Published in final edited form as:

J Appl Biomech. 2011 May ; 27(2): 87–98.

Coordination of Contact Forces During Multifinger Static Prehension

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Abstract

This study investigated the effects of modifying contact finger forces in one direction—normal or tangential—on the entire set of the contact forces, while statically holding an object. Subjects grasped a handle instrumented with finger force-moment sensors, maintained it at rest in the air, and then slowly: (1) increased the grasping force, (2) tried to spread fingers apart, and (3) tried to squeeze fingers together. Analysis was mostly performed at the virtual finger (VF) level (the VF is an imaginable finger that generates the same force and moment as the four fingers combined). For all three tasks there were statistically significant changes in the VF normal and tangential forces. For finger spreading/squeezing the tangential force neutral point was located between the index and middle fingers. We conclude that the internal forces are regulated as a whole, including adjustments in both normal and tangential force, instead of only a subset of forces (normal or tangential). The effects of such factors as EFFORT and TORQUE were additive; their interaction was not statistically significant, thus supporting the principle of superposition in human prehension.

Keywords

prehension; grasping; motor control; occupational therapy

To stably grasp an object the forces of all digits in contact with the object need to be coordinated to satisfy certain constraints. Often following an illness (e.g., a stroke) the ability to control fingers is impaired, making the simple task of holding an object statically in the air difficult or even impossible. Studies of unimpaired finger coordination during static prehension represent an important step toward developing rehabilitation strategies.

The contact forces applied on the object during multifinger prehension are commonly divided into manipulation and internal forces (Kerr & Roth, 1986; Yoshikawa & Nagai, 1991; Gao et al., 2005). Manipulation forces disturb equilibrium and are necessitated by the mechanics of the task (i.e., magnitude and direction of the desired object's acceleration and its inertia). Internal forces are defined as the set of forces that do not disturb the equilibrium of the object (Mason & Salisbury, 1985; Murray et al., 1994; Gao et al., 2005). The elements of the internal force vector cancel each other out, resulting in zero net force and moment. Unlike manipulation forces, internal forces can vary substantially without influencing the performance outcome. Grasp mechanics allow for increasing or decreasing the normal forces—provided that the object is not dropped or crushed—without changing the manipulation force. In robotics, the manipulation and internal forces are controlled independently (Kerr & Roth, 1986; Yoshikawa & Nagai, 1991). In contrast, people

modulate the internal forces with the manipulation force (Smith & Soechting, 2005; Gao et al., 2005; Winges et al., 2007; Gorniak et al., 2010). For example, during vertical object manipulation the grasping pinch forces scale linearly with the effective load force, which depends on the acceleration (Johansson et al., 1992; Flanagan et al., 1993; Flanagan & Tresilian, 1994; Smith & Soechting, 2005). Regulating internal and manipulation forces concurrently may add to the computational cost for the CNS with the benefit of avoiding excessive finger forces (Pataky et al., 2004b).

For a grasped object, oriented vertically, the entire internal force vector can be represented as a collection of two complementing subsets: forces in the normal (F^n) and tangential (F^t) directions (Gao et al., 2005; Zatsiorsky & Latash, 2008). Grasp mechanics allow for independent changes of the internal forces in only one direction, normal or tangential. The majority of prior prehension study protocols have focused on tasks that require manipulation forces to change; however, very few have looked at tasks that require internal forces to change, while manipulative forces remain unchanged (Budgeon et al., 2008; Niu et al., 2008a; Niu et al., 2008b).

In a recent study subjects grasped an instrumented handle with minimal force and then doubled the initial grasping force (Niu et al., 2008a). After force doubling, the torques produced by the F^n 's and by the F^t 's finger forces changed in opposite directions. In addition, the F^t of the virtual finger (VF) decreased, primarily due to a large decrease in the index finger force. The VF is an imaginary finger that has the same mechanical action as all four individual fingers together (Arbib et al., 1985; Iberall, 1987).

Pataky et al. (2008) studied the effects of maximal finger spreading and squeezing. A functional hand center was computed, which “represents an imaginary point of zero force from which the F^t finger forces would originate.” During both tasks (spreading/squeezing) the functional hand center was between the index (I) and middle (M) fingers, which signifies that the I-finger produced force in opposite direction of those of the M-, ring- (R), and little (L)-fingers. The position of the functional hand center during multifinger grasping tasks has not been studied.

The purpose of this study is to explore how finger forces change when subjects increase internal forces in only one direction in a self-paced, ramp-like manner while statically holding an object at rest. Finger forces, both F^n and F^t , were analyzed during the following three tasks (all of which required modulation of a subset of internal forces): (1) slowly increase F^n , (2) slowly spread fingers tangentially, and (3) slowly squeeze fingers together tangentially, all while maintaining static equilibrium. Analysis focused on: (1) changes in internal forces orthogonal to the instructed direction; (2) changes in VF F^t ; and (3) the neutral point during finger spreading/squeezing tasks. In a broader context, this study investigates how changes to one subset of elements affect other elements in a multielement motor system, when changes in the other subset are not mechanically necessitated.

