2), and flexor digitorum superficialis of fingers 1 and 2 (FDS1, FDS2). In a separate experiment, intramuscular electrodes were inserted into the four thumb muscles of the right forearm: the abductor pollicis longus (APL), extensor pollicis brevis (EPB), extensor pollicis longus (EPL), and flexor pollicis longus (FPL).

Electrode insertion and verification of their locations followed standard intramuscular electrode insertion techniques. Briefly, the tips of the two fine wires were de-insulated and folded back to provide stability within the muscle. Muscles were located by palpation and ultrasound. A bipolar fine-wire electrode was inserted into the muscle of interest using a 27-gauge hypodermic needle. EMG activity was observed on a monitor and played through a loudspeaker. Electrode location was verified by applying just enough current to cause a brief muscle contraction using a constant-current stimulator (Digitimer model DS7A; Welwyn Garden City, UK); the resulting motion of the digit confirmed proper electrode location. Each electrode initiated with 0.5 mA of current and was raised in small increments until a muscle contraction was observed. Each electrode site required a different amount of current, but this procedure ensured that the minimum amount of current was used to cause each muscle contraction. The needle was withdrawn, leaving the wire electrodes in place. Implanted wires were then shortened to the minimum length necessary for connection to the data acquisition system and were taped to the skin to minimize motion noise. After electrode insertion, subjects donned a hand splint to standardize hand posture, allow for isometric contractions, and minimize confounding motions from the wrist and digits.

EMG signals were measured using a Delsys Bagnoli-16 system (Delsys, Boston, MA) connected to a personal computer running LabVIEW software (National Instruments, Dallas, TX) and sampling at 3,000 Hz. The Delsys system has hardware bandpass filters set at 20–450 Hz. LabVIEW filtered the EMG signals (4th-order Butterworth filters to bandpass 20–450 Hz and notch 59–61 Hz), computed the root mean square (RMS) using a 200-ms window, recorded both the raw and processed data, and provided real-time visual feedback of muscle activity to subjects.

A maximum voluntary contraction (MVC) was recorded for each muscle or muscle compartment, and each channel was normalized by the associated MVC signal. Red vertical bars, which represent the normalized real-time RMS signal for each muscle, moved up or down during the experiment as subjects modulated their EMG activity. The top and bottom of each bar corresponded to the RMS value for the MVC and no activity for each muscle, respectively. For each trial, the subject was instructed to activate one specific muscle or compartment (the “intended” muscle) and sustain this activity for 3 s at one of three target activity levels: 10, 20, or 30% of MVC. Subjects were instructed to activate the intended muscle to the target level without activating other (“nonintended”) muscles or compartments. The “target zone” was marked in green on the sides of each bar. Target zones had a width of 5% MVC and were centered at the target level for the intended muscle. Target zones for the nonintended muscles and muscle compartments ranged from 0 to 5% MVC.

Subjects were given as much time as they desired to practice each task before data were collected; most subjects felt comfortable with their level of control after 5–10 min. Each trial lasted 3 s and commenced after the subject’s intended muscle activity was in the target zone. The order of muscles tested was randomized for each
subject, and the target activity level order was randomized for each muscle. Subjects completed 10 trials for each muscle at each of the 3 target levels before moving to the next target activity level, thus completing a total of 30 trials for each muscle. Several trials were also recorded at rest to provide background noise measurements.

Data postprocessing and analysis. Both the raw EMG data and filtered RMS data, representing muscle activities, were recorded during the experiment, but only the filtered RMS signals were displayed to the subjects for real-time feedback. The mean noise from each channel was subtracted from the filtered RMS signals to prepare the data for analysis after the experiments were completed. To reduce transient activity and filtering artifacts, 0.5 s was removed from the beginning and end of each trial. The remaining 2 s of data for each trial were extracted and averaged before further analysis. Ensemble averages were also compiled across all 10 trials for each target condition.

