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Activation of intrinsic and extrinsic finger muscles in relation to the fingertip force vector

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Abstract Surface EMG was recorded from two intrinsic and two extrinsic muscles of the index finger during a two-dimensional isometric force task in the plane of flexion and extension. Subjects applied force isometrically at the fingertip in eight equally spaced directions, encompassing 360°. Target forces spanned the range from 20% to 50% of maximum for each direction. The effect of varying the metacarpophalangeal (MCP) and interphalangeal (IP) joint angles was investigated. We found that when applying isometric force with the fingertip, the intrinsic muscles of the index finger behaved as a single unit whose region of activation overlapped that of the extrinsic flexor and extensor muscles. The activation region of the intrinsic muscles also spanned a range of force directions for which the extrinsic muscles were virtually inactive. The activation of all muscles, with the exception of the extrinsic extensor, was modified by changing the MCP and IP joint angles. Both IP flexion and MCP extension produced rotation of the resultant activity vector in the direction of MCP flexion. However, the relative rotation was much greater with IP flexion than MCP extension. The effect of IP flexion is linked to rotation of the force direction where joint torque switches from extension to flexion, while the effect of MCP extension is more likely related to changes in muscle length and MCP moment arm. Our results suggest that the primary role of intrinsic finger muscles is to precisely control the direction of fingertip force, while extrinsic muscles provide stability of the joints.

Keywords Index finger · EMG · Force direction

Introduction

The fingertip force vector is controlled by selecting the magnitude and direction of torque at each of the three finger joints, the metacarpophalangeal (MCP), proximal interphalangeal (PIP), and distal interphalangeal (DIP) joints. The relation between joint torque and fingertip force depends only on the segment lengths and joint angles of the finger. Although segment lengths are fixed, joint angles can be varied to allow different joint torques to achieve the same fingertip force vector. Furthermore, since there are two or more muscles contributing to torque for each direction of rotation at each joint, an infinite number of combinations of muscle force can be used to achieve the same fingertip force vector for a given set of joint angles. This kinematic structure potentially allows for considerable versatility in control.

In activities that involve gripping, manipulating, or tapping an object with the fingers there are generally two requirements. One is producing the desired fingertip forces and the other is insuring mechanical stability. In activities where force is applied isometrically, regulation of finger stiffness is the primary means of insuring stability. Finger stiffness can be varied by changing the joint angles and/or the combination of muscle forces used to achieve the desired fingertip force. We recently examined how finger stiffness varies with the direction of the fingertip force vector and the joint angles (Milner and Franklin 1998). Although the task was more constrained than most natural activities, it explored a larger range of muscle actions than previous studies. We showed that both fingertip force direction, which is controlled by varying the combination of muscle forces, and finger posture, which is controlled by varying the joint angles, profoundly affect the finger stiffness. Gomi and Osu (1998) and Perreault et al. (2001) reported similar characteristics for the endpoint stiffness of the arm when arm posture and endpoint force were varied. They were able to show that this resulted from a linear dependence of joint stiffness on joint torque. However, our results suggested that there was much more variability

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in the relation between joint stiffness and joint torque for the finger than for the arm. We attribute this difference to functional differences in arm and finger muscles. Whereas, many shoulder and elbow muscles span only one joint, all muscles contributing to flexion and extension of the two interphalangeal (IP) joints are multiarticular. There are fingertip force directions for which these muscles act as agonists at the MCP joint and antagonists at the IP joints. Studies of finger muscle activation patterns have demonstrated that agonist/antagonist co-contraction of this nature occurs during tasks involving the application of force to an object with the fingertip (Close and Kidd 1969; Long et al. 1970; Smith and Bourbonnais 1981; Maier and Hepp-Reymond 1995; Valero-Cuevas et al. 1998).

The present study was undertaken to examine the patterns of activation of extrinsic and intrinsic finger muscles in more detail. The objective was to elucidate general principles governing the relationship between muscle activation and the fingertip force vector. This was achieved by examining the spatial distribution of activity in four muscles of the index finger while varying the magnitude and direction of the fingertip force vector. Distinctly different spatial distributions of activity were found for extrinsic and intrinsic finger muscles.

Materials and methods

Fourteen normal healthy subjects (seven male and seven female) participated voluntarily in this study. All subjects were right-handed. The experiments were carried out with the right hand only. All of the subjects gave their informed consent to the procedure, which was approved by the Research Review Committee of Simon Fraser University and conformed to the Declaration of Helsinki.

Experimental setup

Index fingertip force was measured in the plane of flexion and extension by two strain gauge elements, which sensed forces in orthogonal directions. One strain gauge element was attached to a central axis and configured as a torque sensor. Tangential force applied to a bar attached to the torque sensor was calculated by dividing the measured torque by the distance from the point of application of force to the central axis (Fig. 1). The other strain gauge element measured force applied in the orthogonal direction, along the length of the bar. The bar was aligned with the proximal phalange of the index finger. An adjustable hose clamp attached to the bar was used to secure the index finger. Adduction and abduction forces were not measured.