Methods

Subjects

Ten young, healthy, male subjects participated in the experiment. The average age, weight, and height of the subjects were 26.6 ± 3.5 years, 74.7 ± 7 kg, and 177.9 ± 7.8 cm, respectively. All subjects were right-handed and had no previous history of neuropathies or traumas to the upper limbs. The subjects gave informed consent according to the procedures approved by the Institutional Review Board of the Pennsylvania State University.

Apparatus

The testing apparatus consisted of a handle with four six-component force/moment transducers (Nano-17, ATI Industrial Automation, Garner, NC, USA) for each finger and one fake transducer for the thumb (Figure 1). The fake transducer was necessary because subjects produced thumb forces large enough to damage the force transducer model that was available and the data of interest were the finger forces, not thumb forces. An air bubble was attached to the top of the handle to provide handle orientation feedback to the subjects. The distance between the centers of adjacent finger transducers was 3.0 cm and the thumb sensor was positioned directly across from the midpoint between the centers of the M and R finger transducers. The combined mass of the handle, transducers, and the bar was 0.85 kg. Attached to the base of the handle was a bar to which a 0.50 kg load was attached to generate external torques of -0.50 Nm, -0.25 Nm, 0.00 Nm, 0.25 Nm, and 0.50 Nm. To counteract the negative external torques a supination effort was required and a pronation effort was needed to resist positive external torques.

Experimental Procedure

Subjects washed their hands to normalize skin condition. During testing subjects sat in a chair facing a computer monitor that displayed force feedback. The right forearm was supported by a custom pad mounted on top of an adjustable tripod so that the weight of handle apparatus did not cause undue strain on the shoulder. Subjects were positioned such that the right upper arm was in approximately 45 degrees abduction in the frontal plane and 30 degrees flexion in the sagittal plane. The elbow joint was flexed approximately 90 degrees. The forearm was in 90 degrees of pronation.

All trials began with subjects removing the handle from a rack then holding it such that the air bubble was centered in the target and subjects were producing no visible movements of the handle. The subjects performed three tasks: (1) grasp the handle stronger, i.e., slowly increase the finger F^n (SQN); (2) slowly spread fingers tangentially (SPT); and (3) slowly squeeze fingers tangentially (SQT). Subjects were told to increase forces such that a ramp, with constant slope, was produced on the computer screen. Force feedback given was the sum of all finger forces: the sum of normal forces for SQN and the sum of absolute values of F^t for SPT and SQT tasks. The trials were self-paced and no target force was given to subjects. However, they were told that total trial time, from minimum force to maximum force, should be approximately 5–7 s. For each of the tasks 5 trials were performed at each of the external torques, giving a total of 75 trials (3 tasks $\times$ 5 trials $\times$ 5 torques = 75 trials).

Because of the limited maximal F^n range of the sensors subjects were instructed not to exceed 60 N of VF F^n for the SQN trials. It was apparent that subjects could increase force significantly above this level. However, testing submaximal forces was sufficient to investigate the finger force coordination. In general, force changes increased in a linear fashion.

Data Analysis

LabVIEW (National Instruments, NC, USA) software was used to collect force data and to display feedback to subjects. Data were collected at a frequency of 200 Hz and digitally low-pass filtered using a 4th order Butterworth zero-lag filter with a cutoff frequency of 10 Hz using Matlab (Version R2006a, The Mathworks, Inc.). The force data for each trial were visually inspected to ensure that subjects followed the instructions for that task. If subjects did not produce a force increase in the instructed manner (i.e., monotonic changes) the trial was thrown out.

For each trial the data at the start and end were extracted so that they could be compared and the change in variables of interest was calculated (change = end – start). The data were then averaged within subjects. In all cases averaging was performed for the same task-torque conditions, leaving five values of end and start of each response (for each finger and VF), corresponding to each of the external torques. The data were then averaged across subjects to produce graphs of changes in responses that occurred during the trials. Data averaged within subjects were used for statistical tests.

A safety margin (SM) of the grasp during each trial was calculated. The SM is defined as the ratio of actual normal force to minimal normal force needed to prevent slippage (Westling & Johansson, 1984). The SM was calculated, using the previously defined equation (Burstedt et al., 1999; Pataky et al., 2004b):

$$SM_i = \left(F_i^n - \frac{|F_i^t|}{\mu_s} \right) / F_i^n$$

The symbol i denotes the finger (I, M, R, L, or VF).

The coefficient of friction, μ_s , between the fingers and force sensors was approximated to be 1.4 based on previous studies (Pataky et al., 2004b; Savescu et al., 2008). The SM is the proportion of F_i^n that is above the slipping threshold and thus not functioning for slip prevention, with a maximum potential value of 1 (e.g., occurs if the tangential force is zero). A second SM, denoted “virtual” SM, was calculated using the F^t at the end of the trial and the F_i^n at the start of a trial. This calculation was performed to examine whether slipping would occur if the F_i^n stayed the same and the F^t changed. A positive value would indicate no slipping and a negative value would indicate slipping meaning that an increase in F_i^n was mechanically necessary.

