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Prehension synergies: Effects of object geometry and prescribed torques

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Abstract

We studied the coordination of forces and moments exerted by individual digits in static tasks that required balancing an external load and torque. Subjects (*n*=10) stabilized a handle with an attachment that allowed for change of external torque. Thumb position and handle width systematically varied among the trials. Each subject performed 63 tasks (7 torque values × 3 thumb locations × 3 widths). Forces and moments exerted by the digit tips on the object were recorded. Although direction and magnitude of finger forces varied among subjects, each subject used a similar multidigit synergy: a single eigenvalue accounted for 95.2–98.5% of the total variance. When task parameters were varied, regular conjoint digital force changes (prehension synergies) were observed. Synergies represent preferential solutions used by the subjects to satisfy mechanical requirements of the tasks. In particular, chain effects in force adjustments to changes in the handle geometry were documented. An increased handle width induced the following effects: (a) tangential forces remained unchanged, (b) the same tangential forces produced a larger moment T^t, (c) the increased T^t was compensated by a smaller moment of the normal forces T^n, and (d) normal finger forces were rearranged to generate a smaller moment. Torque control is a core component of prehension synergies. Observed prehension synergies are only mechanically necessitated in part. The data support a theory of hierarchical organization of prehension synergies.

Keywords

Prehension; Grasping; Fingers; Force; Hand manipulation; Synergy

Introduction

This study concentrated on coordination of individual digit forces during static stabilization of hand-held objects. To address participation of the central nervous system (CNS) in prehension tasks, we used the notion of a synergy as a task-specific organization of elements in an apparently redundant system (Bernstein 1947, 1967; Gelfand and Tsetlin 1966; for reviews see Turvey and Carello 1996; Latash et al. 2002). A synergy is manifested via (a) adjustments to changes in task parameters; (b) compensation of either or both external and self-inflicted disturbances (for instance, when a force exerted by one finger is voluntarily changed, other fingers compensate for these changes without a time delay, Latash et al. 1998); (c) error compensation reflected in negative correlation among output variables recorded in different trials (Latash et al. 1998, 2001; Li et al. 1998a; Scholz et al. 2002) or in single trials of long duration (Santello and Soechting 2000).

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For the purpose of this study, we adopted the following operational definition: A prehension synergy is a conjoint change of finger forces and moments during multifinger prehension tasks. In the current study, we addressed changes in finger forces caused by variations in task parameters – balanced torque, handle width, and thumb placement.

In the literature, prehension synergies have been approached from different perspectives. In studies of rapid pinch movements of the index finger and thumb from an open-hand position, Cole and Abbs (1987, 1988) found that the finger and thumb are not controlled independently but, rather, behave synergistically as a single unit. Santello and Soechting (2000) recorded oscillations of normal finger forces during object holding with five digits for 30 s. Location of the object's center of mass varied among trials. Oscillations of individual finger forces were synchronous and hence were determined by a common multifinger synergy. Baud-Bovy and Soechting (2000, 2002) investigated the organization of three-digit grasping. Subjects grasped an object from above using the thumb, index finger, and middle or ring finger. Results were consistent with a hierarchical model of control. At a higher level, an apposition space is created between the thumb and a virtual finger located approximately midway between the two actual fingers. (By definition, a virtual finger generates the same mechanical effect as a set of actual fingers Cutkosky and Howe 1990; MacKenzie and Iberall 1994; Iberall 1997). At the next level of control, force directions exerted by the two fingers were determined.

Commonly, only normal forces have been measured in finger-force production studies (Kinoshita et al. 1995; Li et al. 1998a, 1998b; Santello and Soechting 2000), but some authors also have studied forces in three dimensions, e.g., Burstedt et al. (1999), Flanagan et al. (1999), Baud-Bovy and Soechting (2001, 2002), and Li (2002). However, conditions for rotational equilibrium of hand-held objects in multifinger grasps have not been addressed. This issue is important because many everyday tasks combine translation of hand-held objects while preserving their rotational equilibrium; for example, eating with a spoon, bringing a full glass to the mouth, etc.

Methods

This study addressed the question of how the CNS handles the motor redundancy for a specific case of multifinger prehension.

Model

Consider a hand-held object grasped by a prismatic precision grip in which the finger tips and thumb oppose each other (Fig. 1, left panel). We limited consideration to planar static tasks. We assumed that friction at the digit-object interface was sufficiently large to prevent the object from slipping at any exerted digit forces.

