EXAMINING THE INDEPENDENCE AND CONTROL OF THE FINGERS

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INTRODUCTION
Mechanical and neural factors both contribute to the limited independence of finger movement and involuntary force production [4]. The lack of independence is thought to be due to tendinous interconnections or synchronous firing of the motor units in different compartments of the extrinsic finger flexors and extensors [1]. Muscle activity and force measures have been used to investigate the extent to which biomechanical restrictions and neural factors contribute to the lack of independent finger movement and the involuntary force production. Several methods such as the “enslaving effect” [4] and a “selectivity index” [1] have been used to quantify the involuntary force production while the cross correlation function has been used to determine the common signal in finger flexor and extensor electromyography (EMG) [1,3]. A combination of these methods would facilitate a better understanding of force production in the fingers. The purpose of this study was to evaluate the activity of the four compartments of extensor digitorum (ED) and flexor digitorum superficialis (FDS) using surface EMG and finger force during isometric isotonic and ramp finger flexion and extension exertions.

METHODS
Twelve male participants performed a series of finger flexion and extension exertions after providing informed consent. The four fingers were placed in adjustable metal rings oriented vertically and attached to separate force transducers. The forearm rested on an adjustable table with an elbow angle of 120°, mid-prone forearm and neutral wrist. For finger extension exertions (ExtMCP), the rings were placed around the proximal phalanges. Two sets of flexion exertions were performed in which the metal rings were placed around the middle (FlexPIP) and distal phalanges (FlexDIP). Each trial was repeated three times for each finger. The mean of the three trials was used to represent each condition. Maximal and sub-maximal exertions were 5 seconds each and alternated between fingers with 5 seconds between exertions of different fingers. Maximal voluntary contractions (MVC) were used to normalize force and EMG. Isometric isometric exertions were performed at 5, 25, 50 and 75 % MVC. As well, a series of isometric triangular exertions were performed. The ascending and descending phases of the ramp exertions were from 0 to 85 % MVC with the duration of 4.5 seconds each.

Force and EMG were recorded from all 4 fingers and muscular compartments of ED and FDS (30-450 Hz, CMRR > 96 dB, Biometrics Ltd, Gwent, UK). Detailed anatomical and functional testing identified muscle compartments for electrode placement [2]. EMG and force were collected at 1000 Hz. EMG was rectified and low pass filtered with a cut-off frequency of 3 Hz; force was low pass filtered at 10 Hz. Both EMG and force were normalized to maximum and averaged over the middle 3 seconds of the 5-second plateau exertions. For the ascending and descending portions of the ramp exertions, the mean of a 50-ms window about the 4 target force levels was calculated.

Average EMG was determined for each condition and force level, the forces we used to determine the enslaving effect (EE) and the Selectivity index (SI). The SI was calculated from the absolute fractional forces of the fingers during each exertion. The SI ranges from 0 to 1, 0 representing an equal force distribution between all fingers and 1 representing exclusive force production by only one finger. The EE is the relative force production by each of the non-task fingers compared to the task finger. In addition, the cross correlation (CC) analysis produced both peak and zero time shift values for all the combinations of the force and EMG channels using both the filtered and the raw signals.

A series of 3x4 mixed analyses of variance (ANOVA) were used to test for statistical differences (p < 0.05) between the EE and SI for each flexion and extension exertions. There were 3 exertion conditions (plateau, ascending and descending phases) and 4 force levels (5, 25, 50 and 75 % MVC).

RESULTS AND DISCUSSION
The EE was always higher in the fingers adjacent to the task finger versus the non-adjacent fingers. The EE in adjacent fingers was always higher at 5 and 75 % MVC than 25 or 50 % MVC during isometric isometric exertions (plateau). In general, the EEs were higher during extension exertions than flexion exertions and FlexPIP EEs were lower than FlexDIP. The descending phase of the ramp exertions resulted in significantly higher enslaving effects on the adjacent fingers than the ascending phase of the ramp exertions and the plateau phase (p < 0.05)(Figure 1). In most cases, EEs were similar at all force levels in the ascending and plateau exertions (with a few exceptions in the ExtMCP exertions). Among the enslaving forces produced on the adjacent fingers, the ring finger had the highest force during the extension exertion of the little finger and middle finger had the lowest force during the FlexPIP exertion of the index finger.

The enslaving effects in ExtMCP at the highest level of force in the present study (75 % MVC) show similar patterns but are higher than the values reported previously. For example, The
current study found the ring EE on middle finger to be 56 ± 23 % compared to 40.8 ± 16.3 previously [4]). The slight differences are likely due to the orientation of the apparatus (vertical vs. horizontal [4]), the site of force exertion (middle of the proximal phalanx vs. the PIP joint [4]) and the exertion levels (75 % MVC vs. maximal [4]).

As expected, peak CC values between adjacent muscular compartments were higher than non-adjacent compartments. Also, the peak CC values between the task and the adjacent compartments were force independent (except at 5 % MVC). In contrast to EE and SI results, CC values were lower in extension than flexion exertions. This may be attributed to one of the study limitations. While careful functional and anatomical testing was employed prior to electrode placement, the present study was the first attempt (to our knowledge) using surface EMG to determine the activity of the individual compartments of FDS. Previous research [2] was used as a guideline in electrode placements of the ED compartments. Thus, the lower CC values in extension may be due to lower cross-talk between the adjacent electrode pairs.

Similar to the enslaving effect patterns, the selectivity indices (SI) were lower (indicating less selective force production) in the extension exertions compared to the flexion exertions. In general, the fingers had similar selectivity in producing forces by the task finger in the FlexPIP and FlexDIP exertions. During most finger exertions (with a few exceptions at the 5% force level), the SI was highest during the ascending phase of the ramp exertion, lowest during the descending phase with the constant force exertion between. The differences between the ascending phase of the ramp exertion and the other two conditions were statistically significant for the 25, 50 and 75 % force levels (p < 0.05). Interestingly, the fingers tended to be more selective in force production at mid-range levels (25 and 50 % MVC) compared to the low and high force levels (5 and 75 % MVC) (Figure 2). The index finger had the highest SI (0.88 ± 0.04) in the FlexDIP ascending ramp exertion (at 50 % MVC) while the little finger had the lowest SI (0.33 ± 0.06) during the descending phase of the ramp extension exertion (at 5 % MVC).

The SI values found in the present study during the extension exertions were lower than those reported previously [1] with the exception of the middle finger exertion (0.65 ± 0.15 vs. 0.64 ± 0.17 in [1]). In the study by Keen et al. [1], the SI was evaluated during micro-stimulation of different compartments of ED as opposed to the voluntary exertion in the current study. When individual compartments were stimulated, the fingers were more selective in force production on the corresponding finger [1]. However, in the present study when subjects were instructed to produce the desired target force, the fingers were far less selective in force production on the desired task finger. Thus, the inability to exclusively excite the muscle fibres of the desired individual muscular compartments may be restricting the selective force production on the individual fingers.

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CONCLUSIONS
To determine the functional interdependence of the fingers, this study applied a series of established techniques (enslaving effect, selectivity index and cross-correlation) to finger force and surface EMG of the flexors and extensor compartments. Control of the descending portion of the force profile is lower than ascending or isotonic control, and is also less dependent on force level). Combined with previous stimulation studies, our findings suggest that neural factors contribute more to involuntary finger force production than mechanical restrictions between tendons or muscles.

ACKNOWLEDGEMENTS
Funded by an NSERC (Canada) Discovery grant (#217382).

REFERENCES