A variable called the “functional hand center” was calculated, for the tasks SPT and SQT, by fitting a 3rd order polynomial to the F^t values of the four fingers at maximum force production. This was the same method used by Pataky et al. (2008). It was assumed that the position of fingers was constant at $x = 1, 2, 3$, and 4 for the I-, M-, R-, and L-fingers, respectively. The location of the functional hand center is the real solution (x) of the polynomial:

$$f(x) = a_3x^3 + a_2x^2 + a_1x + a_0$$

It represents the geometric center of origin of F^t finger forces. For example, if the location of the origin of the F^t finger forces was exactly in-between M- and R-fingers, the real solution would be 2.5. For an individual trial, the functional hand center was found by first finding the instance in each trial when the sum of the absolute values of the individual finger tangential forces was the greatest. The tangential forces of each finger at this point were then plotted against the position of that finger. Next a 3rd order polynomial was fitted to these four points. Last, the real solution of the equation was found and this value was taken as the location of the functional hand center. This entire procedure was performed with a custom written Matlab function.

Statistical Analysis

Statistical tests were used to answer the three specific questions posed at the beginning of the study. The questions were tested by using two-way repeated measure ANOVAs at the VF level. The statistical tests were performed separately for each task. Factors were

TORQUE (5 levels) and EFFORT (2 levels). The factor EFFORT had 2 levels, corresponding to the start and end of the trial. Responses tested were F^n and F^t . The data were tested for sphericity and, when violated, the ANOVA procedure was corrected using the Greenhouse-Geisser method (Girden, 1992). Statistical analysis was performed using the statistical software Minitab 13.0 (Minitab, Inc., State College, PA, USA) and SPSS (SPSS Inc., Chicago, IL, USA). All statistical analysis was performed at a significance level of $\alpha = .05$.

Results

All subjects were able to perform the tasks without systematic substantial deviations from static equilibrium. The experimenter closely observed the handle during trials, looking for obvious translations or rotations of the handle that would be due to changes in manipulation forces (i.e., violation of static equilibrium equations: $\Sigma F_x = 0$, $\Sigma F_y = 0$, $\Sigma M = 0$). While small object rotations did occur as the peak internal forces were being reached, on the whole the performers were able to change the internal force vector without changing the manipulation force and breaking the object equilibrium. The focus of results is analysis performed at the VF level.

The change in F^n and F^t from single trials, for each task, are shown in Figure 2 A–F. For all tasks the F^n (Figure 2 A, C, E) showed a large increase. The change in F^t showed the following pattern across all tasks: (1) the change in the VF force was in the same direction as I-finger force, (2) the change in I-finger force was largest of all the individual fingers, and (3) the change in I-finger force was in the opposite direction to the M-, R-, and L- force changes.

The average change in F^n , at both VF and IF levels, across tasks and torques is shown in Figure 3. Quantitative data on the average change in F^n are available in Appendix A. The change in F^n for SQN at VF level will not be addressed because the maximal force level was limited by instruction, as mentioned in Methods. For both SPT and SQT the VF F^n showed a large increase across all torques (Figure 3D). The largest changes for SPT and SQT occurred at 0.50 Nm and 0.00 Nm external torques, respectively. The change in VF F^n for SPT and SQT ranged from 23.54 N to 38.72 N and 28.91 N to 36.72 N, respectively. At the IF level consistent trends were observed across torques for both SPT and SQT. For SPT the I-, R- and L-fingers showed relatively large changes in F^n while the M-finger increase was less and did not vary substantially across torques. For SQT the I-finger showed a relatively large increase in F^n compared with M-, R- and L-fingers, which generally showed similar magnitudes of change (Figure 3C).

The VF F^t changed in all tasks (Figure 4D). For the SQN task the VF F^t showed a decrease for 0.00 Nm, -0.25 Nm, and -0.50 Nm torques. As the external torque moved from supination to pronation efforts the magnitude of change decreased, from 2.20 ± 0.44 N to -3.19 ± 0.82 N. In the SPT task the VF F^t increased at all torques, with a range of values from 1.69 ± 1.47 to 4.53 ± 1.31 N. For the SQT task the VF F^t decreased for all torques, with a range of values of the force change from -2.70 ± 1.08 to -8.52 ± 2.63 N. For all tasks and torque levels the VF F^t changed in the same direction as the I-finger force. In general at the IF level the I-finger showed a much larger change in F^t than other fingers. This finding agreed with the data reported by Niu et al. (2008a).

In general, for all tasks and fingers the VF SM was positive and showed an increase from the start to end of trials (Table 1). The amount of increase tended to be larger for pronation than supination efforts. The value of the VF SM was similar for SQN and SPT tasks. The VF SM was highest for SQT. For all tasks the VF SM showed little variation with torque.