For the system to be at rest, the sum of all forces and moments acting on the handle should be equal to zero. Hence, the following three requirements should be satisfied: (1) The sum of the normal forces of the four fingers equals the normal force of the thumb:

$$F_{th}^{n}=F_{i}^{n}+F_{m}^{n}+F_{r}^{n}+F_{l}^{n}=\sum_{f=1}^{4}F_{f}^{n} \tag{1}$$

(2) The sum of the digit tangential forces equals the weight of the hand-held object:

$$L=F_{th}^{t}+F_{i}^{t}+F_{m}^{t}+F_{r}^{t}+F_{l}^{t} \tag{2}$$

(3) The total moment produced by the digit forces is equal and opposite to the external torque exerted on the objects:

$$\begin{aligned} T=&\underbrace{F^{n}_{th}d_{th}+F^{n}_{i}d_{i}+F^{n}_{m}d_{m}+F^{n}_{r}d_{r}F^{n}_{l}d_{l}}_{\text{Moment of the normal forces}\equiv T^{n}} \\ &\underbrace{+F^{t}_{th}r_{th}+F^{t}_{i}r_{i}+F^{t}_{m}r_{m}+F^{t}_{r}r_{r}F^{t}_{l}r_{l}}_{\text{Moment of the tangential forces}\equiv T^{t}} \end{aligned} \tag{3}$$

where subscripts *th*, *i*, *m*, *r*, and *l* refer to the thumb, index, middle, ring, and little finger, respectively; superscripts *n* and *t* stand for normal and tangential force components, respectively; *L* load (object weight), *T* torque, and coefficients *d* and *r* moment arms of the normal and tangential force with respect to a preselected center, respectively. Equations 1–3 impose three constraints on the ten variables (finger force components). Hence, the system has seven degrees of freedom (DoF) that can be manipulated by the performer in different ways.

In experiments, the main parameters of equation 3, namely *T*, *d*, and *r*, systematically varied. The torque *T* was changed by suspending a standard load at different distances from the center of the handle. The different positions of the thumb changed the moment arms of the normal forces (*d*), and changing the width of the grip altered the moment arms (*r*) of the tangential forces.

Subjects

Ten right-handed men served as subjects (age 30.5±3.74 years, weight 74.5±9.5 kg, height 1.786±0.095 m, hand length from middle fingertip to distal crease of the wrist with hand extended 19.1±1.3 cm, hand width 9.2±0.53 cm). Subjects had no previous history of neuropathies or trauma to the upper limbs. All subjects gave informed consent according to the procedures approved by the Office for Regulatory Compliance of the Pennsylvania State University.

Equipment

An aluminum handle was attached to the top edge of an aluminum beam (5.0 cm×85.0 cm×0.6 cm) at the midpoint of the beam in the mediolateral direction (Fig. 1, right panel). Five six-component force/moment transducers (four nano-17 for the fingers, one mini-40 for the thumb, ATI Industrial Automation, Garner, N.C., USA) were mounted on the handle. An eye-hook hanger was located along the bottom edge of the beam; it was used to suspend a weight. The hook position in the mediolateral direction could be varied by sliding the hook in the slot that ran the length of the beam. A level was attached to the top of the handle to monitor its orientation and avoid rotation of the handle/beam unit about the *x* and *z* axes.

The center points of the index and middle finger sensors were located 45.0 mm and 15.0 mm, respectively, above the midpoint of the handle. The center points of the ring and little finger sensors were located −15.0 mm and −45.0 mm, respectively, below the midpoint. The thumb transducer position was varied across trials: (a) middle position – the center line of the thumb sensor was at the midpoint of the handle; (b) bottom position – the center line of the thumb sensor was at the midpoint between the center lines of the ring and little finger sensors; and (c) upper position – situated at the midpoint between the center lines of the index and middle finger sensors. Grip width (distance between the surface of the thumb contact and that of the finger contacts) was also varied across trials: 60 mm, 75 mm, or 90 mm.

Surfaces of the transducers were covered with 100-grit sandpaper. To measure the static friction coefficient between the skin and sandpaper, the subjects were asked to grasp the handle and then to let it slip. The friction coefficient was estimated from the ratio of the tangential and normal force at an incipient slip. For different subjects, the coefficient ranged between 1.4 and 1.5.

The thirty force/moment signals were digitized by a 12-bit A/D converter (PCI-6031, National Instrument, Austin, Tex., USA) at 50 Hz and processed by a PC computer (Gateway AMD800, North Sioux City, S.d., USA).

Experimental procedure

Subjects were given an orientation session before testing to become familiar with the experimental apparatus and to ensure that they were able to accomplish the experimental tasks. Their height, weight, and hand dimensions were measured. Before the experiment, subjects washed their hands with soap and warm water to normalize skin condition.

Subjects sat in a chair alongside a table, with the right upper arm positioned at approximately 45° abduction in the frontal plane and 45° flexion in the sagittal plane. The elbow joint was flexed approximately 45°. The forearm, but not the wrist and hand, rested on the table. The forearm was pronated 90° so that the hand was placed in a natural grasping position. Special attention was given to digit placement on the sensor such that the center of the digit surface coincided with the center of the sensor.

During the experiment, a 0.35-kg load was suspended from the beam at different positions with respect to the middle of the beam. Suspending the load at different positions caused external torques of 0.333 Nm, 0.667 Nm, and 1.0 Nm in both clockwise and counterclockwise directions. Suspending the load in the middle corresponded to a zero torque. Total weight of the apparatus with the load was 14.1 N.

Subjects were instructed to take the handle from a rack, place the forearm on the table, and hold the handle statically in the air while maintaining the horizontal orientation of the level located on the top of the handle. They were then instructed to hold the handle “naturally with minimal force exertion.” When they reported that they were holding the handle comfortably, data recording started. Signals were recorded for 2 s, after which subjects placed the handle back on the rack. On a separate day, the experiment was repeated but the subjects were asked to produce maximal voluntary force (maximal voluntary contraction, MVC) on the handle at each of the 63 experimental tasks, one trial for each task.

