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Inter-digit co-ordination and object-digit interaction when holding an object with five digits

ZONG-MING LI*

Division of Physical Therapy, Walsh University, North Canton, Ohio 44720, USA

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The current study investigated inter-digit co-ordination and object-digit interaction during sustained object holding tasks by using five, six-component force/torque sensors. The sum of the individual finger normal forces and the thumb normal force showed a parallel variation with a mean median correlation coefficient of 0.941. The normal force traces demonstrated the lowest coefficient of variation (about 9% as averaged across digits) as compared with other force/torque traces. The sum for the variances of the normal forces of the index, middle, ring, and little fingers was about 50% of the variance of the summed normal force of the four fingers. Of the five digits, the thumb, index, middle, ring and little fingers accounted for 50.0, 15.4, 14.6, 11.7 and 7.3% of the total normal force; and 39.4, 9.9, 19.3, 14.0 and 17.5% of the total vertical shear force (i.e. the load), respectively. The ratios of the normal force to the resultant shear force were 2.6, 4.5, 1.8, 2.2 and 1.3 for the thumb, index, middle, ring and little finger, respectively. The centre of pressure migration area of a single digit at the object-digit surface during object holding ranged from 0.30 to 1.21 mm^2. The current study reveals a number of detailed object-digit mechanics and multiple digits co-ordination principle. The results of this study may help to improve ergonomic designs that involve the usage of multiple digits.

1. Introduction

Holding an object is a common everyday motor action that entails well co-ordinated mechanical actions between digits and object and among individual digits. The knowledge of the detailed interface mechanics between the digits and object is valuable for designing ergonomic hand tools, as well as to provide necessary inputs for biomechanical modelling. The force co-ordination among digits provides insight on how the central nervous system copes with the stability and redundancy problems (Bernstein 1967, Rosenbaum *et al.* 1993, Flanagan *et al.* 1999).

Since the early 1980s, researchers have extensively investigated grasp stability involving, in particular, precision grip between the thumb and the index finger (Johansson 1996). To prevent slippage of a grasped object, a sufficiently large force normal to the grip surfaces is required. It has been shown that the grip force is adjusted to tangential load (Cole and Abbs 1988), tangential torque (Kinoshita *et al.*

*Current correspondence address: Department of Orthopaedic Surgery, University of Pittsburgh, E1641 Biomedical Science Tower, 210 Lothrop Street, PO Box 71199, Pittsburgh, PA 15213, USA; e-mail: zmli@pitt.edu

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1997), and friction status at the object-digit interface (Johansson and Westling 1988, Edin *et al.* 1992, Cole and Johansson 1993, Flanagan and Wing 1993, Burstedt *et al.* 1999). An adequate safety margin against frictional slipping is maintained without excessive normal grip force (Johansson and Westling 1988, Johansson and Cole 1992).

Most previous studies used uni-directional force sensor to measure the normal force applied at a fingertip. A six-component force sensor enables the advanced study of mechanics at the digit-object interface. For such a force sensor, three orthogonal forces and three orthogonal torques can be measured simultaneously during object manipulation. In addition, the migration of the centre of pressure can be obtained from the force/torque data. Recently, several researchers used six-component force/torque sensors to study how human fingertip forces are controlled at the object-digit interface to maintain grip stability (Kinoshita *et al.* 1997, Burstedt *et al.* 1999, Flanagan *et al.* 1999; Baud-Bovy and Soechting 2001). For example, Kinoshita *et al.* (1997) studied the effects of tangential torque on the control of grip forces during thumb-index precision grip using a single force/torque sensor. Similarly, Burstedt *et al.* (1999) used one force/torque sensor to study fingertip force co-ordination within a hand, between two hands, and between different subjects. Flanagan *et al.* (1999) and Baud-Bovy and Soechting (2001) used three force/torque sensors to study the control mechanisms of object lifting with three digits. However, manual tasks with five digits have not been investigated using force/torque sensors.

Force co-ordination among multiple fingers has been investigated extensively in the past. During maximal voluntary force production by several fingers acting in parallel, the total force is shared among the involved fingers in a specific manner (Latash *et al.* 1998b, Li *et al.* 1998a). The force produced by a given finger in a multi-finger task is lower than the force generated by this finger in a single-finger task, i.e. *force deficit* (Ohtsuki 1981, Li *et al.* 1998a, Li *et al.* 2001). Fingers that were not required to produce force by instruction were involuntarily activated together with voluntarily activated fingers, i.e. *force enslaving* (Zatsiorsky *et al.* 1998, 2000). Fingers demonstrated compensation behaviour so that the variability of total force output is minimized (Latash *et al.* 1998a, Li *et al.* 1998a). However, only the normal force component was used to analyse finger co-ordination in these studies.

It is advantageous to study finger co-ordination during various manual tasks using force/torque sensors with six degrees-of-freedom, as they provide mechanical parameters such as shear force and centre of pressure migration at the digit-object interface. The purpose of the current study was to investigate inter-digit co-ordination and object-digit interaction when performing sustained holding tasks using five miniature force/torque sensors. The specific aims were to examine: (1) normal and shear force sharing patterns among digits, (2) variation of force/torque components, (3) correlation of the opposing normal forces of the thumb and the four fingers, and (4) the centre of pressure migration of individual digits.

2. Methods

2.1. *Participants*

Five men and three women (mean age of 26.3 years, SD = 4.9 years, mean height of 1.72 m, SD = 0.06 m, and mean weight of 85.1 kg, SD = 6.3 kg) participated in the study. The participants had no history of neuromuscular or musculoskeletal disorders related to the upper extremities. Prior to the experiment, each participant signed a consent form that was approved by the Institutional Review Board.