Surface EMG activity was recorded using custom-built active bipolar electrodes with a 30- to 500-Hz bandwidth and variable gain. The recording configuration consisted of 3-mm-diameter stainless steel contacts separated by 13 mm. The entire assembly was housed in a 13×22 mm box that could be taped to the skin overlying the muscle of interest. We have previously shown that electrodes of this type can selectively record activity from muscles that are in close proximity to each other (De la Barrera and Milner 1994). The EMG was sampled at 2 kHz and stored on disk for subsequent analysis.

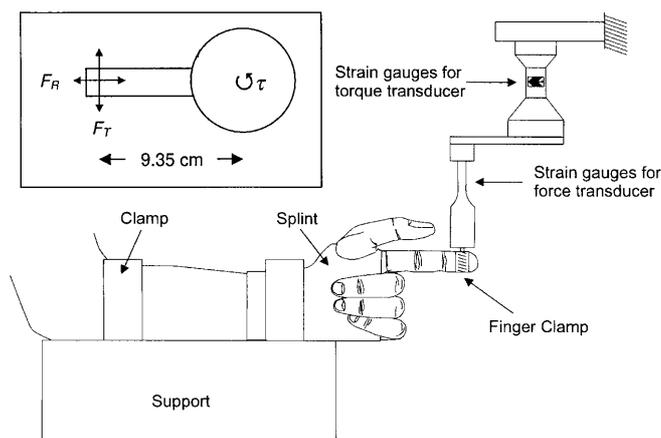


Fig. 1 Wrist splint, finger clamp, and strain gauge arrangement for measuring isometric fingertip force in the plane of finger flexion and extension. *Inset at the top left* is a view of the torque transducer and attached bar from above, indicating the direction of radial force, F_R , measured by the force transducer, and the direction of tangential force, F_T , calculated from the torque, τ , measured by the torque transducer

Protocol

Surface electrodes were placed at two locations on the hand, overlying the first dorsal interosseus (IDI) and lumbrical (LUM) muscles. Electrodes were also placed at two locations on the forearm, overlying the flexor digitorum superficialis (FDS) and extensor digitorum communis (EDC) muscles. The IDI electrode was placed over the center of the muscle belly on the dorsal surface of the hand. The LUM electrode was placed on the palmar surface of the hand lateral to the second metacarpal bone. The FDS electrode was placed on the anterior surface of the forearm just proximal to the head of the radius. The EDC electrode was placed centrally on the posterior surface of the forearm approximately midway between the elbow and wrist. The position of each electrode was adjusted to obtain the largest signal from the muscle of interest during test movements which isolated that muscle's action from the actions of neighboring muscles. The three remaining muscles of the index finger, flexor digitorum profundus, extensor indicis, and first palmar interosseus, are situated under other muscles. Consequently, their activity could not be recorded reliably with surface electrodes.

The hand was placed in a molded splint that prevented wrist motion, but permitted free movement of the fingers. The splint held the wrist at 0° of flexion and extension, i.e., in a neutral position. The forearm was supported in semipronation with the splint rigidly secured to a forearm support and the fingertip was held securely by a hose clamp (Fig. 1). The strain gauge apparatus, which was suspended above the finger, measured fingertip force applied only in the plane of flexion and extension. This force was represented on a computer display as a line vector. A target force window was displayed, which consisted of two parallel lines oriented at 90° to the target force direction. The distance between the lines represented 10% of the target force magnitude. The lines subtended an angle of 10°, also providing a target window for force direction. The subject was instructed to generate an isometric force that would place the end of the line vector into the target window. Once the subject's force was within the target window, the experimenter manually triggered the data acquisition. A 1-s record of force and EMG was then acquired and processed.

Recording consisted of sessions on 2 separate days. Testing on the 1st day was used to determine the subject's maximum isometric force in each of eight directions at 45° increments around a circle. The direction of the target force was referenced to the metacarpal bone of the index finger, which defined the 90° and 270° force

directions. Maximum force in each direction was determined for four postures of the DIP and PIP joints, ranging from near full extension of the two joints to near full flexion. Target force levels of 20%, 30%, 40%, and 50% of maximal voluntary force (MVF) were calculated for each combination of force direction and IP flexion. In the most extended posture the PIP joint angle was 160°, i.e., flexed 20° relative to full extension, and in the most flexed posture it was 90°. The DIP joint was allowed to assume its natural angle, which is tightly coupled to the PIP joint angle (Buchner et al. 1988). Intermediate flexion postures were specified in terms of the distance from the center of the MCP joint to the center of the distal phalange of the index finger. Using this metric, the two additional postures were specified by dividing the distance between the two extreme postures into thirds. The EMG was recorded during the maximal force tests to determine which combination of force direction and IP posture produced the greatest activity in each of the five muscles. A template of the joint angles for each subject, consisting of lines connecting the centers of rotation of wrist and finger joints, was drawn on a transparency. During the experiment, the template was held over the index finger while adjusting the position and orientation of the wrist splint.