We wanted to determine which muscles would be suitable for use with dual-differential myoelectric control (Williams 1990). SPSS statistical software (IBM, Armonk, NY) was used to test the difference between the mean activities of the intended muscle and nonintended muscles at each target level. This is a constraint imposed by using dual-differential myoelectric control. A linear mixed-effects model was used for this analysis, and Bonferroni correction was used to account for the multiple pairwise comparisons. The null hypothesis stated that there was no difference between mean activity levels of the intended muscle and another muscle. The null hypothesis was rejected when there was a statistically significant difference between mean activity levels at the $P = 0.05$ level. Statistically, the test only measured for a difference between the two activity levels, regardless of whether the difference was positive or negative. In all instances when there was a statistical difference, the intended muscle’s activity was larger than the nonintended muscle’s and could be assumed to be viable to control a prosthetic device.

RESULTS

Experiments were conducted to test subjects’ ability to generate and sustain individual contractions in index and middle finger compartments of three extrinsic finger muscles (EDC, FDP, and FDS) and each of the four extrinsic thumb muscles (APL, EPB, EPL, and FPL). Subjects were able to achieve and hold the target activation levels of 10, 20, and 30% in all intended muscles and muscle compartments. However, coactivity was frequently observed in nonintended muscles or muscle compartments despite subjects’ attempts to minimize all nonintended muscle activity. The relative amount of coactivity observed varied depending on the subject and on the intended muscle or muscle compartment. Figure 1 shows EMG activity from the six finger muscles during an example trial (columns) for each intended muscle (black) along with coactivity from nonintended muscles (gray).

Fig. 1. Columns represent an example trial showing electromyographic (EMG) signals from each tested finger muscle. Rows represent EMG from a particular muscle. Black traces represent the activity of the intended muscle during that trial, and gray traces represent EMG activity from nonintended muscles.
Activation of extrinsic finger muscles. Figure 2A presents an example of individual activation of an intended muscle and an example of intended muscle activity with high levels of coactivity from nonintended muscles. The data in Fig. 2 represent the mean finger muscle activity for each muscle compartment, measured when either EDC1 (A) or EDC2 (B) was the intended muscle compartment. Each bar represents the activity of the muscle compartment averaged across all trials and all 7 subjects for each target activity level (10, 20, or 30% MVC).

Figure 2A shows the data for the index finger extensor, EDC1, as the intended muscle (red bars). Subjects were able to consistently sustain the 10, 20, or 30% MVC target activity levels while minimizing coactivity from the other muscle compartments. The mean activity of EDC1 was statistically different \( (P < 0.05) \) from the mean activity of the other muscles at each target level.

Figure 2B shows the data for the middle finger extensor, EDC2, as the intended muscle (blue bars). EDC2 was capable of sustaining target activity levels at the 10, 20, and 30% MVC ranges, but there was substantial coactivity from the index finger extensor, EDC1 (red bars) at each target level such that activity of the EDC2 muscle compartment was not statistically different from the EDC1 activity at any target level \( (P > 0.05) \). However, coactivity from the flexor muscles FDP and FDS were found to be significantly different \( (P < 0.05) \).

Table 1 shows mean activity and standard deviation for each finger muscle compartment. Data were averaged across trials and subjects for each combination of intended muscle compartment and target activity level. Mean activities of intended muscles are bold along the diagonal. Highlighted values indicate nonintended muscle activity that was not statistically different from that of the intended muscle compartment. Activity of EDC1 was not statistically different from the activity of EDC2 during trials when EDC2 was the intended muscle. This demonstrates that subjects were unable to individually activate only the EDC2 compartment. However, subjects were able to individually activate the EDC1 compartment by itself (first 3 rows). Please note that subjects were instructed to maintain all nonintended muscle activities at “rest” (within the 0–5% MVC range).

Activation of extrinsic thumb muscles. Four thumb muscles were tested for their ability to individually activate. Table 2 shows a summary of mean activity and standard deviation for each thumb muscle when each was the intended muscle, at the three target activity levels (10, 20, or 30% MVC). Mean activities of intended muscles are bold along the diagonal. Nonintended muscle activity that did not show a significant difference from intended muscle activity is highlighted.