2.2. *Apparatus*

Five, six-component sensors (4 × Nano17, 1 × Mini40, ATI Industrial Automation, Apex, NC) were attached to a rectangular plastic handle (6 × 79 × 140 mm, 0.131 kg) via mounting tape for gripping tasks (figure 1(b)). Each sensor measures force and torque signals (F_x, F_y, F_z, T_x, T_y, and T_z, see figure 1(b) for co-ordinate designation for each sensor), and then converts force and torque into amplified analogue strain-gauge signals. Thirty channels of force and torque signals from the five sensors, after being amplified and multiplexed, converged to a 12-bit analogue-digital converter (PCI-6031, National Instrument, Austin, TX) via 30 BNC (BNC2090, National Instrument, Austin, TX) cable connections. The digitized signals were then transformed into force and torque data by a proper vector and matrix computation associated with each sensor. The force and torque data were instantly constructed and displayed on the screen while a subject was performing a grip task. The resolution for Nano17 is 0.013 N for F_x and F_y, 0.025 N for F_z, and 0.063 N-mm for T_x, T_y, and T_z. The resolution for Mini40 is 0.02 N for F_x and F_y, 0.06 N for F_z, and 0.5 N-mm for T_x, T_y, and T_z. The sensors have an approximate gain shift error of 0.1% per °F. The temperature effect was compensated within the software by automatic initialization of each sensor at the beginning of each trial. A flexible LabVIEW (National Instrument, Austin, TX) program with a variety of features (designed by the author) was used for both data acquisition and processing.

Sandpaper (Medium 80, 3M Construction and Home, St. Paul, MN) was attached to each sensor surface to alter friction conditions as well as to minimize temperature effect from each finger. Sensors for the index, middle (M), ring (R), and little (L) fingers were distributed 30 mm apart in the radioulnar direction, but were adjustable in the direction along the fingers. The sensor for the thumb on the opposite side of the handle was located 6.0 mm ulnarly from the centre of the sensor of the middle finger. This location was shown to be the optimal for force production during gripping tasks (Li *et al.* 1998b). The combined mass of the handle and the sensors was 142 g. An additional 907 g (2 lb) weight was attached to the bottom of the handle, creating a total lifting weight of 1049 g (10.3 N).

2.3. *Procedures*

The instrumented handle was hung from the ceiling at a height that enabled each subject to make comfortable grips with the shoulder at 0° of flexion and the elbow at 90° of flexion from a standing position (figure 1 (a)). Prior to data collection, each subject performed 3–5 practice trials of gripping, lifting and holding. The practice session allowed the experimenter to make any necessary adjustments of sensor positions along the length of the finger direction. The adjustment of sensors also helped to ensure that only the digit pads were in contact with the handle during task performance. After the practice trials, participants washed their hands with liquid soap and dried them prior to the experimental session.

Each subject completed three trials of lifting and holding the handle. For each trial, after an auditory prompt, the subject slowly lifted the handle slightly and maintained the lifted handle as stationary as possible for 60 s. The participants could see the handle and their hands throughout the experiment. The data were sampled at a frequency of 100 Hz. Force and torque data were saved on the hard disk for future analysis.