At the start of the 2nd day of testing, baseline electrode noise levels were determined by recording EMG while the index finger was completely relaxed. Maximal force tests were then conducted only for the combinations of force direction and IP flexion that had yielded the largest root mean squared (rms) EMG for each muscle during the 1st day of testing. The subject then performed a series of 384 trials, consisting of all possible combinations of eight force directions, four force levels, four IP postures, and three MCP joint angles (120°, 150°, and 180°). The trials were performed in blocks in which target force direction and level were randomized. The MCP joint angle and IP flexion were kept constant for each block. These blocks were nested within a higher order block for which MCP joint angle was held constant while IP posture was chosen randomly. The higher order blocks were also presented in a random order. The target size and location remained invariant while the line vector, representing actual force, was scaled according to the target force level. This provided subjects with a higher resolution display at low force levels. Eleven subjects (five male and six female) participated in this aspect of the study.

Because of the small size of the LUM muscle and its close proximity to the larger 1DI and adductor pollicis muscles, two tests were conducted to establish that EMG crosstalk was negligible. In one test, surface EMG was simultaneously recorded for 2-s intervals from the 1DI and LUM muscles while subjects produced isometric forces of 50% MVF in each of the eight directions with the index finger in the most extended posture. Force directions were excluded from the analysis if both muscles were inactive, i.e., if the rms EMG was not more than 20% greater than during relaxation. For all included force directions, the rms EMG of one or both muscles was at least 150% greater than the relaxed baseline value. Cross-correlation analysis revealed that independent signals were recorded from the two muscles. The mean cross-correlation coefficient for the three subjects, who participated in the test, was 0.17 (SD 0.10), indicating that there was virtually no crosstalk between the two recording sites. In the other test, EMG was simultaneously recorded from the LUM and adductor pollicis muscles of one of the authors while he produced isometric force in the different directions. The adductor pollicis electrode was placed adjacent to the LUM electrode, between the thumb and index finger, overlying the muscle belly. Strong signals were recorded in response to thumb adduction. When index finger muscles were strongly activated to produce isometric force modulation of LUM, activity was observed as the force direction changed, ranging from 0 (relaxed baseline) to 8.9 μ V rms. However, adductor pollicis activity did not change at all, remaining at its relaxed baseline for all force directions. Since the adductor pollicis was not active during the task it did not produce crosstalk.

An additional experiment was performed with one of the authors as the subject. Intramuscular EMG was recorded from the FDS and flexor digitorum profundus (FDP) muscles using a pair of fine wires inserted with a hypodermic needle. The purpose of the

recording was to compare the relative activation of the two muscles for force directions which required flexor torque at the PIP and DIP joints since FDP is the only flexor of the DIP joint.

Analysis

The rms EMG was computed for each trial and these values were used in all subsequent analyses. The rms EMG of the relaxed muscle was subtracted and the result normalized by dividing by the maximum value recorded from that muscle during the maximal force tests at the beginning of the session. The muscle activity was then represented graphically as a polar plot, where the angle, θ_i , represents force direction and the distance from the center, r_i , represents the normalized rms EMG. The force direction, θ , was expressed relative to a line oriented perpendicular to the long axis of the metacarpal bone. Thus, 0° was to the right of the metacarpal, 90° was outward along the metacarpal, 180° was to the left of the metacarpal, and 270° was inward along the metacarpal. The activity in a given direction was represented as a vector $\mathbf{r}_i = (r_i \sin \theta_i, r_i \cos \theta_i)$. The tips of adjacent vectors were joined by straight lines to form an octagon, which will henceforth be referred to as an activation diagram.

Activation diagrams were quantified in terms of orientation and directionality. The orientation was set equal to the direction of the resultant activity vector ($\Sigma \mathbf{r}_i$). An index of directionality was defined as

$$\frac{\max\{r_i \cos \alpha_i\}}{\max\{r_i \sin \alpha_i\}}, i = 1, \dots, 8$$

where α_i is the angle between r_i and the resultant vector. This index is a measure of the ratio of relative height to breadth of the activation diagram, i.e., how broadly the muscle activation is distributed around the polar plot. The more narrow the distribution of activity, the higher the index of directionality.

Two-way ANOVA, with subjects as random factor, was performed to determine the effects of force level, posture, and MCP joint angle on orientation and directionality of the activation diagrams. Wilcoxon's signed ranks test was used to compare differences in orientation and directionality between muscles for statistical significance. Because multiple comparisons were made, the level of significance was set at $P < 0.01$.

Results

General features

Activation diagrams for the four muscles are shown for the extended and flexed finger postures when the MCP angle was 120° (Fig. 2) and 180° (Fig. 3). These figures illustrate several of the key findings. First, it is evident that the effect of force level (20–50% MVF) was a progressive increase in muscle activation, which was relatively uniform for all directions in which a muscle was appreciably activated. This was confirmed statistically since force level had no significant effect on either the orientation or the directionality of the activity of any muscle.