Only the flexor and extensor muscles of the distal joint, FPL and EPL, were found to be capable of activating with a significant difference from coactivity from other muscles, at all three tested target levels. When the abductor muscle, APL, was the intended muscle, the coactivities from the EPL and FPL muscles were significantly different \( (P < 0.05) \) at the 20 and 30% MVC target levels, but not at the 10% MVC target level. Intended APL mean activity was not found to be significantly different from coactivity from the EPB muscle at any target level. Intended EPB mean activity was significantly different from the coactivity of FPL at all target levels.

DISCUSSION

Muscle coactivity, not muscle cross talk, was determined. The cross-correlation analysis performed on preliminary data (Birdwell et al. 2011) verified that the EMG measurements from each electrode were representative of individual muscles and muscle compartments and were not corrupted by muscle cross talk. This analysis determined that the correlation coefficient between any pair of muscle activity signals was <0.1. Previous work has shown that values lower than 0.3 represent signals that are not contaminated with muscle cross talk (Andreasen and Rosenfalck 1978; Brochier et al. 2004; Hargrove et al. 2007; Overduin et al. 2008). These preliminary findings confirmed that electrodes within the muscle compartments of interest to this study were capable of measuring individual compartment activity. In addition to this preliminary analysis, auditory and visual EMG examination was performed and electrical stimulation was conducted for each electrode to verify electrode placement and the absence of muscle cross...
talk. These steps were similar to those described by van Duinen et al. (2009) to verify satisfactory electrode placements. This was an important finding because electrodes were in adjacent muscle compartments. Consequently, any simultaneous activities measured during the current experiments are likely due to neurologically based coactivation of muscles and muscle compartments and not due to muscle cross talk between EMG sensors. No conclusions are drawn from these results about the effects of mechanical coupling between muscles, tendons, or compartments because the hand splint inhibited any motions and no forces were measured during these experiments.

Neural drive of extrinsic finger muscles. Four of the six finger muscle compartments tested could be activated with minimal coactivity from other compartments. The muscle compartments EDC2 and FDP2 were not capable of activating without large amounts of coactivity from other finger muscle compartments. Subjects were unable to individually activate the middle finger extensor compartment, EDC2. Intentional activation of EDC2 elicited coactivity from EDC1 that was not significantly different. However, when EDC1 was the intended muscle, subjects were able to individually activate it, meaning that there was a significant difference from any coactivity from other muscles, including EDC2. This limited control of individual EDC compartments is similar to findings presented by other studies looking at individual finger extension tasks while monitoring activity of EDC compartments (van Duinen et al. 2009).

Activation of the middle finger compartment of the FDP muscle (FDP2) resulted in substantial levels of coactivity from