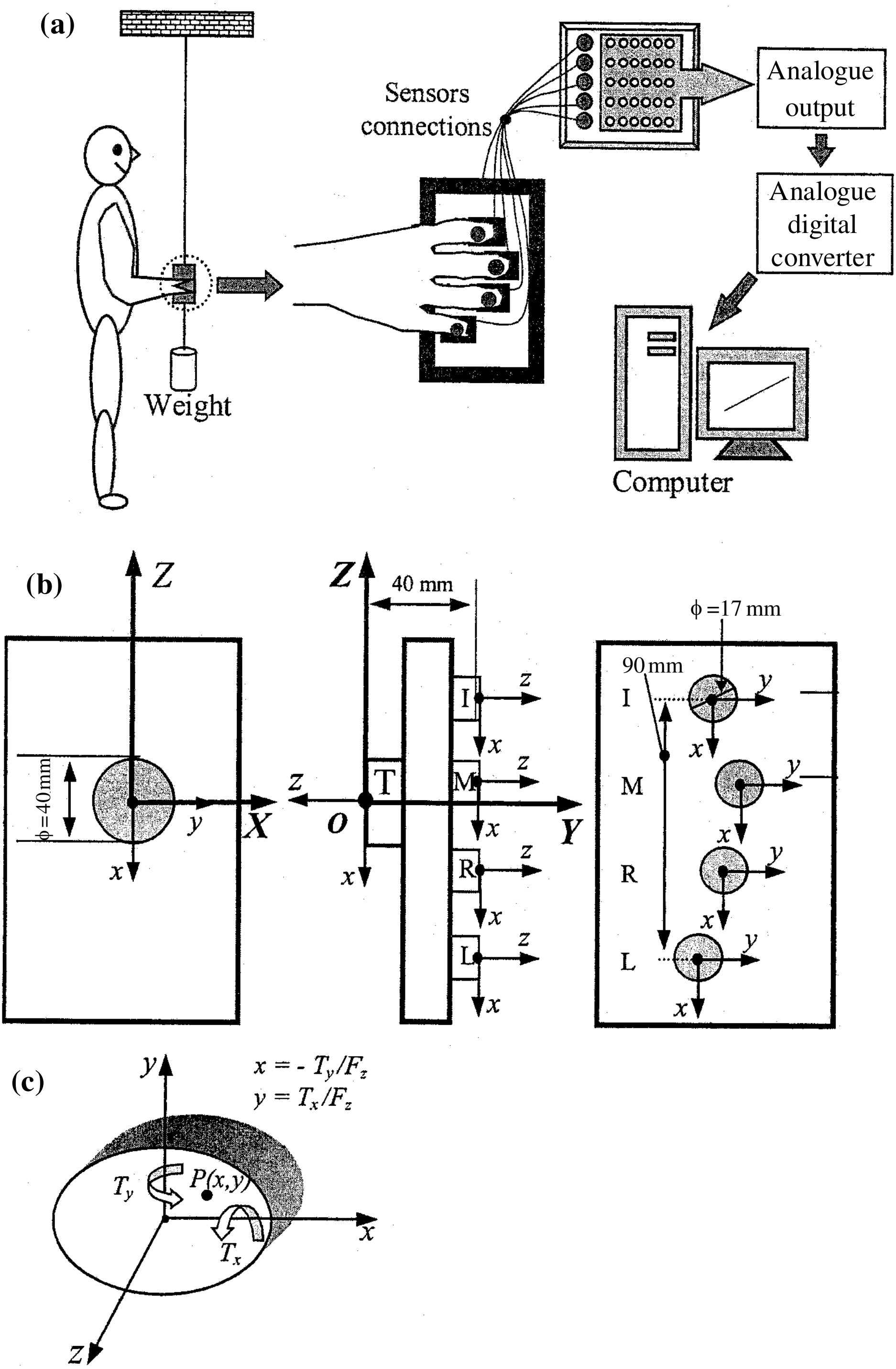

Figure 1. A schematic illustration of the experimental set-up: (a) Task performance and data collection; (b) Instrumented handle with 5 force sensors viewed from the thumb side, the edge side, and the finger side. Each sensor has its own local co-ordinate system that originates from the centre of the gripping surface; (c) Force and torque designation on

2.4. *Data processing*
Two types of data were processed: force/torque data and centre of pressure (COP) data derived from force and torque data. For the force/torque data, the coefficient of variation (CV) was calculated to represent the variability of the signal. The CV is a ratio of the standard deviation to the mean, multiplied by 100%.

The COP during gripping at each digit-object interface was calculated by using the torques about the *x* and *y* axes of the grip surfaces (T_x and T_y) and the normal force (F_z). The location of the COP with respect to the centre of the gripping surface (P_x, P_y) was calculated as follows (figure 1(c)): $P_x = T_y/F_z$, and $P_y = -T_x/F_z$. The COP for each digit was represented relative to its own co-ordinate system. The COP area of individual digits during a sustained gripping task was represented by the elliptical envelope of the COP scattering as determined by a method of principal component analysis (Oliveira *et al.* 1996).

One-way ANOVA and Student *t*-tests were performed for statistical analysis at a significance level of 0.05.

3. Results

3.1. *Raw data*
Figure 2 shows force-time and torque-time curves of individual digits for a representative subject during the first 20 s. A task was generally composed of three phases: preparing, lifting and holding. During the lifting phase, individual digits showed simultaneous increases in forces and torques. The correlation between any pair of digits for any force or torque component ranged from 0.953 to 0.999 during the lifting phase, indicating their simultaneous increase in force and torque production during this phase.

3.2. *Force and force sharing*
The force and force sharing of individual digits in both vertical (F_x) and normal (F_z) directions are shown in table 1. In the vertical direction, all five digits act synergistically to share the load. Of the five digits, the thumb had the highest shear force, accounting for 39.4% of the total load, followed by the middle finger, 19.3%. The index finger shared about 10% of the load, lowest among the five digits (*post-hoc* comparison, $p < 0.05$). In the direction that is perpendicular to the gripping surface, the four fingers and the thumb act in opposite directions. As expected, the sum of individual finger normal forces was equal to the thumb normal force (Student's *t*-test, $p = 0.94$); otherwise, the handle would not be at equilibrium in the horizontal direction. The force percentages are 50.0, 15.4, 14.6, 11.7 and 7.3% for the thumb, index, middle, ring, and little fingers, respectively.

3.3. *Coefficient of variation during holding*
During the holding phase, individual digits demonstrated considerable oscillation in each force or torque component (figure 2). The coefficients of variation (CVs) of the force (F_x, F_y, F_z) and torque (T_x, T_y, T_z) of individual digits are presented in table 2. The first 10 s were excluded from analysis to ensure that the subject had obtained a

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one sensor, as well as calculation of centre of pressure applied on a sensor surface by a fingertip. All of the forces and torques follow the 'right-hand rule'. I for Index, M for Middle, R for Ring, and L for Little fingers.