Second, the orientation of muscle activity was more similar between the intrinsic muscles than between the intrinsic and extrinsic muscles, although the intrinsic muscle activity was oriented closer to the extrinsic flexor, FDS, than the extrinsic extensor, EDC. Activity of the 1DI was chosen as a reference to which the activity of the other muscles was compared, using Wilcoxon's signed

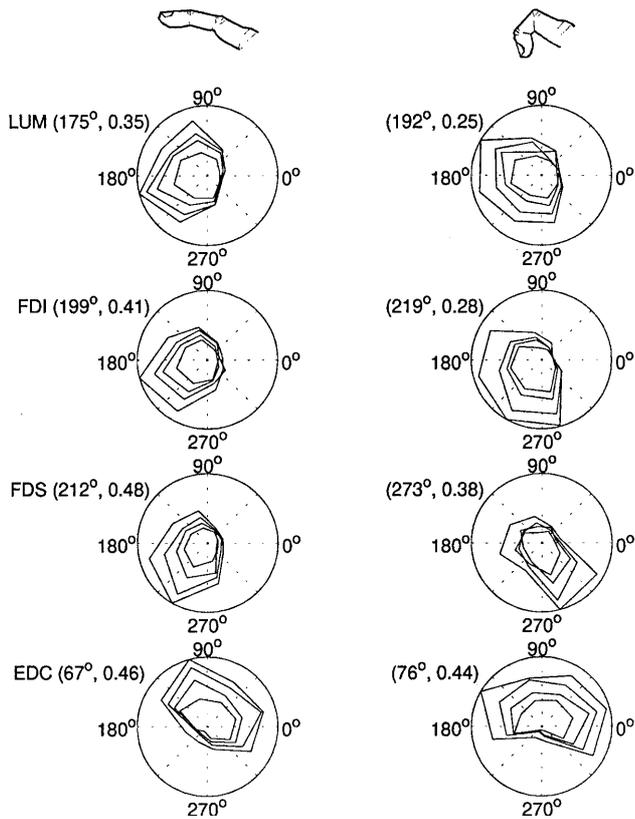


Fig. 2 Activation diagrams (normalized EMG as a function of force direction) for four muscles of the index finger with the metacarpophalangeal (MCP) joint at an angle of 120°. *Left and right panels* show mean activation diagrams of ten subjects in the extended [proximal interphalangeal (PIP) \angle 160°] and flexed (PIP \angle 90°) interphalangeal (IP) postures, respectively. The 90° force direction is parallel to the carpal bone of the index finger. Orientation of finger relative to force directions is indicated at *top* of figure. *Concentric octagons* represent activation diagrams for force levels of 20%, 30%, 40%, and 50% maximal voluntary force (MVF), proceeding from the innermost to the outermost octagon. *Numbers in brackets* indicate the orientation angle of the activation diagram and the normalized EMG represented by *circumscribed circle*. Maximum normalized EMG is equal to 1.00. *LUM* Lumbrical, *FDI* first dorsal interosseus, *FDS* flexor digitorum superficialis, *EDC* extensor digitorum communis

ranks test. The variation in orientation angle with MCP joint angle and IP flexion is shown in Fig. 4. The LUM activity was always oriented clockwise with respect to 1DI activity. This is evident from Figs. 2 and 3. The mean difference in orientation between 1DI and LUM, across all subjects and conditions, was 21° ($P < 0.0001$). On the other hand, FDS activity was oriented counterclockwise with respect to 1DI activity with a mean difference in orientation of 39° ($P < 0.0001$). The EDC activity was oriented 145° clockwise with respect to 1DI activity ($P < 0.0001$).

Third, FDS activity was the most directional of any muscle, i.e., the muscle activation diagrams for FDS were most narrow. The variation in directionality with MCP joint angle and IP flexion is shown in Fig. 5. The directionality of LUM and 1DI was not statistically

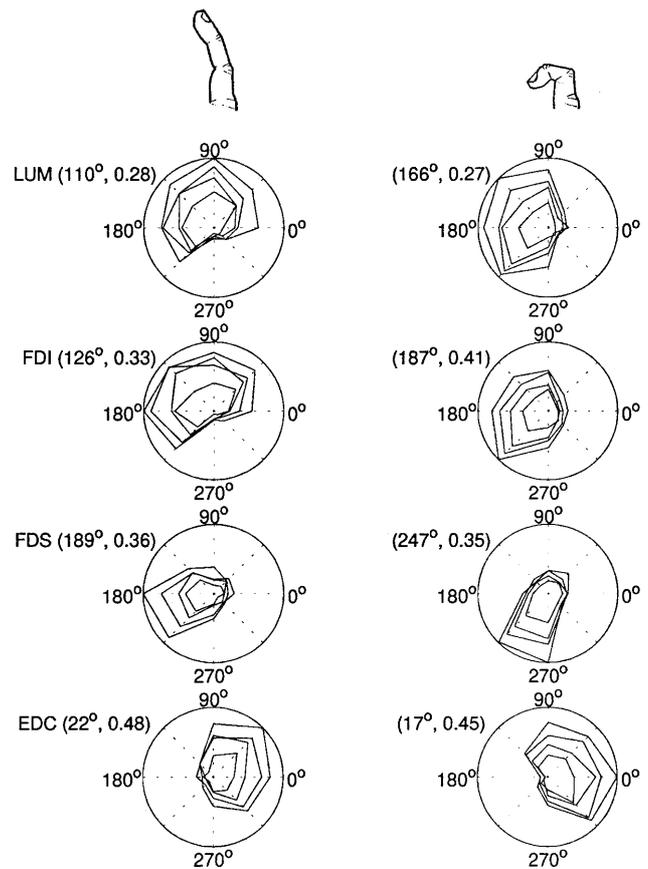


Fig. 3 Activation diagrams for four muscles of the index finger with the MCP joint at an angle of 180°. *Left and right panels* as in Fig. 2

different, EDC activity was slightly less directional than 1DI (mean difference -0.16 ; $P < 0.0001$), while FDS activity was considerably more directional (mean difference 0.63 ; $P < 0.0001$).