### Table 1. Mean finger muscle activity

<table>
<thead>
<tr>
<th>Intended Muscle</th>
<th>Target Activity Level</th>
<th>EDC1</th>
<th>EDC2</th>
<th>FDP1</th>
<th>FDP2</th>
<th>FDS1</th>
<th>FDS2</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDC1</td>
<td>10% MVC</td>
<td>14.15 ± 3.76</td>
<td>2.39 ± 2.10</td>
<td>1.94 ± 2.33</td>
<td>1.02 ± 1.89</td>
<td>0.01 ± 1.13</td>
<td>0.71 ± 0.87</td>
</tr>
<tr>
<td>EDC1</td>
<td>20% MVC</td>
<td>21.86 ± 3.74</td>
<td>3.12 ± 2.17</td>
<td>2.69 ± 2.98</td>
<td>0.90 ± 1.43</td>
<td>0.33 ± 1.46</td>
<td>1.34 ± 2.35</td>
</tr>
<tr>
<td>EDC1</td>
<td>30% MVC</td>
<td>29.44 ± 5.21</td>
<td>6.32 ± 4.02</td>
<td>4.24 ± 4.97</td>
<td>1.31 ± 1.77</td>
<td>0.75 ± 2.50</td>
<td>2.85 ± 4.25</td>
</tr>
<tr>
<td>EDC2</td>
<td>10% MVC</td>
<td>7.92 ± 9.87</td>
<td>11.82 ± 2.87</td>
<td>0.88 ± 0.91</td>
<td>1.01 ± 1.63</td>
<td>0.30 ± 1.11</td>
<td>0.60 ± 1.37</td>
</tr>
<tr>
<td>EDC2</td>
<td>20% MVC</td>
<td>16.39 ± 2.165</td>
<td>20.20 ± 2.78</td>
<td>2.96 ± 2.85</td>
<td>3.46 ± 5.04</td>
<td>0.70 ± 2.05</td>
<td>3.17 ± 4.20</td>
</tr>
<tr>
<td>EDC2</td>
<td>30% MVC</td>
<td>22.18 ± 25.65</td>
<td>29.64 ± 2.93</td>
<td>5.13 ± 3.87</td>
<td>2.54 ± 4.35</td>
<td>1.01 ± 2.18</td>
<td>2.77 ± 5.28</td>
</tr>
<tr>
<td>FDP1</td>
<td>10% MVC</td>
<td>0.82 ± 1.23</td>
<td>2.02 ± 2.54</td>
<td>10.72 ± 2.44</td>
<td>1.15 ± 1.97</td>
<td>1.66 ± 2.77</td>
<td>1.21 ± 1.32</td>
</tr>
<tr>
<td>FDP1</td>
<td>20% MVC</td>
<td>1.06 ± 2.81</td>
<td>3.08 ± 3.93</td>
<td>19.23 ± 2.75</td>
<td>1.55 ± 2.93</td>
<td>1.52 ± 2.11</td>
<td>1.69 ± 1.47</td>
</tr>
<tr>
<td>FDP1</td>
<td>30% MVC</td>
<td>6.57 ± 11.20</td>
<td>6.88 ± 5.43</td>
<td>28.47 ± 2.91</td>
<td>1.97 ± 2.94</td>
<td>2.99 ± 3.61</td>
<td>1.88 ± 1.93</td>
</tr>
<tr>
<td>FDP2</td>
<td>10% MVC</td>
<td>2.76 ± 3.89</td>
<td>1.41 ± 2.80</td>
<td>6.09 ± 8.14</td>
<td>9.04 ± 5.25</td>
<td>1.32 ± 2.54</td>
<td>6.39 ± 4.87</td>
</tr>
<tr>
<td>FDP2</td>
<td>20% MVC</td>
<td>7.46 ± 11.39</td>
<td>4.13 ± 5.85</td>
<td>10.78 ± 11.49</td>
<td>16.25 ± 7.72</td>
<td>2.87 ± 3.93</td>
<td>11.27 ± 8.51</td>
</tr>
<tr>
<td>FDP2</td>
<td>30% MVC</td>
<td>8.30 ± 9.09</td>
<td>5.55 ± 8.23</td>
<td>19.27 ± 14.81</td>
<td>24.47 ± 11.11</td>
<td>4.74 ± 5.62</td>
<td>15.07 ± 10.02</td>
</tr>
<tr>
<td>FDS1</td>
<td>10% MVC</td>
<td>1.48 ± 3.46</td>
<td>1.49 ± 2.74</td>
<td>1.55 ± 2.90</td>
<td>0.47 ± 2.03</td>
<td>7.94 ± 5.74</td>
<td>1.96 ± 3.65</td>
</tr>
<tr>
<td>FDS1</td>
<td>20% MVC</td>
<td>3.15 ± 5.07</td>
<td>5.08 ± 5.58</td>
<td>4.43 ± 4.71</td>
<td>1.23 ± 2.93</td>
<td>14.86 ± 8.76</td>
<td>2.86 ± 2.71</td>
</tr>
<tr>
<td>FDS1</td>
<td>30% MVC</td>
<td>7.14 ± 12.33</td>
<td>9.06 ± 5.85</td>
<td>7.98 ± 6.96</td>
<td>2.02 ± 3.74</td>
<td>23.37 ± 15.59</td>
<td>5.55 ± 4.86</td>
</tr>
<tr>
<td>FDS2</td>
<td>10% MVC</td>
<td>1.34 ± 2.23</td>
<td>0.45 ± 1.52</td>
<td>1.12 ± 0.78</td>
<td>0.87 ± 1.34</td>
<td>2.42 ± 3.25</td>
<td>11.73 ± 1.84</td>
</tr>
<tr>
<td>FDS2</td>
<td>20% MVC</td>
<td>2.33 ± 3.00</td>
<td>2.15 ± 3.56</td>
<td>1.73 ± 1.03</td>
<td>0.84 ± 1.27</td>
<td>3.71 ± 4.13</td>
<td>21.77 ± 2.05</td>
</tr>
<tr>
<td>FDS2</td>
<td>30% MVC</td>
<td>4.26 ± 4.86</td>
<td>2.78 ± 4.02</td>
<td>3.07 ± 2.12</td>
<td>1.29 ± 1.69</td>
<td>4.82 ± 5.39</td>
<td>30.74 ± 2.61</td>
</tr>
</tbody>
</table>