The range of the “virtual” SM for SQN, SPT, and SQT was 0.85–0.81, 0.75–0.80, and 0.89–1.00, respectively. Because in the SQT task the VF F^t decreased during the trials the “virtual” SM in this task was larger than the SM at the trial start. At the IF level only the I-finger displayed a negative “virtual” SM, which occurred in one instance for the SPT task at 0.50 Nm torque (Table 2).

The p -values for repeated-measures ANOVA are presented for all response variables in Table 3. All tasks showed significant effect of EFFORT (i.e., change from start to end of trial) for the VF F^n and F^t ($p < 0.01$). In other words, (a) when performers—following instruction—changed one subset of the internal force vector, F^n or F^t , they also changed the other complementary subset; and (b) when they squeeze/spread the fingers they also changed the resultant VF F^t . The effect of TORQUE on the VF F^n was significant for SQN and SQT tasks ($p < .00$) and on the VF F^t for all tasks ($p < 0.01$). In addition, for all tasks the interaction of EFFORT and TORQUE was nonsignificant on both VF F^n and VF F^t .

The functional hand center was computed for finger spreading/squeezing tasks, SQT and SPT. Averaged across subjects data are given in Figure 5. For both SQT and SPT the functional center was between the I- and M-fingers (i.e., $1 < \text{functional center} < 2$ where $I = 1$, $M = 2$). There was no evident pattern of functional hand center being affected by torque. The results are similar to the data reported by Pataky et al. (2008). Hence the location of the functional hand center in spreading/squeezing tasks is similar during pressing (Pataky et al., 2008) and grasping tasks (this study).

Discussion

The questions posed at the beginning of the study have been clearly answered by the data. In particular, we observed changes in both subsets of internal forces under all the tested conditions. We also observed changes in the tangential force (F^t) produced by the virtual finger under all conditions. In contrast, there were no significant changes in the location of the neutral point of the hand under the finger spreading and squeezing tasks. The discussion will address the following: (a) how instructed force change in one direction affects force change in the orthogonal direction, (b) changes in VF F^t , and (c) functional hand center.

The results showed that instructed force changes in one direction result in force changes in the orthogonal direction. The mechanics of the task did not always necessitate this to occur (provided that the friction is large enough to prevent slipping when the tangential force increases). In the SQN tasks the changes of the F^t are mechanically unnecessary. The rotational equilibrium of the handle could be maintained by a proper distribution of the normal forces of the fingers without changing the VF F^t . In the SQP and SPT tasks, where finger tangential forces change under instruction, the negative virtual SM, that indicates imminent slip, was observed in only 1 task of 40, while the F^n increase was observed in all cases. From a standpoint of task mechanics, there are at least two reasons to change the normal finger forces when the tangential force changes. One reason is to prevent slipping. In our experiment, the friction at the finger-sensor interface was intentionally made very high (the friction coefficient was 1.4, i.e., for slipping to occur the tangential force should be much larger than the normal force). The second reason is to compensate for the changed moment of the tangential force by opposite changes of the moment of the normal forces. Note that the force changes occurring due to that reason may alter the SM in either positive or negative direction.

One of the possible explanations for the exertion of substantial forces in the direction orthogonal to the instructed direction might be a general—anatomical and motor control—predisposition of fingers for exerting forces in oblique directions. Previous studies have

shown that the line of action of muscles involved in finger flexion/extension and abduction/adduction is not purely in these directions (An et al., 1983; Fowler et al., 2001; Kutch et al., 2008). For example the line of action of finger flexors often has some component in the abduction/adduction direction. This is variable between subjects due to anatomical differences as well as practice. It has also been shown that for a single-joint isometric contraction muscles other than those producing force in the intended direction are active, which may potentially lead to force being produced in directions other than the intended one (Buchanan et al., 1986).

Another explanation may follow from a hypothesis on normal-tangential force coordination suggested by Pataky (2005). According to the hypothesis the central controller selects finger normal and tangential forces to minimize the strain energy accumulated at the fingertip tissues during the finger force exertion. It is known that (a) during finger tip deformation the mechanoreceptor activity is strongly associated with strain energy (Dandekar et al., 2003) and (b) fingertip mechanoreceptors generate strong afferent signals that may activate finger flexor motoneurons (McNulty et al., 1999). In the study of Pataky (2005) the strain energy and the conditions for its minimum were computed from a finite element model of the fingertips. Additional research is necessary to check whether the Pataky's hypothesis can explain the findings of this study.

For the three tasks the VF F^t showed a significant change. The VF F^t force change was in the negative direction for SQN and SQT but positive for SPT. The negative change for SQN agreed with an earlier study (Niu et al., 2008a). The change in force of the VF F^t for the spreading/squeezing tasks was in the same direction as change in force of the I-finger, which in both instances was of much greater magnitude than for any other single finger.