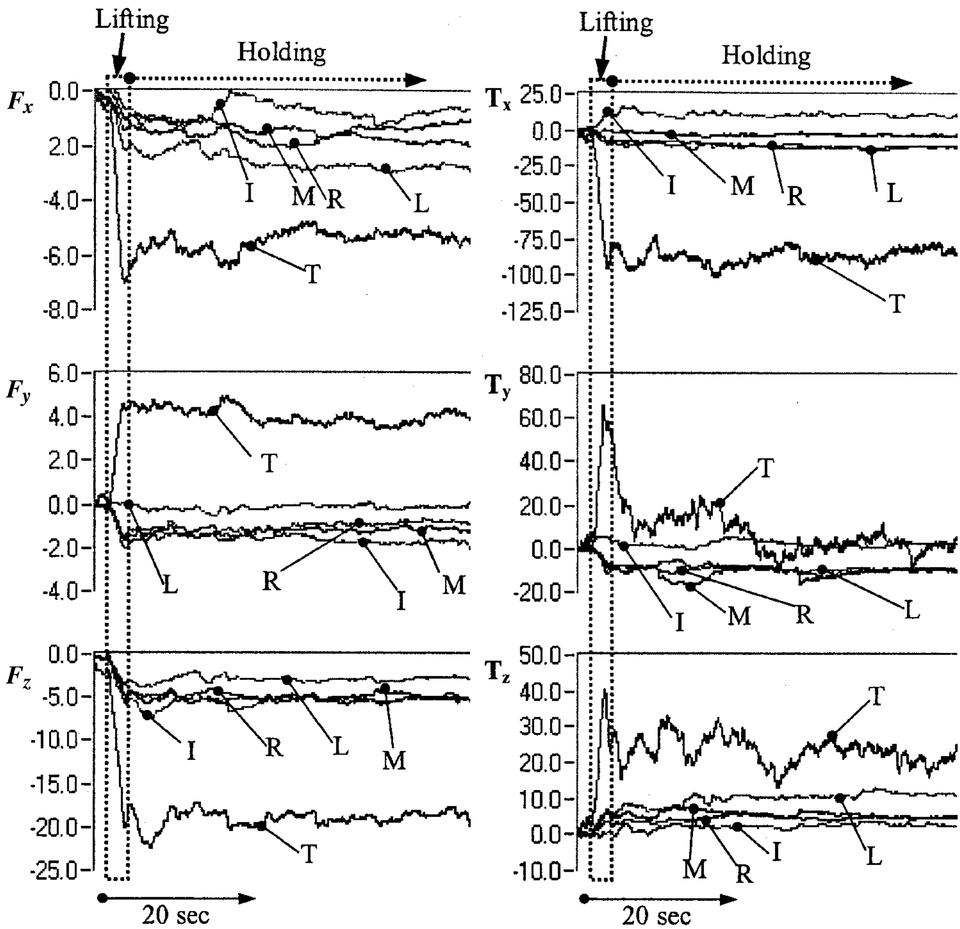

Figure 2. Force and torque traces while lifting and holding the heavy load (10.4 N) weight. Unit for force is N. Unit for torque is N-mm. Note that only a portion (20 s) of the holding phase is shown. The data are represented in their local co-ordinates.

Table 1. Force (N) and force sharing (%) among digits in the vertical (F_x) and normal (F_z) directions during holding phase. Mean (SD) from eight participants.

	Index	Middle	Ring	Little	Thumb
Force (N)					
Vertical	–1.0	–2.0	–1.5	–1.8	–4.1
	(0.5)	(0.6)	(0.6)	(0.7)	(1.0)
Normal	–4.7	–4.4	–3.6	–2.3	–15.6
	(1.7)	(1.4)	(1.4)	(1.4)	(5.0)
Sharing (%)					
Vertical	9.9	19.3	14.0	17.5	39.4
	(5.6)	(5.8)	(5.3)	(7.2)	(7.0)
Normal	15.4	14.6	11.7	7.3	50.0
	(1.5)	(2.1)	(2.3)	(2.6)	(0.5)

comfortable grip, as well as to exclude possible non-stationarity of the force/torque signals at the beginning of the experiment. The CV values ranged from 5.8 to 56.4% (mean = 22.7%) for forces and torques. F_x and F_z showed relatively lower CV values as compared to other force or torque components. For example, the F_z CVs of individual digits ranged from 7.0% to 10.8%.

3.4. *Variances*

Variance analysis provides a tool to investigate the relative dependence of the involved components in producing a common output (Li *et al.* 1998a). The Bienaimé Equality theorem states that for mutually independent and random variables the sum of the variances is equal to the variance of the sum (Loeve 1955).

The sum of the variances of individual finger normal forces, Sum(Var), the variance of the summed individual finger normal forces, Var(Sum), and the variance of the thumb normal force, Var(Thumb), are listed in table 3. It was found that the Sum(Var) was less than Var(Sum) ($p < 0.05$, paired t-test). On average, Sum(Var) was about 50% of Var(Sum). There was no difference between Var(Sum) and Var(Thumb) ($p > 0.05$).

3.5. *Correlation*

The sum of the individual finger normal forces showed a high correlation with the normal force of the thumb. The median correlation value across participants was 0.941 (range from 0.907 to 0.987). Figure 3(a) shows an example of the close match between the two force traces. The mean forces in 50 s were 14.63 N and 14.65 N for the summed force trace and the thumb force trace, respectively. However, a zoom-in

Table 2. Coefficient of variation, (%) of normal force (F_z) and vertical shear force (F_x) during 50 s of sustained holding. Mean data from eight participants.

		Index	Middle	Ring	Little	Thumb	Mean across digits
F_x	Mean	20.0	7.0	12.3	8.6	5.8	10.7
	SD	18.2	3.4	16.3	2.8	2.7	
F_y	Mean	38.8	12.8	23.0	56.4	6.9	27.6
	SD	56.5	3.2	15.7	23.8	3.5	
F_z	Mean	10.0	9.0	7.7	10.8	7.0	8.9
	SD	3.7	5.2	3.9	3.3	3.0	
T_x	Mean	23.7	25.2	24.1	30.4	11.8	23.0
	SD	15.9	20.9	25.5	34.3	10.7	
T_y	Mean	33.1	33.2	23.1	44.9	16.9	30.2
	SD	38.2	47.7	10.6	54.3	10.4	
T_z	Mean	31.0	28.2	22.0	48.4	36.2	33.2
	SD	24.2	31.9	17.6	57.8	31.2	

Table 3. Sum of the variances of individual finger normal forces, Sum(Var), variance of the summed individual finger normal forces, Var(Sum), variance of thumb normal forces, Var(Thumb), and ratio values.

	Sum(Var)	Var(Sum)	Var(Thumb)	Sum(Var)/Var(Sum)	Var(Sum)/Var(Thumb)
Mean	1.04	2.29	2.35	0.48	0.94
SD	0.98	2.16	2.50	0.16	0.12

graph of 2.5 s (figure 3 (b)) demonstrates deviations between the two forces, leading to a decrease in the correlation coefficient ($r = 0.755$). The correlation of the normal forces among the index, middle, ring, and little fingers were inconsistent across participants as well as across trials.