Signals were set to zero before each trial. The order of the trials was pseudo-randomized. Breaks of at least 90 s were provided between trials to avoid fatigue. The total duration of each experiment was approximately 2 h.

Data analysis

Data acquisition software written in LabVIEW (National Instrument, N.C., USA) was used to convert digital signals into force and moment values. Data were digitally low-pass filtered with a second-order Butterworth filter at 5 Hz. For each trial, data were averaged over 1.8 s of the holding period (excluding 0.1 s at the beginning and at the end of the period). Data reduction was performed using Matlab (Mathworks, Inc., Natric, Mass., USA). Statistical analysis was performed in Minitab (Minitab Inc,. State College, Pa., USA).

In the transducer-fixed reference system, forces normal to the transducer surface corresponded to the z direction F_z. In this experiment, F_z was oriented horizontally with respect to the environment. Due to technical reasons, the transducers were mounted on the handle such that the x and y axes deviated from the horizontal and vertical axes, respectively. Thus, the resultant of the forces F_x and F_y exerted in the x and y directions was computed (the tangential force).

Since the task was static, the tangential force always acted in the vertical direction. Upward tangential forces and counterclockwise moments were defined as positive.

1. Wrench reconstruction. The finger-sensor interaction was modeled as a soft-finger contact (Mason and Salisbury 1985). In soft-finger contacts, the sticking of the fingertip to the sensor is not allowed; finger forces are unidirectional (the fingers can only press on the object but they cannot pull on it), and the vector of free moment M_C is normal to the sensor surface. Fingers can, however, roll on the sensor surface. Hence, the point of force application can displace. With six-component force/moment sensors, the wrench W_O is collected as a six-component vector $W_O=(F_x, F_y, F_z, M_x, M_y, M_z)$. The position of the point of force application on the sensor surface (x, y) and free moment M_C were solved as

   $$(x, y)=\left(-\frac{M_y}{F_z}, \frac{M_x}{F_z}\right); \; M_C=M_z - xF_y - yF_x \tag{4}$$

   In the studied tasks, free moments were found to be small, e.g. the average value of the free moment exerted by the thumb was only 0.014±0.008 Nm. Free moments will not be discussed in this paper.

2. Moment arms of normal forces. Moments of the normal finger forces were computed with respect to point of application of the thumb force. Because the fingertips deform and roll on the object surface, the points of finger point application displace. Therefore, the moment arms d_f are different in various trials. For a finger f, the moment arm of the normal force with respect to the point of the thumb-force application was computed as:

   $$d_f=d_f^s+d_f^{tr} - d_{th}^{tr} \tag{5}$$

   where the superscript s refers to the projected distance from the center of the finger sensor to the center of the thumb sensor (see Fig. 1), and the superscript tr refers to the distance from the point of digit force application to the center of the sensor in a given trial tr.

   Displacement of the points of finger forces application was less than 3.0 mm. However, displacement of the point of thumb force was substantial – up to 11 mm. These data will not be discussed here.

3. Moment arms of tangential forces. Moments of tangential digit forces were computed with respect to the midpoint between the surfaces of the thumb and finger sensors. Moment arms for the digits were equal in magnitude, but the thumb's moment arm had the opposite sign to the finger forces. As a result, tangential forces of the fingers and thumb pointing in the same direction generated moments of force in opposite directions. The following equation is valid:

   $$T^t=\left(\sum_{f=1}^{4} F_f^t - F_{th}^t\right)r \tag{6}$$

   Hence, the moment of tangential forces is proportional to the difference between the total tangential force of the four fingers combined (tangential IMRL force) and the tangential force of the thumb.

4. Data homogeneity. Data recorded on an individual subject during one task were considered one ten-dimensional vector, with the normal and tangential components of the five digit forces as the elements. The cosines of the angles formed by the vectors were computed using usual procedures of vector algebra:

$$C=\frac{\mathbf{P}\cdot\mathbf{Q}}{PQ} \tag{7}$$

   where **P** and **Q** are the ten-dimensional force vectors recorded on two subjects, *P* and *Q* are the magnitudes of these vectors, the expression **PQ** denotes the scalar product of the vectors, and *C* is the cosine of the angle formed by the two vectors in the ten-dimensional space. *C* is analogous to Pearson's coefficient of correlation between the two vectors: the mathematical procedures used for computing the cosines and correlation coefficients are identical. *C* signifies a level of similarity between the force sets obtained from two subjects. Eigenvalue and eigenvector analysis was then performed on the matrices of the cosines obtained in each of the 63 tasks. This analysis is similar to principal component analysis known in statistics.

5. Factorial repeated measure MANOVA was employed to analyze the effects of three factors – torque (seven levels), width (three levels), and thumb position (three levels) – on ten outcome parameters, the digit normal, and tangential forces. In addition, a three-factor ANOVA was performed to assess the effects of the factors on each individual variable.