Values are mean muscle activity (± SD) for each finger muscle and compartment (columns). Each row represents the data for an intended muscle at the specified target activity level. Intended muscle activity values are bold along the diagonal. Values in italics represent nonintended muscle activity that was not statistically different from the intended muscle’s activity.

### Table 2. Mean thumb muscle activity

<table>
<thead>
<tr>
<th>Intended Muscle</th>
<th>Target Activity Level</th>
<th>APL</th>
<th>EPB</th>
<th>EPL</th>
<th>FPL</th>
</tr>
</thead>
<tbody>
<tr>
<td>APL</td>
<td>10% MVC</td>
<td>10.59 ± 2.31</td>
<td>8.40 ± 5.62</td>
<td>7.64 ± 5.94</td>
<td>12.41 ± 24.47</td>
</tr>
<tr>
<td>APL</td>
<td>20% MVC</td>
<td>20.44 ± 2.55</td>
<td>18.34 ± 17.44</td>
<td>10.37 ± 12.27</td>
<td>8.54 ± 16.55</td>
</tr>
<tr>
<td>APL</td>
<td>30% MVC</td>
<td>29.05 ± 1.89</td>
<td>25.11 ± 21.60</td>
<td>20.96 ± 21.93</td>
<td>17.13 ± 37.40</td>
</tr>
<tr>
<td>EPB</td>
<td>10% MVC</td>
<td>8.71 ± 6.54</td>
<td>9.80 ± 2.78</td>
<td>8.60 ± 7.55</td>
<td>3.06 ± 3.35</td>
</tr>
<tr>
<td>EPB</td>
<td>20% MVC</td>
<td>16.55 ± 8.53</td>
<td>19.26 ± 3.85</td>
<td>18.36 ± 12.04</td>
<td>2.93 ± 3.19</td>
</tr>
<tr>
<td>EPB</td>
<td>30% MVC</td>
<td>25.32 ± 9.68</td>
<td>27.74 ± 2.10</td>
<td>24.50 ± 14.97</td>
<td>6.95 ± 7.38</td>
</tr>
<tr>
<td>EPL</td>
<td>10% MVC</td>
<td>2.85 ± 3.52</td>
<td>2.98 ± 2.36</td>
<td>9.35 ± 2.52</td>
<td>0.24 ± 0.63</td>
</tr>
<tr>
<td>EPL</td>
<td>20% MVC</td>
<td>8.84 ± 4.57</td>
<td>9.02 ± 2.90</td>
<td>18.60 ± 1.81</td>
<td>0.77 ± 1.39</td>
</tr>
<tr>
<td>EPL</td>
<td>30% MVC</td>
<td>10.88 ± 6.11</td>
<td>13.18 ± 4.87</td>
<td>28.48 ± 3.03</td>
<td>2.61 ± 8.91</td>
</tr>
<tr>
<td>FPL</td>
<td>10% MVC</td>
<td>0.87 ± 1.07</td>
<td>1.24 ± 1.88</td>
<td>1.44 ± 1.13</td>
<td>8.85 ± 2.13</td>
</tr>
<tr>
<td>FPL</td>
<td>20% MVC</td>
<td>2.58 ± 2.85</td>
<td>1.59 ± 1.54</td>
<td>3.95 ± 3.39</td>
<td>18.35 ± 2.18</td>
</tr>
<tr>
<td>FPL</td>
<td>30% MVC</td>
<td>4.20 ± 5.70</td>
<td>5.09 ± 6.49</td>
<td>5.96 ± 5.58</td>
<td>28.13 ± 2.31</td>
</tr>
</tbody>
</table>