A high-pass filter was applied to the thumb normal force and the summed normal forces of the four fingers, and the correlation between the two was then calculated. Figure 4(a) presents the change of the correlation coefficient after high-pass signal filtering at various cut-off frequencies. At a low cut-off frequency of 0.01 Hz, most of the signal components were retained, thus the correlation was close to 1.0, similar to that shown in figure 3(a). The correlation coefficient decreased with increasing cut-off frequency, and reached a negative plateau after about 4 Hz (figure 4 (a)). The mean correlation coefficient after a 4 Hz cut-off was −0.420 (range from −0.537 to −0.232). The negative correlation between the two force traces was readily appreciable in a zoom-in graph (figure 4 (b)).

3.6. *Centre of pressure*

The centre of pressure can be presented in a time series or mapped in the contact surface plane, i.e. *x-y* plane. Figure 5 shows the COP migration of individual digits

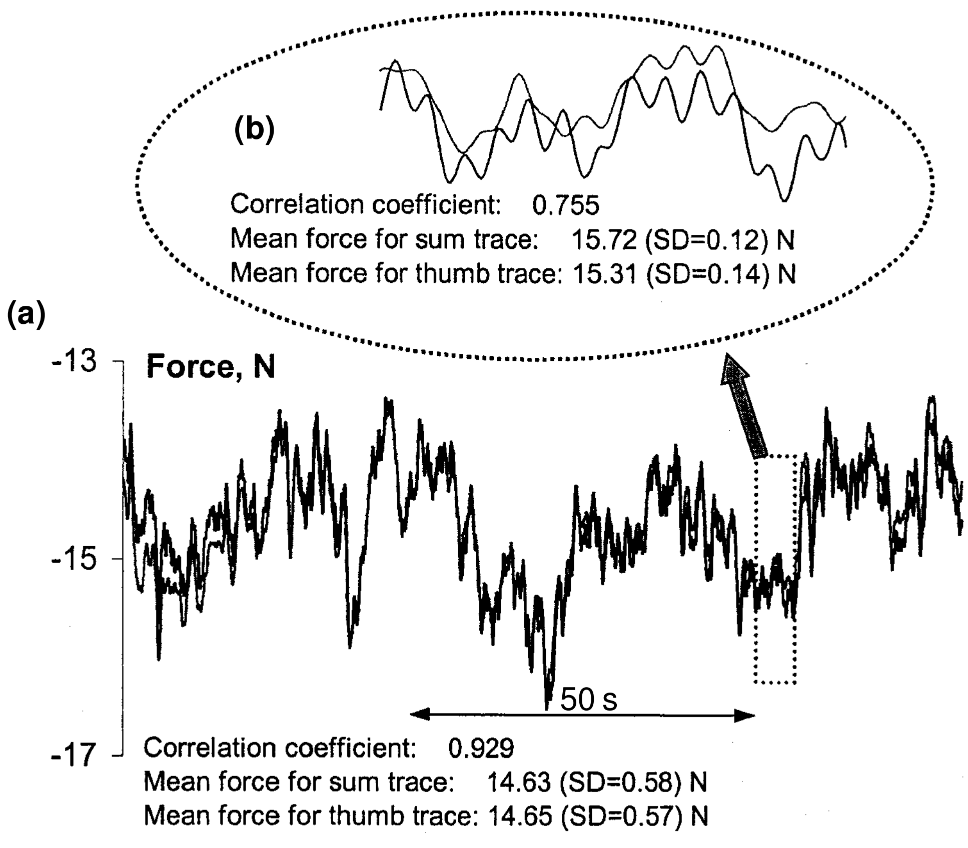

Figure 3. Normal force (N) produced by the thumb and summed normal forces of the index, middle, ring and little fingers. (a) A representative trial in 50 s, and (b) a zoom-in graph of 2.5 s.

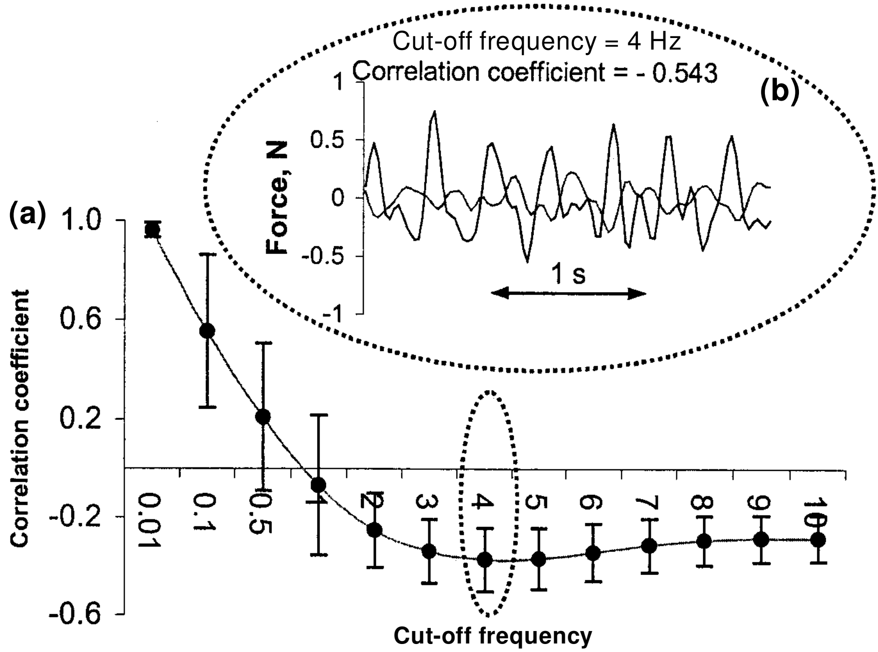

Figure 4. (a) Correlation of the normal force of the thumb and the sum of the normal forces of the four fingers after filtering using high-pass filter at different frequencies (a period of 50 s). Mean of median value ± SE from 8 participants. (b) A zoom-in graph (1 s) showing the anti-phase relationship (negative correlation) between the two force traces for a representative subject.