Results

Intersubject variability versus consistency of individual data

Magnitude and direction of digit forces in single tasks varied substantially among subjects (Fig. 2). Based on these observations, the question was posed whether different subjects use similar force patterns (with some individual variations) or the differences between subjects are so large that subjects fall into two or more distinct groups. The computed cosines values were large – on average, 0.96 – with the standard deviation 0.08 (from the total number of 2,835 cosines = 63 tasks × 45 paired comparisons). In each of the 63 matrices of the paired cosine values, the eigenvalue analysis yielded only one significant value that accounted for 95.2–98.5% of the total variability. The largest second eigenvalue was only 2.2%. Hence, in spite of the apparent differences among subjects, all employed essentially similar patterns of finger forces and thus analysis of pooled data, including MANOVA and ANOVA, was justified.

MANOVA and ANOVA results

MANOVA tests of significance (Wilk's, Lawley-Hottelling's, and Pillai's) confirmed that the main effects of each of the three factors – torque, width, and thumb position – were statistically significant ($P<0.001$). Detailed MANOVA results explaining the effects of each factor and their interaction on each individual variable cannot be presented here due to space limitations. Therefore, we limit ourselves to ten, three-factor ANOVAs (see Table 1).

Torque variations induced statistically significant changes in all digit forces, both normal and tangential ($P<0.001$). The handle width variations did not affect tangential forces. Width variations produced statistically significant effects on the normal force of the little finger ($P=0.003$); effects on middle-finger normal force were close to significant ($P=0.084$). Variations in thumb position resulted in statistically significant changes in tangential forces ($P<0.001$ for all five digits); changes in normal forces were statistically significant only for the index and middle fingers.

Normal forces of the virtual and real fingers

Action of the four fingers combined (the IMRL force) can be replaced by an action of one imaginary finger, the virtual finger (Cutkosky and Howe1990; Mackenzie and Iberall 1994; Baud-Bovy and Soechting 2001). Plotting virtual finger force versus thumb force yielded one positive rectilinear relationship between the two forces (this result was expected from equation 1), (Fig. 3a). Graphs for actual finger forces were more complex, (Fig. 3b, c, d, e). Curves resembled rotated and distorted letters V, with the branches corresponding to pronation and supination torques, respectively. Note that for the radial and ulnar pairs of fingers, the left (upper) and right (bottom) branches of the V-curves corresponded to different directions of force production. Hence, the normal force of the virtual finger behaved differently from individual finger forces. This finding justifies separate analyses of the virtual and real finger forces.

Virtual finger forces

When the torque changed from −1.0 Nm to 1.0 Nm, the tangential force of the thumb decreased (Fig. 4a) while the tangential force of the virtual finger increased (Fig. 4b). Thumb position substantially affected the magnitude of the tangential forces, whereas handle width induced much smaller effects. When the thumb was in the upper position, the tangential thumb force decreased whilst the virtual finger tangential force increased by the same amount. Opposite changes were observed with the thumb in the bottom position. As a result, a plot of the thumb versus the virtual finger tangential forces yielded one rectilinear negative relationship that was independent of thumb position and handle width (Fig. 4c). The latter result was expected from equation 2.

Equations 1–3 do not specify the percentage contribution of normal and tangential forces into total torque production, T^n and T^t. Hence, selection of T^n and T^t represents a subject's preference (Fig. 5).

When the thumb was in the middle position, the relation was approximately linear. Regression equations were for the width 60 mm: T^n=0.03+2.22T^t (R^2=0.97); for the width 75 mm: T^n=0.073+1.29T^t (R^2=0.98); and for the width 90 mm: T^n=0.032+1.06 T^t (R^2=0.99). Intercepts of the regression equations were small. This means that, on average, the percent contribution of T^n and T^t remained approximately constant throughout the entire range of generated moments. The percent contribution depended on handle width and, for T^t, equaled approximately 31.1% at the width 60 mm, 43.7% at the width 75 mm, and 48.5% at the width 90 mm. Hence, although the tangential forces of the thumb and virtual finger did not change systematically with handle width, (see Table 1 and Fig. 4a, b), the percent contribution of tangential forces into the total moment increased with handle width. The reason behind this change is the increase of the moment arms, r_i: tangential forces of the same magnitude produced larger moments when the moment arms increased.

With the thumb at the top and bottom positions, the percentage contribution of T^n and T^t into the total torque varied throughout the entire range of the torque changes (see Fig. 5a). It was sharply different for the pronation and supination torques.

Because the contribution of T^t to the total moment is not mechanically necessitated, individual subjects may be expected to show different percentages of total torque produced by T^t (Figs. 5b and 6). For the majority of subjects, moments of normal forces, and correspondingly moments of tangential forces, were not zero at zero total torque values. When no torque was required, subjects tended to generate a certain moment of normal forces that were counterbalanced by an equal and opposite moment of tangential forces. This fact was much more evident in individual subjects' data than in the group averages.