Maximal strength in four-finger abduction/adduction during pressing tasks has previously been studied (Pataky et al., 2008) and the findings agree with our data: the absolute sum of forces is larger in adduction than abduction. The lateral fingers (I- and L-fingers) produced more force in both, the abduction and adduction, directions than the medial fingers (M- and R-fingers), on average the lateral fingers contributed $72.1 \pm 27.9\%$ of the total abduction/adduction force. The I-finger has been shown to display the most independence among the fingers during multiforce production (Zatsiorsky et al., 2000) which may explain why it acted in the opposite direction to the other fingers during spreading/squeezing tasks. In addition, previous findings (Li, 2002) have shown that, in terms of percent sharing of normal force, the resultant normal force location is closer to the M-finger than R-finger. This implies that the I-finger F^n must counteract the F^n produced by R- and L-fingers.

For both spreading/squeezing tasks the functional hand center—the imagined point from which F^t originated—lay between the I- and M-fingers, not between the M- and R-fingers (in contrast to the point of application of the resultant normal force in pressing tasks, Li et al., 1998). Several factors may cause this to occur. The most obvious reason is the muscle architecture of the hand. The primary muscles responsible for finger adduction and abduction are the palmar interossei and dorsal interossei, respectively. Typically, the I-finger is involved in more adduction/abduction in everyday tasks than the other fingers, so that it becomes stronger in these motions, which could be expected to shift the functional hand center toward the I-finger. In addition, the first dorsal interosseus is larger than the other dorsal interossei muscles, giving it more abduction strength. A less obvious reason why the functional hand center was found to be between the I- and M-fingers is that the central nervous system (CNS) may represent the fingers as two VF's instead of one. The two VF's would be: VF 1 = {I} and VF 2 = {M, R, L}. This may be an effective strategy to simplify control during prehension, which is used in robotics to decouple the simultaneous control of two performance variables (Zuo & Qian, 2000). However, this result may not be applicable

to finger pressing tasks. During finger pressing tasks the finger forces create a moment about the wrist. It has been previously found that the location of the resultant normal force is such that the secondary moment for flexion/extension (Li et al., 1998) and also for adduction/abduction (Vigouroux et al., 2008) is minimized. During the current task, no moment was created at the level of the wrist by the internal forces (as they compensate each other), consequently the location of the functional hand center is only an effect of the two proposed arguments (muscular architecture and two VFs) without any influence of the minimization of secondary wrist moments.

The SQT and SPT results lend support to the point of view that the lateral finger forces in grasping are actively controlled rather than follow from passive mechanical properties of the fingers (Pataky et al., 2004a). Such an active control of the individual tangential finger force is maybe the most important feature that distinguishes grasping mechanics in human and contemporary robots, where the joints connecting the “palm” and fingers are simple hinges with one DOF.

The main shortcoming of the study was the fact that thumb forces were not recorded. Using the equations of equilibrium, it is possible to calculate thumb forces based on recorded finger forces; however, the accuracy would undoubtedly be lower than actually recording digit forces. From visual inspection the handle remained static during trials but this could have been verified from thumb forces, allowing for filtering out “bad” trials.

In conclusion, three important findings are reported. The first is that although, it was possible for subjects to complete the task by strictly following the instruction and changing only one subset of the internal forces (i.e., only change F^n for SQN), they changed the entire set of internal forces. This indicates that the CNS prefers higher computational costs rather than to produce excessive forces.

Second, it was observed that, while the effects of EFFORT and TORQUE were both highly significant, their interaction was statistically nonsignificant. In terms of motor control this fact indicates that the effects of the central commands associated with different EFFORTs and TORQUES were additive. Similar additive patterns were reported previously for such factors as LOAD, TORQUE and INERTIAL FORCES associated with the fast handle movements (Gao et al., 2006). The observed additivity agrees with the principle of superposition according to which some complex actions, for example, prehension, can be decomposed into elemental actions controlled independently (Shim et al., 2003; Zatsiorsky et al., 2004). It is not clear at this time whether the discovered additivity of the command effects represents a general feature of the prehension control, or even a general feature of motor control in general (what happens, for instance, when people walk at different speeds and up/down different slopes and the changes in the gait patterns at different SPEEDs and SLOPEs are recorded; are the effects additive or not?). We are going to test the *additivity hypothesis* in more detail in our future studies.

Third, two subsets of fingers: {I} and {M, R, L} behaved differently. This was seen in the finger spreading/squeezing tasks in which these subsets of fingers produced tangential force in the opposite directions (Figure 4) and also in the functional hand center results (Table 3). This may imply that the CNS simplifies control of prehension by sending commands to the two sets of fingers as opposed to sending distinct commands to individual fingers. Based on this and previous research we may surmise that the CNS may essentially represent the hand as a set of three entities: (1) thumb, (2) index and (3) middle, ring, and little fingers and send commands that regulate grasping force and torque separately. This agrees with the concept of neural control of fingers being regulated by a two-level hierarchy (Arbib et al., 1985; MacKenzie & Iberall, 1994). At the higher level there is the VF, or perhaps two VFs, and

thumb that exert the necessary forces on the object. At the lower level the fingers comprising the virtual finger work together to produce the output of the VF.