during a sustained holding period (50 s). Both temporal and *x*-*y* spatial data are shown, as well as the SD values over 50 s. The elliptic areas were derived from spatial scattering of COP_x and COP_y data. The COP fluctuated (e.g. figure 5(a)A1) or migrated (e.g. figure 3(d)D1) in both the *x* and *y* directions. Similar to the regional patterns that were previously described by Duarte and Zatsiorsky (1999) in prolonged unconstrained standing (30 min), two types of regional manifestations were observed in the gripping task: single-region (figure (a)A3) and multi-region (figure (c)C3) gripping. For example, the little finger demonstrated 'stay and go' diagonal COP movement. However, not all participants or all fingers demonstrated the multi-region patterns.

The COP areas derived from force/torque signals, on average, ranged from 0.30 to 1.21 mm^2 (table 4). The COP areas were different for different digits (F (4,70) = 12.05, $p<0.001$). The thumb demonstrated the largest COP area, followed by the little finger, which was followed by comparable COP areas of the index, middle and ring fingers. The standard deviation of the temporal COP in the *x* and *y* directions ranged from 0.13 to 0.39 mm for all digits.

4. Discussion

4.1. *Variability*

While a perfect constant performance output is not expected for the human motor system, the same is true when applying grip force to hold a constant load. When a subject is asked to maintain a force over an extended period of time with digit

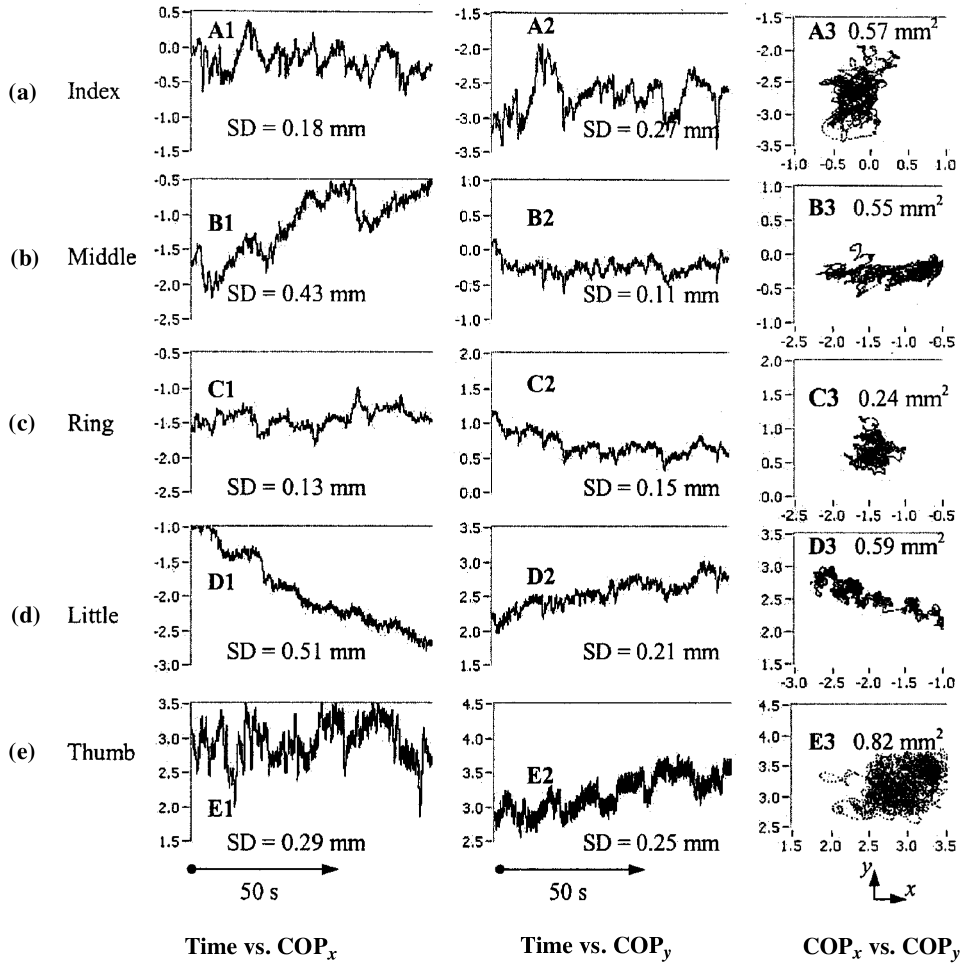

Figure 5. Centre of pressure (COP) temporal migration and spatial scattering of individual digits during a 50 s holding period. *x-y* co-ordinates are in the local co-ordinate system (mm). Subject FP.

Table 4. COP areas (mm^2) of individual digits from eight participants.