Subjects who tend to produce a larger/smaller percentage of the total torque with T^n in one task were inclined to do so in other tasks. Fig. 5b illustrates this assertion: at any value of the moment of the tangential force T^t, subject 7 generated a moment of normal forces T^n larger than the group average, while subject 8 always produced T^n smaller than the average. Among 21 coefficients of correlation between moments of normal forces (MN), 11 exceeded the level of statistical significance ($P<0.05$). For instance, correlation coefficients between MN R1, MN R2 and MN R3 (middle thumb location, w1) were equal to $r_{12}=0.906$, $r_{13}=0.801$, and $r_{23}=0.772$, respectively. However, correlations of sharing percentages with (a) the maximal grip force recorded at a given torque-thumb position-width combination, (b) the total normal force $\sum F_f^n$ in a trial; and (c) hand dimensions were close to zero. None of these variables affected the percentage contribution of normal and tangential forces into total torque production. Attempts to find a canonical correlation between the different sets of input and output variables failed also; correlation coefficients were low and nonsignificant.

Discussion

The present discussion addresses the following topics: (a) torque control as a core constraint of prehension synergies; (b) ‘local’ solutions versus ‘chain’ effects; (c) hierarchical organization of prehension synergies; (d) control of virtual forces; and (e) control of individual finger forces.

Torque control

Static equilibrium requirements (equations 1–3) impose mechanical constraints on digit forces and moments. Torque constraint (equation 3) includes all experimental variables, ten force components, and the corresponding moment arms, while each of the other two equations deal with five force components only. Hence, we view this constraint as potentially a core one, defining prehension synergies; this constraint was responsible for the complex changes in the finger force pattern observed when independent variables were manipulated.

Consider as an example a task where the thumb changes its position from the central position to the mid-distance between the index and middle fingers. Thumb displacement changes the moment arms of normal finger forces with respect to application point of the thumb force; in particular, the moment arm of the index finger force decreases and the moment arm of the little finger force increases. If the fingers exert the same normal and tangential forces as previously, the handle would rotate clockwise. To prevent the rotation (to satisfy equation 3), the central controller has several options. For instance, it can increase the normal force produced by the index finger and leave other finger forces unchanged. (The thumb normal force must increase to satisfy equation 1.) Or, it can leave the pattern of the normal forces unchanged but compensate the emerging moment by an additional moment of tangential forces. (In this case the tangential forces should satisfy both equations 2 and 3.) No matter which solution is selected, at least two equations should be satisfied simultaneously. Equation 3 is always one of them. The options are numerous: three equations impose only three constraints on the variables whose number can be estimated as 10 (if only magnitudes of the normal and tangential force components are considered) or 15 (if displacement of the points of force application is also taken into account as a control parameter). Hence, the system is highly redundant. In spite of the redundancy, all subjects produced approximately similar force patterns: in all tasks, the matrices of the paired cosine values (they are equivalent to the correlation matrices) yielded a single significant eigenvalue representing more than 95.0% of the total variability. The similarity of these force patterns suggests that different subjects solve the problem of coordination of individual digits using similar synergies, or perhaps even a single synergy. This finding gives a good reason for asking what people do exactly when they manipulate handheld objects and why they prefer particular force production patterns to others.

Local solutions versus chain effects

Among theoretically available solutions, some involve changes in a smaller number of controlled finger forces. For instance, a change in moment arms of normal forces (induced by thumb displacement) can be compensated, at least theoretically, only by a rearrangement of normal forces. Changes of moment arms of tangential forces (induced by handle width change) can be compensated by a rearrangement of tangential forces only. Obtained data suggest that the central controller does not employ such ’local’ solutions. Unlike biomechanists, the CNS seems to make no distinction between normal and tangential forces provided the desired effect is achieved. Contrarily, (a) moment arm changes of normal forces d_f induced large changes in tangential forces (see Table 1 and Fig. 4a, b); and (b) moment arm variations of tangential forces r did not affect these forces significantly (see Table 1), while they did change the patterns of normal forces. For instance, the normal forces of the peripheral fingers (little and index), changed systematically with handle width. These fingers have the largest moment arms, and their forces were adjusted to minimize moment of normal forces when the handle width increased (Fig. 7)

Observed modifications of finger forces can be described as chain effects in a sense that they can be viewed as a sequence of particular local changes, and their consequences can be either necessitated mechanically or involve choice by the controller. An increase in handle width, and correspondingly of the r_is, did not result in changes of tangential forces as could be expected from a local solution. Instead, the following chain of events was observed: (a) unchanged tangential forces produced a larger moment of tangential forces T^t; (b) increased T^t was compensated by a smaller moment of normal forces T^n; and (c) to decrease the T^n, normal finger forces were rearranged. As a result, normal forces were modified in response to an alteration of moment arms of tangential forces and vice versa. The observed adaptations fit perfectly into the classic prediction made by N. Bernstein (1967), that a synergy “never responds to detailed changes by a change in its detail; it responds as a whole to changes in each small part.” (See Turvey and Carello 1996 for a discussion on synergies in human movements.) The present data suggest that these multi-faceted reactions may result from chain effects.