Further research as to how commands sent to fingers are organized may be beneficial in the fields of rehabilitation, haptics, and ergonomics.

Acknowledgments

We would like to thank Jason Friedman, Xun Niu, and Jim Metzler for assistance in various stages of this study. This study was funded by NIH grants AG-018751, NS-035032, and AR-048563.

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Appendix A

A1 Changes in F^n

Table A1

Effect of digit manipulation on the F^n ; average change in $F^n \pm SE$ (units in N)

Torque (Nm)	Finger				
	I	M	R	L	VF
SQN					
0.50	5.14 $\pm$ 0.73	6.00 $\pm$ 0.94	7.12 $\pm$ 1.51	2.09 $\pm$ 1.30	20.35 $\pm$ 3.75
0.25	6.23 $\pm$ 1.38	5.55 $\pm$ 0.96	7.51 $\pm$ 1.14	4.81 $\pm$ 0.83	24.11 $\pm$ 2.67
0.00	8.16 $\pm$ 1.29	5.36 $\pm$ 0.93	8.01 $\pm$ 1.45	4.02 $\pm$ 0.55	25.55 $\pm$ 2.85
-0.25	8.77 $\pm$ 1.63	5.39 $\pm$ 0.98	7.60 $\pm$ 1.16	3.66 $\pm$ 0.75	25.43 $\pm$ 3.30
-0.50	5.62 $\pm$ 1.72	5.40 $\pm$ 0.85	7.60 $\pm$ 1.01	3.67 $\pm$ 0.94	21.28 $\pm$ 3.16
SPT					
0.50	14.25 $\pm$ 2.03	3.94 $\pm$ 1.44	12.55 $\pm$ 2.95	7.98 $\pm$ 1.33	38.72 $\pm$ 6.55
0.25	10.71 $\pm$ 1.89	3.03 $\pm$ 1.13	7.42 $\pm$ 1.99	9.30 $\pm$ 1.86	30.45 $\pm$ 4.73
0.00	6.45 $\pm$ 2.13	3.48 $\pm$ 1.25	7.19 $\pm$ 2.54	6.55 $\pm$ 1.68	23.66 $\pm$ 5.86
-0.25	10.57 $\pm$ 1.86	3.89 $\pm$ 1.05	6.92 $\pm$ 1.42	7.52 $\pm$ 1.73	28.89 $\pm$ 4.38
-0.50	5.94 $\pm$ 1.85	3.42 $\pm$ 0.88	8.55 $\pm$ 1.84	5.63 $\pm$ 1.15	23.54 $\pm$ 3.57
SQT					
0.50	9.07 $\pm$ 2.32	4.49 $\pm$ 0.99	1.76 $\pm$ 0.89	3.93 $\pm$ 1.12	21.24 $\pm$ 3.99
0.25	15.69 $\pm$ 3.57	6.05 $\pm$ 2.27	6.12 $\pm$ 1.59	3.75 $\pm$ 1.03	31.61 $\pm$ 7.42
0.00	16.27 $\pm$ 3.57	7.70 $\pm$ 2.27	6.99 $\pm$ 1.59	5.76 $\pm$ 1.03	36.72 $\pm$ 7.42
-0.25	11.45 $\pm$ 2.44	5.89 $\pm$ 1.41	6.47 $\pm$ 1.43	5.11 $\pm$ 1.16	28.92 $\pm$ 5.22
-0.50	14.36 $\pm$ 2.55	5.01 $\pm$ 1.23	4.17 $\pm$ 1.33	5.38 $\pm$ 1.24	28.91 $\pm$ 5.27

A2 Changes in F^t

Table A2

Effect of digit manipulation on the F^t ; average change in $F^t \pm SE$ (units in N)

Torque (Nm)	Finger				
	I	M	R	L	VF
SQN					
0.50	1.50 $\pm$ 0.60	0.33 $\pm$ 0.35	0.31 $\pm$ 0.16	0.05 $\pm$ 0.24	2.20 $\pm$ 0.44
0.25	-0.19 $\pm$ 0.33	0.16 $\pm$ 0.51	-0.14 $\pm$ 0.19	0.48 $\pm$ 0.22	0.30 $\pm$ 0.48
0.00	-0.50 $\pm$ 0.86	0.03 $\pm$ 0.28	-0.63 $\pm$ 0.25	0.33 $\pm$ 0.24	-0.77 $\pm$ 0.78
-0.25	-1.59 $\pm$ 0.73	0.00 $\pm$ 0.23	-0.23 $\pm$ 0.33	0.46 $\pm$ 0.27	-1.36 $\pm$ 0.80
-0.50	-3.34 $\pm$ 0.76	-0.45 $\pm$ 0.25	-0.05 $\pm$ 0.35	0.65 $\pm$ 0.29	-3.19 $\pm$ 0.82
SPT					
0.50	8.49 $\pm$ 1.48	-0.81 $\pm$ 0.82	-3.80 $\pm$ 1.36	-0.46 $\pm$ 1.08	4.30 $\pm$ 0.68