Finally, Figs. 2 and 3 clearly illustrate that there is considerable overlap in the activation diagrams of the different muscles. The region of activation of the two intrinsic muscles is very similar. Furthermore, the range of force directions for which the intrinsic muscles are active overlaps almost completely with that of FDS and encompasses part of the activation region of EDC. In addition, it can be seen that there is some overlap in the activation regions of FDS and EDC.

Effects of finger flexion on activation

Changes in the MCP or IP joint angles mainly affected orientation of the activation diagrams. Flexing the MCP joint by 60°, starting from a 180° joint angle, produced a corresponding counterclockwise rotation in orientation of the activation diagrams of all muscles (Fig. 4). The mean rotation was 43° for LUM, 46° for 1DI, 34° for FDS, and 52° for EDC. Although this change in orientation was significantly greater than zero for all muscles ($P < 0.0001$),

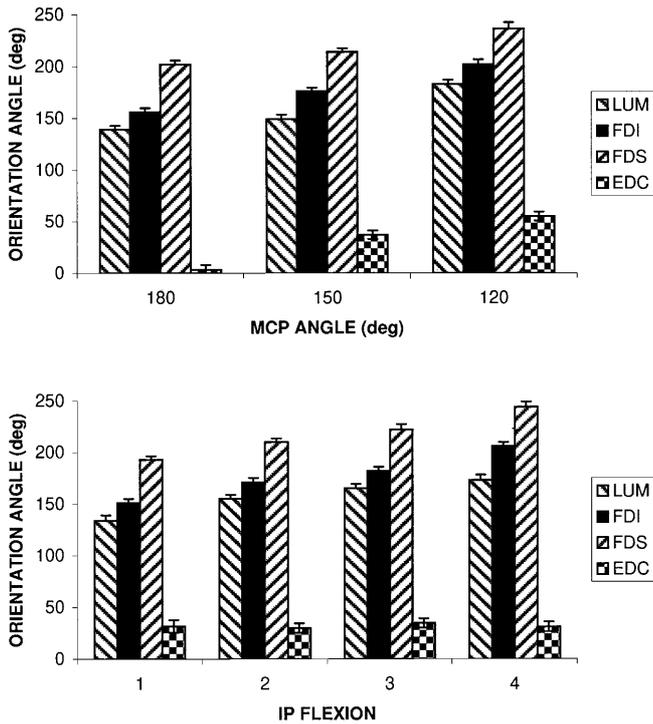


Fig. 4 Mean orientation angle of muscle activation diagrams across force levels (4) and subjects ($n=10$). *Top panel* shows variation in orientation with MCP joint angle. Angles are expressed in the coordinate system of Fig. 2. *Error bars* indicate standard errors. *Bottom panel* shows variation in orientation with IP flexion, going from the most extended (1) to the most flexed (4) posture

it was less than the amount of joint rotation. For LUM and FDS the change in orientation was significantly less than 30° in the 150° posture ($P<0.0005$). It was significantly less than 60° for 1DI, as well as LUM and FDS, in the 120° posture ($P<0.00025$). However, for EDC the change in orientation was not significantly different from the amount of MCP joint rotation in either posture. For all muscles except EDC, IP flexion produced a profound counterclockwise rotation in orientation (Fig. 4). The mean rotation in going from the most extended to the most flexed IP posture was 39° for LUM ($P<0.0001$), 49° for 1DI ($P<0.0001$), and 51° for FDS ($P<0.0001$). Again, there was no significant change in orientation of EDC activity. Only in the case of LUM was there a significant interaction effect between MCP joint angle and IP posture ($P=0.0005$).

There was no significant effect of MCP joint angle on the directionality of the activity of any muscle. However, IP flexion did affect the directionality of FDS. There was a dramatic increase in the directionality of FDS activity with IP flexion, which is quantified in Fig. 5 (mean increase of 0.97; $P<0.0001$), and is also apparent in Figs. 2 and 3.

As an aid to the interpretation of the muscle activation diagrams, net joint torque was plotted as a function of force direction for the extended and flexed finger postures (Fig. 6). Net joint torques were computed from the