Hierarchical organization of prehension synergies

Apparent differences in force patterns of the virtual and real fingers (Fig. 3) support an idea that prehension synergies are organized hierarchically. Here, we view digit force and moment production as controlled by a hierarchical system with at least three levels. At the highest level, task parameters were defined for the hand. At the middle level, force and torque constraints were distributed between the thumb and virtual finger (cf. Baud-Bovyand Soechting 2001). For instance, equality of thumb and normal virtual finger forces is maintained for all values of task parameters, i.e., torque, and handle geometry. At the lower level, the force and torque of the virtual finger are distributed among the four fingers.

Formally, this consideration is equivalent to replacement of equations 1–3 by three sets of equations that define:

1. Forces of the thumb and virtual finger (subscript v stands for virtual):

$$F_{th}^{n}=F_{v}^{n} \tag{8a}$$

$$F_{th}^{t}+F_{v}^{t}=L \tag{8b}$$

$$T = T^n + T^t = F^n_v d_v + \left(F^t_v - F^t_{th}\right) r \tag{8c}$$

where d_v is the moment arm of virtual finger normal force, i.e. projected distance from the resultant of normal finger forces to the point of application of thumb force.

2. Normal finger forces:

$$\begin{gathered} F^n_v = F^n_i + F^n_m + F^n_r + F^n_l \\ d_v = \tfrac{1}{T^n}\left(F^n_i d_i + F^n_m d_m + F^n_r d_r + F^n_l d_l\right) \end{gathered} \tag{9}$$

and

3. Tangential finger forces:

$$F^t_v = F^t_i + F^t_m + F^t_r + F^t_l \tag{10}$$

Equation 8 represents the equilibrium conditions at the virtual finger level, while equations 9 and 10 specify finger force sharing patterns at the lower level of the hierarchy.

Control of virtual forces

In equation 8, there are three equations with five unknowns: F^n_v, F^n_{th}, F^t_v, F^t_{th} and d_v Hence, the system has two DoFs that can be controlled by the performer at will. Performers have a freedom to select the values of normal forces, $F^n_{th} = F^n_v$ (provided that the forces are sufficient to prevent slipping) and to decide on the values of T^n or T^t. Selection of T^t specifies the forces F^t_v and F^t_{th} (Equations 3 and 8c). It also specifies T^n and – because F^n_v is already specified– it also specifies d_v. Hence, for a given handle geometry (values of d_s and r), load L, and torque T, any two variables specify all other variables in equation 8. For instance, the thumb force – the normal and tangential components – uniquely defines: (a) total normal force of the four fingers; (b) total tangential force of the four fingers; (3) moment of tangential forces; (4) moment of normal forces, and (5) point of application of the resultant of normal finger forces.

With only two DoFs in which precise values are not prescribed by the task mechanics, the system under consideration belongs to the class of marginally redundant systems (Latash et al. 2001), i.e., systems with a small number of DoFs permitting detailed analysis of the task mechanics and control. However, even at this level of analysis, explanation of the obtained facts is challenging. The percentage contribution of T^n and T^t into the total torque attracts particular interest (Figs. 5 and 6). It is not clear why people prefer the observed percentage distribution to others.

Control of individual finger force

Individual fingers do not produce force in the same direction (Fig. 2). Force generated by the index finger was always directed differently from other fingers. In particular, during supination tasks at −0.67 Nm and −1.0 Nm, the force was directed downward. This finding refutes an explanation that tangential finger forces are generated by pronation or supination of the forearm, and the fingers serve simply as passive force transmitters (the load is taken by the structural elements of the hand, for instance by the fingertips, without either or both active abduction and adduction efforts of the fingers). Such a mechanism is realized in multifingered robotics hands (Gorce et al. 1994; Xiong and Xiong 1997) where normal finger forces are generated by joint actuators while tangential finger forces are resisted passively by hand structure (the finger joints are 1-DoF hinge joints). In human grasping tasks, the fingers are individually controlled (cf. Schieber 1996;Hager-Ross and Schieber 2000), and tangential forces are, at least in part, due to active muscle efforts; otherwise, all fingers would produce forces in similar directions. Still, the reasons behind the observed sharing pattern of tangential forces are unclear. Because moment arms of tangential forces are the same for all fingers, the four finger forces are subjected to one constraint only–equation 10. Hence, there is no mechanical necessity in prescribing a certain percentage of the total tangential force to a given finger.

In the literature, the successful prediction of the individual normal finger forces during torque production tasks was accomplished by minimization of the ‘central commands’, the hypothetical neural variables accounting for the interfinger interaction (‘enslaving’) and computed via artificial neural networks (Zatsiorsky et al. 2002; Zatsiorsky et al. 1998, 2000; Li et al 2002; Danion et al. (2003)). The tangential finger forces and the mechanisms/rules behind their sharing have not been addressed so far.

We would like to finish by emphasizing the following central issues that need to be addressed in subsequent research: (a) the reason behind the observed patterns of sharing the total torque between torques of normal and tangential forces, and (b) the sharing of the total tangential force among individual fingers. Discovering the mechanisms behind the observed sharing patterns is a challenging task.