Values are mean muscle activity (± SD) for each intended thumb muscle (rows). Each row represents the data for an intended muscle at the specified target activity level. The intended muscle activity values are bold along the diagonal. Values in italics represent nonintended muscle activity that was not statistically different from the intended muscle’s activity.
the middle finger compartment of FDS and index finger compartments of EDC and FDP (see Table 1: FDS2, EDC1, and FDP1 columns when FDP2 was the intended muscle). However, FDP2 activity was statistically different \( (P < 0.05) \) from the activity of each of the other muscles and compartments. Reilly and Schieber (2003) suggested that the human FDP muscle has “incomplete functional subdivision” of its compartments because they observed coactivity in nonintended finger compartments during single-finger flexion tasks. Findings presented here agree with those from Reilly and Schieber, except that the index finger compartment of FDP is much closer to being “functionally distinct” than the middle finger compartment.

The FDS compartments for the index and middle finger each activated without large coactivation from the adjacent compartment of FDS or from compartments from the EDC and FDP muscles. These findings bolster those found by other researchers regarding FDS (Butler et al. 2005) and provide new insights on the simultaneous activity of other extrinsic finger muscles (EDC and FDP). Previous studies have examined extrinsic muscle compartment activity of a single muscle during single-digit motions, single-digit force generation, or grasping tasks, but they only observed the activity of compartments within a single muscle (e.g., FDP), whereas the present work simultaneously examines multiple compartments in multiple muscles.

**Coordinated activity patterns in finger muscles.** FDP tendons run across all the joints in the fingers and insert on the palmar side of the distal phalanx. When subjects attempted to activate the FDP muscle of the middle finger, we observed coactivity in the other flexor muscle for that finger (FDS2) as well as extensor and flexor activity in the index finger (EDC1 and FDP1, respectively). This implies that while both flexor muscles are working to essentially curl the middle finger, the index finger is “stiffened” by coactivity of both a flexor and an extensor. We observed in several subjects that an adjacent finger would stiffen or activate muscles to move in the opposite direction to the intended activity. For example, if subjects tried to extend the middle finger, adjacent fingers would either stiffen or flex. This opposing motion may act as an assistive strategy, i.e., “pushing down” with some fingers assists with “pulling up” of another. This phenomenon is similar to that observed by Reilly and Schieber (2003). This coordination pattern could be an inherent method to stabilize the hand or maximize force generation in the intended digit. However, the goal of this study was to attempt to isolate activations, and no force information was measured or relayed to the subjects during the experiments.

It was interesting to note which muscle compartments coactivated with EDC2. Extensor digitorum inserts just distal to the metacarpophalangeal (MCP) joint in the fingers and primarily extends that joint. Extending fingers against load is not a common task, and it is even less common to extend the middle finger alone; however, the index finger is frequently used by itself. Furthermore, the index finger has additional extrinsic muscles that assist it in extension, such as extensor indicis. This supports the individual activations of EDC1, but not EDC2, observed in this study. Furthermore, these findings support those found by van Duinen et al. (2009), who measured EDC compartment activity and observed that individual finger extension tasks resulted in the recruitment of motor units in the intended and nonintended compartments.

Activity from each intended muscle induced some level of coactivity in other examined muscles. It is apparent from looking at the patterns of coactivity during the 10, 20, and 30% target levels, for any given intended muscle, that the coactivity pattern generally remained the same but scaled in proportion to the level of the intended muscle’s activity. This implies that the subjects’ control strategy remained consistent during the three target activity level tests. We infer that patterns of coactivity would scale through the entire range of intended muscle activity such that the same relative levels of coactivity would be obtained at all intended muscle activation levels.