Torque (Nm)	Finger				
	I	M	R	L	VF
0.25	6.37 ± 1.30	-0.49 ± 1.45	-1.11 ± 0.86	-2.52 ± 1.17	3.36 ± 1.13
0.00	4.91 ± 1.64	-0.94 ± 1.18	-2.40 ± 1.10	-0.64 ± 1.24	2.87 ± 1.22
-0.25	6.08 ± 1.28	-0.82 ± 1.47	-2.42 ± 0.69	-1.31 ± 0.97	4.54 ± 1.31
-0.50	5.17 ± 1.32	-2.64 ± 1.35	-1.78 ± 0.55	-2.58 ± 0.77	1.69 ± 1.47
SQT					
0.50	-6.18 ± 0.52	0.79 ± 0.29	0.92 ± 0.48	1.78 ± 0.38	-2.70 ± 0.24
0.25	-9.18 ± 0.58	1.10 ± 0.42	0.30 ± 0.39	2.69 ± 0.44	-5.09 ± 0.43
0.00	-11.03 ± 0.58	0.22 ± 0.42	0.20 ± 0.39	2.54 ± 0.44	-8.52 ± 0.43
-0.25	-8.80 ± 0.45	0.75 ± 0.52	0.47 ± 0.24	1.97 ± 0.34	-5.61 ± 0.46
-0.50	-11.83 ± 0.47	0.49 ± 0.48	0.44 ± 0.20	2.91 ± 0.52	-7.99 ± 0.52

A3 Safety Margin

Table A3

Effect of digit manipulation on the SM; average change in SM ± SE (units in N)

Task	Finger	Torque (Nm)				
		0.50	0.25	0.00	-0.25	-0.50
SQN	I	-0.10 ± 0.05	0.06 ± 0.04	0.10 ± 0.03	0.14 ± 0.03	0.19 ± 0.03
	M	0.14 ± 0.10	0.22 ± 0.06	0.29 ± 0.07	0.33 ± 0.09	0.35 ± 0.08
	R	0.01 ± 0.01	0.03 ± 0.02	0.05 ± 0.03	0.10 ± 0.03	0.05 ± 0.03
	L	0.01 ± 0.02	0.04 ± 0.03	0.03 ± 0.04	0.06 ± 0.05	0.02 ± 0.05
SPT	I	-0.27 ± 0.04	-0.19 ± 0.05	-0.16 ± 0.04	0.12 ± 0.04	-0.12 ± 0.05
	M	0.19 ± 0.07	0.16 ± 0.11	0.27 ± 0.11	0.30 ± 0.10	0.59 ± 0.11
	R	-0.08 ± 0.03	0.00 ± 0.03	0.00 ± 0.03	0.03 ± 0.03	0.11 ± 0.03
	L	0.06 ± 0.04	0.03 ± 0.03	0.12 ± 0.05	0.14 ± 0.05	0.32 ± 0.06
SQT	I	-0.04 ± 0.06	-0.01 ± 0.04	-0.04 ± 0.04	0.08 ± 0.03	0.09 ± 0.03
	M	0.00 ± 0.04	0.08 ± 0.06	0.22 ± 0.11	0.19 ± 0.05	0.17 ± 0.04
	R	-0.04 ± 0.02	0.00 ± 0.02	0.02 ± 0.02	0.00 ± 0.02	0.01 ± 0.02
	L	-0.09 ± 0.03	-0.19 ± 0.04	-0.13 ± 0.03	0.11 ± 0.04	-0.18 ± 0.05

Figure 1.

(A) Schematic of handle apparatus. Four force/moment sensors and one fake sensor were instrumented on the handle. A bar was fixed to the handle base to which a mass was hung that generated an external torque on the handle. An air bubble was attached to the top of the handle to provide orientation feedback. (B) Local transducer coordinate system.

Figure 2.

Exemplary trials of change in F^n and F^t versus time (as a percent of trial duration). (A) and (B) are F^n and F^t , respectively, from a SQN trial. (C) and (D) are F^n and F^t , respectively, from a SPT trial. (E) and (F) are F^n and F^t , respectively, from a SQT trial. I—index, M—middle, R—ring, and L—little fingers, VF—virtual finger.

Figure 3. Changes in finger normal forces with the torque changes for the tasks: (A) SQN, (B) SPT, and (C) SQT. Figure 3D illustrates the change in VF F^n for SPT and SQT tasks. Error bars are standard error. Abbreviations are the same as in Figure 2.