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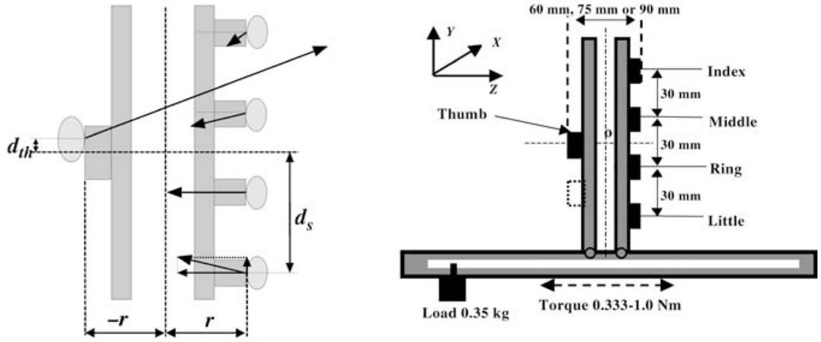
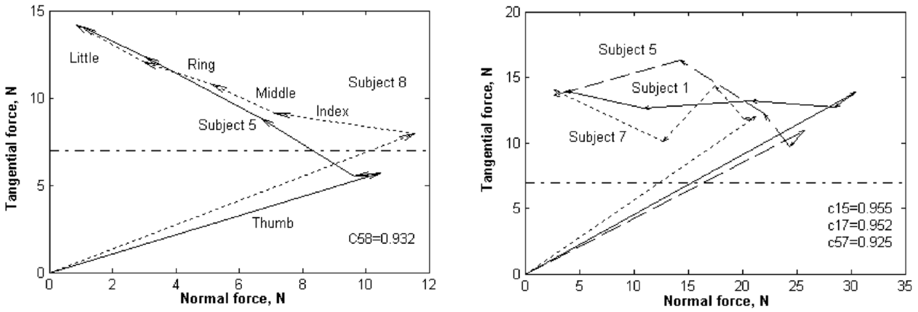


Fig. 1.

Schematic of experimental handle (*left panel*) and experimental ‘inverted-T’ handle/beam apparatus (*right panel*). (r moment arm of tangential digit forces, d_s projected distance from the center of a finger sensor to the center of thumb center, d_{th} displacement of point of application of thumb force with respect to the center of the thumb sensor.) If displacement of the points of application of finger forces is ignored, moment arms of normal finger forces equal the sum d_s+d_{th}. The force components in the z and y directions are called *normal* and *tangential forces*, respectively. The *black rectangles* on the handle represent the sensors. The width of the thumb sensor is 40 mm and the width of the finger sensors is 17 mm. During the experiments, the thumb could be in one of three different locations: the middle position (*black rectangle*), the bottom position (*dotted rectangle*), and the upper position (not shown). Subjects were required to maintain the handle in an upright position. The figure is not drawn to scale



(a) (b)

Fig. 2.

Force vectors for individual subjects (examples). Vectors represent the forces of the thumb, and index, middle, ring, and little fingers, respectively, in a counterclockwise sequence. Middle-thumb position width 60 mm. *Left panel*: torque 0 Nm. *Right panel*: supination torque −1.0 Nm. C_{nk} is a cosine between the ten-dimensional force vectors for subjects *n* and *k*, a measure of similarity of the sets of digit forces. The *horizontal broken lines* correspond to 50% of the load. When a tip of the thumb force vector is above this line, tangential thumb force exceeds the total tangential force of the four fingers, and a moment of the tangential forces is in the clockwise direction (supination). When the tip of the thumb force vector is below the line, the tangential forces generate a pronation torque