	Index	Middle	Ring	Little	Thumb
Mean	0.53	0.48	0.52	0.88	1.21
SD	0.31	0.39	0.38	0.39	0.55

flexors, the force is not constant, but it fluctuates instead (Mai *et al.* 1985, Gandevia and Kilbreath 1990, Jones 1998). Gandevia and Kilbreath (1990) found a coefficient of variation of about 15% in tasks when participants matched a force generated by one muscle (flexor digitorum profundus, first dorsal interosseus, adductor pollicis, flexor pollicis longus, or biceps bracchii) by generating a force of similar perceived amount with the similar muscle of the contralateral side. Mai *et al.* (1985) reported a higher accuracy of force control (1 – 4% absolute error) when participants maintained a force with visual feedback using a thumb-index precision grip, but the performance error increased to about 6% when only proprioceptive cues were available without visual feedback. In the current study, tasks with five digits resulted in a mean coefficient of variation of about 9%, which falls between the error reported for thumb-index precision grip (Mai *et al.* 1985) and the error reported for the matching task (Gandevia and Kilbreath 1990). The relatively high variation found in the matching task of Gandevia and Kilbreath (1990) is thought to be due to errors that involved dual processes of force perception and force generation (Jones 1998). It is generally believed that the index finger is the best-controlled finger (Fahrer 1981, Valero-Cuevas *et al.* 1998, Zatsiorsky *et al.* 1998). Therefore, it is well equipped to precisely control force such as in precision grip tasks. It can be expected that when the four fingers are combined to form an assemblage to oppose the thumb, the capability of force control is less accurate than the thumb-index set. Surprisingly, the index finger demonstrated relatively high variation as compared with other fingers (table 2) in five-digit gripping. In the framework of synergy (Turvey and Carello 1996), the index finger may be viewed as a flexible component that is constantly called up to compensate for the variation in other fingers.

When a motor task involves multiple contributors, variability has been studied in terms of the 'end product' and the contributing factors (Bernstein 1967, Cole and Abbs 1986, Darling *et al.* 1988, Li *et al.* 1998a). For example, the blacksmiths in Bernstein's study demonstrated better trajectory reproducibility at the end-point than at the involved individual joints. Cole and Abbs (1986) reported that joints in the finger and thumb co-ordinated in order to minimize variations in the distal point of contact.

In consecutive maximal voluntary contraction (MVC) attempts with all four fingers in parallel, people do not generally reproduce the same magnitude of total force or forces with individual fingers (Li *et al.* 1998a). It has been reported that the sum of the variances of individual fingers is greater than the variance of the total force, i.e. the variations of individual finger forces are negatively correlated (Li *et al.* 1998a). This means that individual fingers act in a compensatory manner so that the total force output is changed minimally. According to the central ceiling hypothesis (Li *et al.* 1998b), if one finger, in one attempt, consumes a larger-than-usual neural drive, another finger is unfavourably affected in sharing neural drive. The compensation (or synergy) among a set of individual effectors has been viewed as a self-organized, autonomic level of motor control, and has been suggested as an important mechanism in solving the redundancy problem (Latash 1998a,b, Turvey and Carello 1996).

The current study investigated the force variances of individual digits over an extended period of time when holding an object, rather than the variability due to multiple MVC tasks. It was found that the sum of the variances of normal forces of individual fingers was less than the variance of the normal force of the thumb (table 3). This data is opposite to the findings of Li *et al.* (1998a). According to the two-level control hypothesis, another source of variability in the total force output is attributable to the 'noise' of the central nervous system (Turvey and Carello 1996). If all the variability in total force production were only due to the variability of the CNS neural drive, forces of individual fingers would change in parallel, leading to a greater variance for the total as compared to the sum of the variance of the individuals; on the other hand, if individual components act with synergy under a relatively constant central neural drive, the variance of the sum is smaller than the sum of the variances of the components (Li *et al.* 1998a).

The finding that the variance of the sum is greater than the sum of the variance of the individual may be due to increased variability at the upper level, i.e. increase in CNS noise, and/or decreased variability at the synergy level. First, in contrast to MVC tasks, the submaximal contraction of finger flexors during holding a relatively light object renders more room for the oscillation of the central neural drive. Second, positive correlations among the digits is necessitated by the task mechanics, i.e. keeping the handle stationary in the air. For example, if the index finger increases its force production, the handle tends to rotate with respect to the thumb support in the direction of pronation; the ulnar fingers (i.e. the ring and little fingers) must increase their forces to prevent the rotation. The task constraints may prompt the individual components to act as a structural unit, leading to less degrees of freedom and less redundancy.

4.2. *Correlation*

In the grip tasks employed in the current study, the four fingers act as a group to form a 'virtual finger' (MacKenzie and Iberall 1994), opposing the thumb in the direction that is perpendicular to the gripping surface. The normal force of the thumb and the summed normal force of four fingers displays a positive correlation at the 'macroscopic' level and negative correlation at the 'microscopic' level. Macroscopically, the two opposing forces varied in parallel, i.e. an increase in the normal force by the virtual finger was accompanied by an increase in the thumb normal force, and vice versa. When the trendline of each force signal was removed by a high-pass filter at above 3–4 Hz, the two forces were somewhat anti-phased as indicated by the negative correlation.

A single force trajectory may be considered to be composed of two components: an equilibrium trajectory and a 'trembling' trajectory. The equilibrium component is a low frequency component that underlies its co-variation with its opposing force. This tight co-variation between the opposing forces is necessitated by the task constraint, i.e. maintaining the balance of the handle in the air.

The trembling trajectory is the component that is superimposed on the equilibrium trajectory, and may be attributable to horizontal acceleration that resulted from physiological hand tremors (Allum *et al.* 1978, Sakamoto *et al.* 1992, Jones 1998, Morrison and Newell 1999). A sinusoid-type movement is associated with tremoring, leading to alternating acceleration (Jones 1998). The acceleration induces an inertial force that superimposes to one side of the grip surface and de-imposes to the other side of the grip surface, which explains the negative correlation between the trembling components. Peak oscillation frequency has been reported in the range of 2–25 Hz. Sakamoto *et al.* (1992) reported that each digit has two peak tremulous frequencies at 10 and 25 Hz, and suggested that the lower frequency component originated from the central nervous system as a long loop, and the higher frequency originated from the muscle-spine loop system as a short loop. The oscillation frequency shifts toward lower frequency domain when external load is imposed upon the fingers (Brown *et a*l. 1982, Arihara and Sakamoto 1999). For example, Allum *et al.* (1978) found a local peak force fluctuation frequency of 6–10 Hz when normal participants hold stationary isometric contractions with the thumb and the index finger, regardless of the level of contraction force. Brown *et al.* (1982) reported a regular oscillation frequency of 3–6 Hz when the terminal phalanx flexed against a compliant spring for an extra inertial load. Morrison and Newell (1999) reported two prominent hand tremor frequency peaks of 2–4 Hz and 8–12 Hz for an outstretched arm.