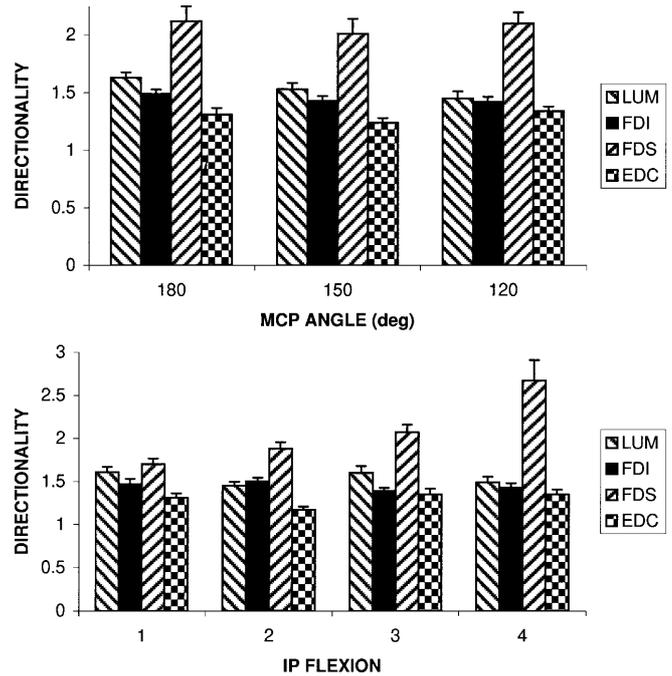


Fig. 5 Mean index of directionality of muscle activation diagrams across force levels (4) and subjects ($n=10$). *Top panel* shows variation in directionality with MCP joint angle. For scale perspective refer to the 50% MVF activation diagrams in the right panel of Fig. 3, where the index of directionality is 2.5 for FDS and 1.3 for EDC. *Error bars* indicate standard errors. *Bottom panel* shows variation in directionality with IP flexion, going from the most extended (1) to the most flexed (4) posture

measured fingertip force and finger geometry. This relation can be expressed in a compact mathematical form as $\tau = \mathbf{J}^T \mathbf{F}$, where \mathbf{J}^T is the transpose of the Jacobian of the finger (Milner and Franklin 1998). There is a marked decrease in MCP torque relative to torque at the more distal joints as the finger is flexed. There is also a counterclockwise rotation in the force direction for which the greatest torque is required at all three joints. This rotation is about 45° for the MCP joint, 90° for the PIP joint, and 110° for the DIP joint. As a result, the regions of flexor and extensor torque rotate in a similar manner.

Comparative activation of extrinsic flexor muscles

Intramuscular EMG, recorded simultaneously from the FDS and FDP muscles, indicated that the FDP muscle was very active for force directions in which the FDS muscle was virtually silent. With the MCP joint extended and the finger in a slightly flexed posture, the force direction was rotated from 180° to 315° while the subject attempted to keep the same level of FDP activation. The activity of the FDS progressively declined, virtually disappearing for the 315° force direction (Fig. 7). Force was not recorded in this experiment, but it required greater subjective effort to produce the activity recorded in the 315° direction than in

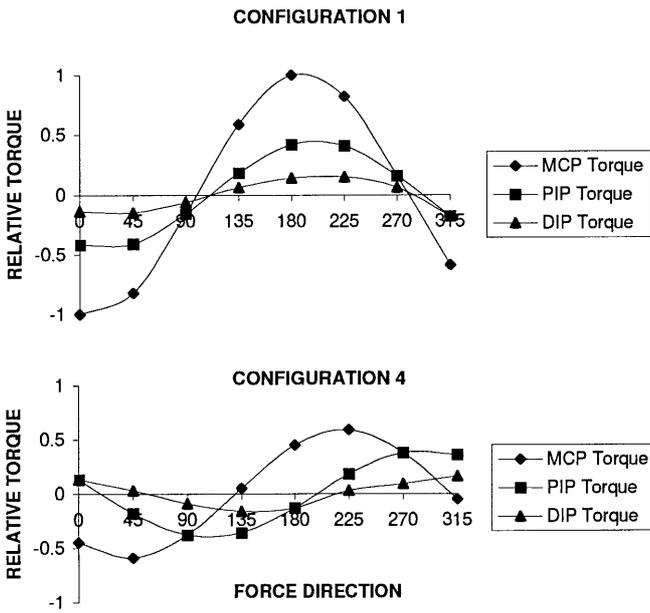


Fig. 6 Relative torque magnitudes at the three joints of the index finger as a function of force direction. Torque is normalized so that a value of 1.0 represents the maximum torque at any joint for any configuration of the joints. Positive values represent flexor torque while negative values represent extensor torque. *Top panel* shows relative torque when the IP joints are extended (posture 1). *Bottom panel* shows relative torque when the IP joints are flexed (posture 4). Note that torque is independent of MCP joint angle if force directions are expressed relative to the orientation of the proximal phalange, which is aligned with the carpal bone in Fig. 2

the 180° direction. This was the force direction which required the greatest DIP flexion torque (Fig. 6).