Figure 4. Changes in F^l for the tasks: (A) SQN, (B) SPT, and (C) SQT. Figure 4D illustrates the change in the VF F^l for each of the three tasks. Error bars are standard error. Abbreviations are the same as in Figure 2.

Figure 5.

Average functional hand centers for each task: (A) SPT, and (B) SQT. The cubic regression lines and equations are shown. The X-axis shows fingers designated by numbers: 1—index, 2—middle, 3—ring, and 4—little.

Table 1

Safety margin (SM) results at the VF level

Task	SM Type	Torque (Nm)				
		0.50	0.25	0.00	-0.25	-0.50
SQN	Virtual	0.84 ± 0.05	0.85 ± 0.04	0.85 ± 0.04	0.81 ± 0.03	0.81 ± 0.03
	Trial End	0.92 ± 0.10	0.93 ± 0.01	0.93 ± 0.01	0.91 ± 0.02	0.92 ± 0.02
	Trial Start	0.92 ± 0.03	0.86 ± 0.02	0.82 ± 0.03	0.77 ± 0.03	0.77 ± 0.03
SPT	Virtual	0.80 ± 0.03	0.80 ± 0.04	0.80 ± 0.04	0.75 ± 0.06	0.76 ± 0.05
	Trial End	0.93 ± 0.01	0.92 ± 0.02	0.90 ± 0.02	0.88 ± 0.02	0.87 ± 0.03
	Trial Start	0.94 ± 0.02	0.92 ± 0.02	0.89 ± 0.02	0.88 ± 0.03	0.81 ± 0.02
SQT	Virtual	1.00 ± 0.03	0.96 ± 0.03	0.89 ± 0.03	0.97 ± 0.03	0.97 ± 0.03
	Trial End	1.00 ± 0.01	0.98 ± 0.01	0.96 ± 0.03	0.99 ± 0.03	0.98 ± 0.02
	Trial Start	0.92 ± 0.01	0.87 ± 0.02	0.84 ± 0.03	0.81 ± 0.03	0.78 ± 0.02

Note. Table 1 contains SM ($\pm$ SE) results at VF level (group averages). Values given at the VF are for the Virtual SM, SM at the start of trials, and SM at the end of trials.

Table 2

Safety margin (SM) results at the IF level

Task	Finger	Torque (Nm)				
		0.50	0.25	0.00	-0.25	-0.50
SQN	I	0.72 ± 0.10	0.92 ± 0.07	0.88 ± 0.09	0.95 ± 0.04	0.96 ± 0.04
	M	0.67 ± 0.18	0.60 ± 0.15	0.54 ± 0.10	0.45 ± 0.10	0.51 ± 0.10
	R	0.92 ± 0.02	0.98 ± 0.03	0.97 ± 0.06	0.90 ± 0.05	0.92 ± 0.05
	L	0.93 ± 0.04	0.78 ± 0.07	0.81 ± 0.10	0.68 ± 0.09	0.71 ± 0.09
SPT	I	<u>-0.65</u> ± 0.22	0.08 ± 0.29	0.50 ± 0.16	0.38 ± 0.18	0.54 ± 0.09
	M	0.96 ± 0.07	0.86 ± 0.38	0.77 ± 0.18	0.69 ± 0.27	0.81 ± 0.15
	R	0.67 ± 0.11	0.91 ± 0.09	0.82 ± 0.09	0.83 ± 0.06	0.92 ± 0.04
	L	0.97 ± 0.10	0.75 ± 0.16	0.97 ± 0.12	0.94 ± 0.21	0.94 ± 0.13
SQT	I	0.28 ± 0.48	0.21 ± 0.20	0.27 ± 0.50	0.68 ± 0.08	0.67 ± 0.05
	M	0.72 ± 0.14	0.48 ± 0.13	0.75 ± 0.17	0.45 ± 0.05	0.52 ± 0.16
	R	0.94 ± 0.03	0.93 ± 0.06	0.92 ± 0.10	0.90 ± 0.04	0.84 ± 0.05
	L	0.76 ± 0.05	0.62 ± 0.10	0.48 ± 0.13	0.55 ± 0.10	0.42 ± 0.20

Note. Table 2 contains SM (± SE) results at IF level (group averages). At the IF level only the Virtual SM is given. The negative value is underlined. See the Appendix for additional SM values at IF level.

Table 3

VF repeated-measures ANOVA results

Response	SQN			SPT			SQT		
	Δ	T	$\Delta \times T$	Δ	T	$\Delta \times T$	Δ	T	$\Delta \times T$
F^m	0.000	0.000	0.366	0.000	0.091	0.188	0.000	0.000	0.222
F^f	0.000	0.000	0.226	0.000	0.000	0.863	0.000	0.000	0.084

Note. Values are p -values for the VF forces. Δ represents change in the outcome variable during instructed force increase (EFFORT factor) and T represents the effect of TORQUE. $\Delta \times T$ is the interaction of Δ and T. Significant values are in bold.