4.3. *Safety margin*

To grasp and hold an object, grip force is adjusted automatically at a level that is adequate for slippage prevention (Johansson 1996). Greater load provokes greater grip force so that a constant ratio of grip force to load force is maintained with respect to a specific friction condition (Johansson and Westling 1988). However, most of the previous studies employed index-thumb precision grips. When all four fingers are formed as a virtual finger and are used to oppose the thumb in gripping tasks, the individual unit of the virtual finger acts synergistically in sharing the load force. Surprisingly, the index finger assumed only 1.0 N (9.9%) of total shear force when holding the weight (10.3 N), which was much lower than the proportion held by the little finger (1.8 N, 17.5%). In contrast, the index finger had the highest force sharing among the four fingers in the normal direction. Thereby, individual digits demonstrated different safety margins (table 1). The ratios of normal force, F_z, to the resultant shear force, square root of the squared sum of F_x and F_y, are 2.6, 4.5, 1.8, 2.2 and 1.3 for the thumb, index, middle, ring and little finger, respectively. The little finger has the lowest safety margin, which might be close to the critical level for slippage. The other digits had considerable 'reserve' in preventing the object from slipping.

Each digit had different safety margins in maintaining a load. The question arises as to why not increase the normal force from the little finger, and decrease the normal forces from other digits such that the safety margins are equal, thus decreasing the total amount of normal forces needed to maintain the load. Mechanical and neural control may underlie the facts. First, when holding a stationary object in the air, not only does the tangential load need to be balanced by the friction force between the object-digit interface, but also the rotational effect must be balanced. If the normal force by the little finger is increased, it will bring an increase in the torque in the direction of supination with respect to the pivot point (the thumb). A counterclockwise torque is needed to balance this torque, which further increases the normal forces of the radial fingers, such as the index finger. Second, it has been found that individual fingers share a total force in a specific manner when they act in parallel (Amis 1987, Li *et al.* 1998a). The sharing pattern is rather robust against perturbation (Latash *et al.* 1998b). If the force sharing percentage is recalculated (multiplied by 2) by excluding the thumb, the values are 30.8, 29.2, 23.4 and 14.6% for the index, middle, ring and little fingers, respectively, which is in good agreement with results found in the literature (Amis 1987, Li *et al.* 1998a). It seems that when holding a weight, the central nervous system preserves the sharing pattern of normal force among digits, rather than a constant safety margin of individual digits. Therefore, the vertical shear force of individual fingers may be deemed as one of the by-products of normal force production patterns (Li *et al.* 1998b).

4.4. *Centre of pressure*

Both standing and object-holding involve stability establishment against gravity via interaction between the human body and the environment. The current study applied the traditional approach used in posturographic studies to holding tasks.

Certain slippage may occur at the object-digit interface while the object is held with multiple digits. In the experiment of this study, all participants commented that the 60-s holding tasks were easy to finish without fatigue. However, certain fingers may experience a total COP displacement as large as 1.7 mm in the vertical direction (see, for example, figure 5(c)C3). This relatively large COP migration suggests that slippage may have occurred between the object-digit interface. During precision grip with the thumb and the index finger, it is known that slight slippage of a grasped object through the fingers triggers an increased grip force with a latency as small as 30 ms (Johansson and Westling 1988). It appears that a certain amount of slippage at certain fingers occurred or was allowed to occur without compromising the holding task. Furthermore, the convergent movement of flexing fingers toward the scaphoid tubercle is known in functional anatomy (Tubiana 1981). The movement tendency of the ulnar fingers, in particular the little finger, in the radial direction make them prone to displace at the object-digit interface.

The COP under certain fingers demonstrated a multiple stepwise pattern for temporal data and a multiple regional pattern for spatial data. Recently, three major patterns of COP migration during prolonged, unconstrained standing were reported: shifting, fidgeting and drifting (Duarte and Zatsiorsky 1999). Shifting, as described by Duarte and Zatsiorsky, is a fast, step-like displacement of the average position of COP from one region to another. This is also referred to as 'multi-region standing' when the COP co-ordinates are mapped on the supporting surface. The possible explanation for the COP displacement pattern might be that the COP migration under a finger may occur up to a certain threshold level or even without being detected; however, when the COP (with possible microslips) has accumulated to a certain amount or at a certain speed, the cutaneous afferents under the fingerpad is provoked and additional grip force is applied to prevent further slippage. However, not all fingers demonstrated similar COP migration pattern, agreeing with the findings of Burstedt *et al.* (1999) regarding the independent neural network mechanisms that emerge from local interactions between the object and digits.

In summary, the utilization of five, six-component force sensors enables the study of inter-digit co-ordination and object-digit mechanical interaction during grasping tasks. The total normal force of individual fingers is precisely opposed by the normal force of the thumb when an object is vertically held against gravity. The sum of the variances of the normal forces of the four fingers was smaller than the variance of the summed normal force of the fingers. Individual digits have different safety margins when sharing the vertical load, and demonstrate different centre of pressure migration patterns at the object-digit interfaces. The results of this study may help to improve ergonomic designs that involve the usage of multiple digits.

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