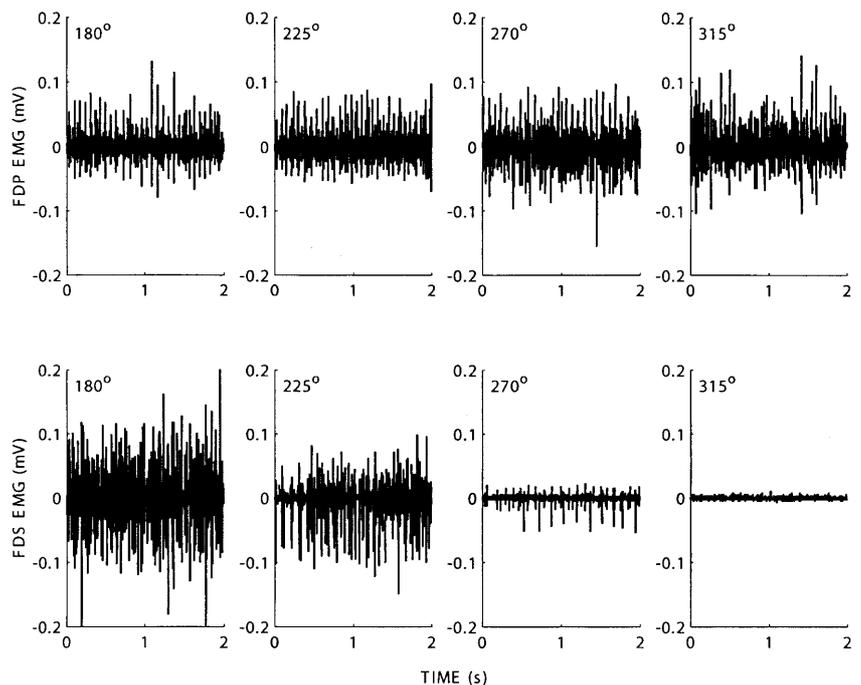
Discussion

The principal finding of this study is that when applying isometric force in the plane of flexion and extension, the activation region of intrinsic muscles of the index finger is distinctly different from that of extrinsic muscles, although there is some overlap with both that of the extrinsic flexor and extensor muscles. Activation diagrams of all muscles shift with flexion of the MCP and IP joints.

Relating activation to biomechanics

The activation region of LUM and 1DI spans a range of force directions, from directions in which extensor torque is required at all three joints to directions in which flexor torque is required (Fig. 6). Some insight into this result may be derived by reviewing the anatomical arrangement of finger muscles. The LUM tendon inserts on the extensor mechanism, which extends the IP joints, while 1DI inserts on the lateral aspect of the proximal phalange and has no action at the IP joints. The 1DI and LUM produce flexor and abductor moments at the MCP joint, and LUM also produces an extensor moment at the IP joints. The EDC also inserts on the extensor mechanism and produces extensor moments at all three joints as well as an abductor moment at the MCP joint. The FDS and FDP produce flexor and adductor moments at the MCP joint and flexor moments at the PIP joint. The FDP is the

Fig. 7 EMG recorded from flexor digitorum profundus (FDP; *top panels*) and FDS (*bottom panels*) muscles with intramuscular wires during isometric contraction. The finger posture corresponded approximately to posture 2, i.e., slight flexion, and the MCP joint angle was 180°. FDP activity was kept relatively constant while fingertip force direction was varied, as indicated in each panel. Force direction is expressed in the coordinate system of Fig. 2. FDS activity progressively diminished as the applied force was rotated in a counterclockwise direction



only muscle which produces a flexor moment at the DIP joint (An et al. 1983).

While the extent of the region of activation of LUM and its rotation with IP flexion might be explained by its flexor action at the MCP joint and extensor action at the IP joints, it is not obvious why 1DI should be so active for force directions requiring MCP extensor torque, nor for that matter, why LUM is active over a range of force directions where flexor torque is required at all three joints. The LUM is a relatively weak flexor of the MCP joint compared to FDS, FDP, and 1DI. Quite possibly, common activity of the intrinsic muscles was used to balance abduction and adduction moments at the MCP joint created by the extrinsic flexor or extensor muscles, even though this was not required by the task because the finger was constrained. Because the finger is frequently used to apply forces that require flexion and extension moments without abduction or adduction, there may be hardwired synergies or automatic coactivation commands that couple activity of the intrinsic muscles to stabilize the MCP joint during strong flexion or extension efforts. Such activity is difficult to suppress as demonstrated by Scheidt and Rymer (2000), who found that uniaxial shoulder muscles remained active during isolated elbow movements after motion of the humerus had been prevented by a mechanical constraint at the elbow. The common activation of intrinsic muscles may also aid in stabilizing the joints in the transition region between activation of the extrinsic flexor and extensor muscles. Reduced activity of the extrinsic muscles in this region would reduce the joint stiffness, diminishing joint stability, which may be compensated to some degree by coactivation of intrinsic muscles. This explanation has particular merit for the extended finger posture where the torques at all joints change from extension to flexion at approximately the same fingertip force direction.

Using the product of moment arm and physiological cross-sectional area as an index of strength, the intrinsic muscles can produce close to 30% of the flexor torque at the MCP joint and extensor torque at the PIP joint. Because of their relatively small moment arms though, they contribute substantially less to the joint stiffness, which is proportional to the square of the moment arm. The contribution to joint stiffness would be about 15% of the total flexor stiffness at the MCP joint and 20% of the total extensor stiffness at the PIP joint. This would suggest that their principal function is not to stiffen the joints, but to control the direction of force. The greater stiffness of the extrinsic muscles makes them much more suitable stabilizers. Thus, intrinsic muscles likely play a critical role in controlling force direction in a region between the principal pulling directions of extrinsic finger extensor and flexor muscles, where they are most active. This is similar to the conclusion reached by Maier and Hepp-Reymond (1995) that intrinsic muscles provide finely graded forces during pinch.