**Individual thumb muscle activity.** These experiments also tested the ability of subjects to individually activate the four extrinsic thumb muscles. These muscles consisted of a thumb flexor (FPL), abductor (APL), and two extensor muscles (EPB and EPL). Kaufman et al. (1999) demonstrated that individual thumb muscles generate forces in multiple anatomically defined directions, such as flexion and adduction. Furthermore, they also showed that force generation in a single “motion” resulted in activity from multiple thumb muscles. These studies restricted thumb motions with a hand splint and ignored force generation by only providing subjects with muscle activity feedback.

The FPL and EPL muscles control the distal joint of the thumb and were each capable of individually initiating and sustaining activations with significant difference from each of the other three extrinsic thumb muscles’ coactivity. Voluntary activation of the EPL muscle did result in minor coactivity from the EPB muscle, and attempts to individually activate EPL resulted in no significant difference from coactivity from EPL or APL. The APL muscle was able to sustain activations with a significant difference from coactivity from the FPL and EPL muscles, but only at the 20 and 30% MVC target levels. Individual activation of APL always coactivated the EPB muscle. These results suggest that the APL, EPL, and EPL muscles may receive common motor commands, whereas EPL may also receive unique motor commands, allowing it to be more functionally distinct and activate apart from the other thumb muscles.

**Interactions between finger and thumb muscles.** Able-bodied individuals coordinate motions of the thumb and fingers to gesture and interact with objects in the environment. It is natural and necessary for some applications that the thumb and fingers move simultaneously to successfully accomplish a task, such as grasping an object. However, one major limitation of these experiments is that they only examined subjects’ ability to activate extrinsic thumb or finger muscles but did not measure interactions between these two groups of muscles.

It has been demonstrated that interactions exist and that coactivations and motor unit synchronizations occur between the muscles of the thumb and those of the fingers during multidigit grasping tasks (Fuglevand 2011; Hockensmith et al. 2005; Johnston et al. 2005; Kilbreath and Gandevia 1993, 1994; Winges et al. 2006). If these muscles were used to control an artificial hand, the coordinated activities of both sets of muscles would cause simultaneous motions of the thumb and fingers. This may be beneficial because it could accurately replicate the way people naturally move their hands to grasp objects. However, this may cause confounding issues if only single-digit motions were desired.
**Motor control implications for commanding a prosthesis.**

Motorized prosthetic arms and hands are commanded using EMG signals from the user’s residual limb. It is more standard for people to “think” about controlling their body’s position and generated forces rather than the amount of activity their muscles produce. Therefore, prosthesis users must learn to modulate their residual muscles’ EMG activity as a means of interfacing with their device. This study tested subjects on EMG tasks to emulate the interface used in prosthesis control. New devices are being developed that allow for many controllable degrees of freedom; therefore, gaining access to the neural information in extrinsic muscles via intramuscular electrodes could provide users with a better method of commanding these devices. Weir et al. (2003, 2009) have been developing permanently implantable wireless EMG sensors to acquire EMG activity from multiple individual residual muscles, but a better understanding of the motor control structure of hand muscles is still needed before they can be fully utilized.

Muscle activity does not need to be completely isolated to be used as a control input for direct prosthesis control. Rather, a consistent difference between the activities of agonist and antagonist muscles is necessary. Given this condition, all of the muscles investigated would qualify as suitable control sites. Although subjects coactivated EDC1 and EDC2, these muscles were activated independently from FP1 and FP2. This implies that subjects could independently flex their index and middle fingers but would often extend these fingers together when only middle finger extension was desired. The EPL and FPL muscles are individually controllable and natural agonist-antagonist muscles that would provide an intuitive interface to control flexion and extension of a prosthetic thumb. The activity from the abductor muscle, APL, could be used at higher activity levels to command a second degree of freedom for the thumb.

The results of these experiments represent a foundation for understanding the ability to individually control extrinsic finger and thumb muscles. However, additional investigation is need to draw conclusions about the interactions between the finger, thumb, and wrist muscles. These interactions need to be understood to fully utilize an artificial hand with similar capabilities to that of the human hand.

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**DISCLOSURES**

No conflicts of interest, financial or otherwise, are declared by the authors.

**AUTHOR CONTRIBUTIONS**


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