Relating activity of intrinsic muscles to previous studies

We compared the muscle activation values for 50% MVF listed in Table 2 of Valero-Cuevas (2000) to our mean values for comparable joint angles, force level, and force directions. Like us, he found that the activity of the intrinsic muscles increased when isometric force shifted from the dorsal (ca 55°) to the distal (ca 145°) direction and then decreased from the distal to the palmar (ca 235°) direction. The absolute difference in normalized muscle activation between his values and ours is relatively small. For the four muscles and three force directions for which comparisons could be made, the difference never exceeded 0.14 and was generally less than 0.10. The difference would be even smaller if we were to make adjustments for the 10° difference between his force directions and ours, based on our activation diagrams. Some of the difference may also have been due to a difference in the experimental apparatus. Our apparatus allowed the subject to apply fingertip torque, as well as force, whereas the apparatus of Valero-Cuevas required that the subject apply fingertip force with negligible torque.

The common activation of 1DI and LUM in the plane of flexion and extension, while consistent with the observations of Valero-Cuevas (2000) who used a similar paradigm, has generally not been found in studies of muscle activation during isometric grip or manipulation involving motion of the index finger. In particular, while squeezing an object with a power grip, 1DI is active without LUM (Long et al. 1970), whereas during precision pinching or grasping with the index finger extended, LUM may be active without 1DI (Close and Kidd 1969). During object manipulation or isolated movement of the index finger, the relative activation of the intrinsic muscles depends on whether the joints are flexing or extending and whether or not there is a load. For example, when gripping an object with a precision grip and pushing it away from the palm by means of IP extension and MCP flexion, all intrinsic muscles are active. However, when pulling the same object toward the palm, 1DI is active, but not LUM (Long et al. 1970). In contrast, when extending the unloaded finger, LUM is active without 1DI (Close and Kidd 1969). Clearly, these differences in activation patterns are task related.

Effects of finger flexion on activation

There is a noticeable gap between the activation diagrams of FDS and EDC in the 225° to 315° region, which depends on MCP joint angle and amount of IP flexion. The experiment to examine the relative activation of FDS and FDP indicates that this region is covered by the FDP muscle. It is almost certain that FDP would be active for force directions up to 45° when the IP joints are fully flexed since DIP flexor torque is required up to that point (Fig. 6). This would suggest that its activation diagram could be as broad as that of EDC. However, no systematic

attempt was made to determine the full range of FDP activation.

The change in orientation of activity of the intrinsic muscles and FDS that occurs with IP flexion is similar to the change in force directions for which flexor or extensor torque is required at the MCP joint. However, it is considerably less than the change in force directions for which flexor or extensor torque is required at the IP joints. This may be related to the greater torque capacity of these muscles at the MCP joint than at the PIP or DIP joints (An et al. 1983). What is surprising is that the orientation of EDC muscle activity hardly changes with finger flexion despite the counterclockwise rotation in force directions requiring extensor torque at the three joints. The activation diagrams suggest that this may be because the range of force directions for which EDC is active expands in the counterclockwise direction while the maximal activity rotates in the opposite direction. Expansion in the counterclockwise direction is readily explained by the rotation of the extensor torque region, noted above. The lack of reduction in activity for more clockwise force directions, where little or no extensor torque is required at the MCP joint, is likely necessary to counteract the flexor torque produced by the FDP muscle, which must be strongly activated to produce flexor torque at the DIP joint for these force directions when the IP joints are flexed.

As the MCP joint is flexed, the activation diagrams rotate in the same direction as the MCP joint. However, for all muscles except EDC, the change in orientation of the activation diagram was significantly less than the change in MCP joint angle. This implies that there was a counterclockwise shift in the balance of muscle activity, which was greatest for FDS. This may be related to changes in joint mechanics. The MCP moment arm changes for all muscles except the extrinsic extensors as the MCP joint is flexed (An et al. 1983). The LUM and 1DI likely become weaker because their moment arms decrease and they become shorter. Although FDS also becomes shorter, its moment arm increases. The counterclockwise shift in the balance of FDS activity may occur to compensate for reduced MCP flexor torque contribution by LUM and 1DI, whose activation diagrams have a more counterclockwise orientation. This, in turn, would reduce the need for LUM and 1DI activity in the most clockwise portion of their activation region and would account for the small counterclockwise shift in the balance of activity of these muscles.

The dramatic narrowing of the FDS activation diagram with IP flexion, may be due to the reduced range of force directions for which both MCP and PIP flexion torque are required. With the finger extended, this region spans about 170°. However, in full flexion the clockwise boundary is rotated in the counterclockwise direction by 90°, as previously noted, while the span is reduced to approximately 120°.

A major contribution of this work has been the quantification of index finger muscle activation for the entire range of force directions in the plane of flexion and extension during isometric contraction. With the exception of recent studies by Valero-Cuevas et al. (1998, 2000), previous work has focused principally on a very limited range of force directions associated with pinch and power grips. Furthermore, ours is the first study in which the effect of varying the MCP and IP joint angles on muscle activation patterns has been systematically examined. As a result, we have been able to show that the force directions in which the intrinsic muscles are most active represent a transition region between the principal directions of activation of the extrinsic flexor and extensor muscles, as well as pointing to their primary role in controlling the direction of fingertip force.

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