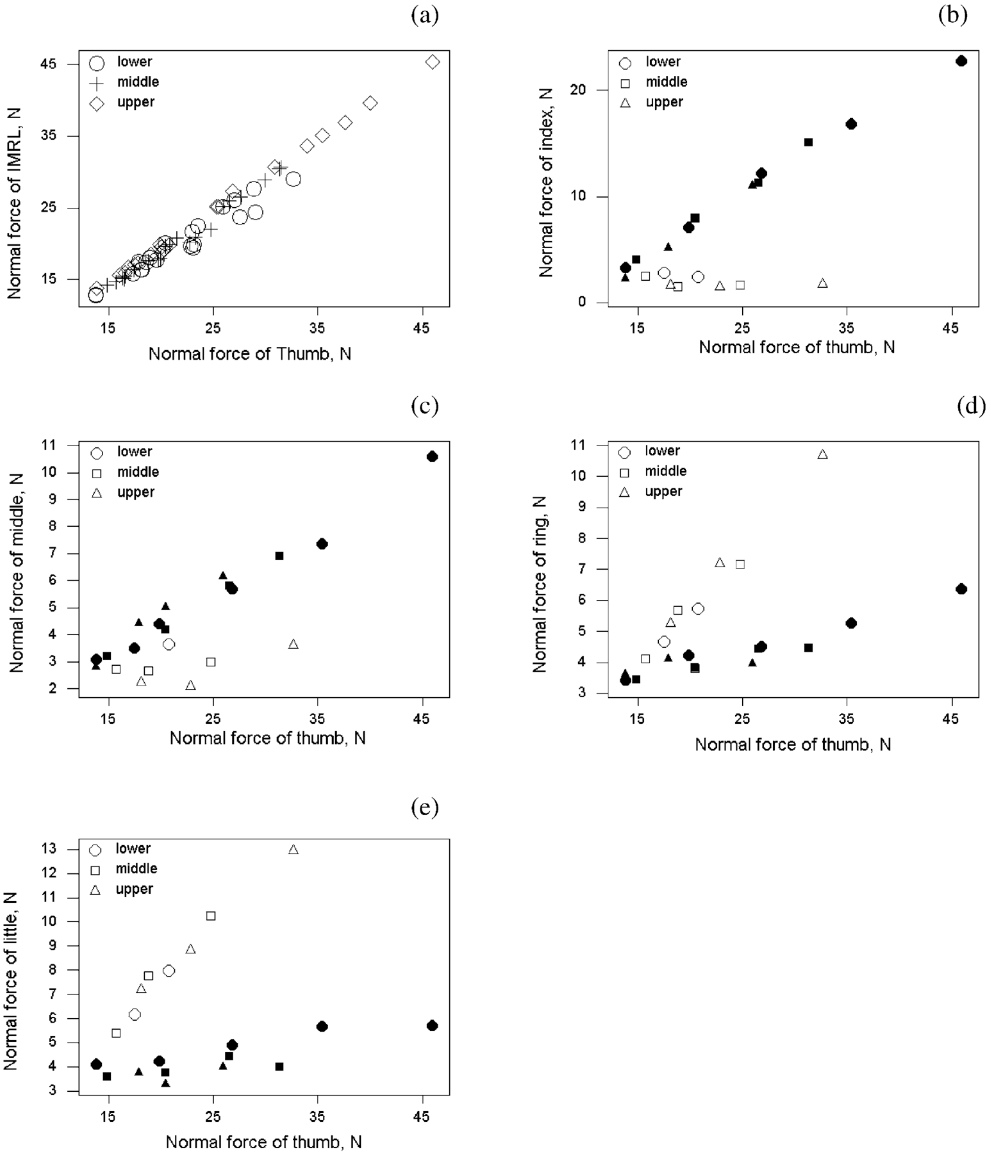
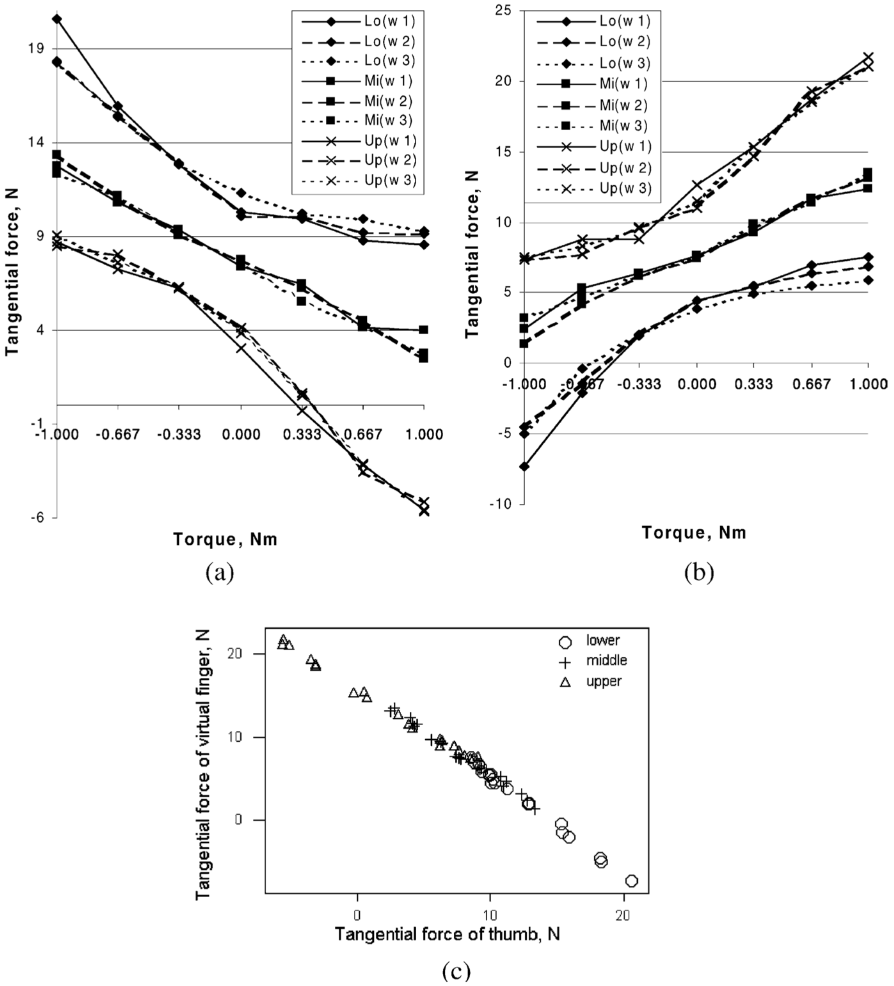


Fig. 3.

Relationships between normal thumb forces and the fingers. **a** Virtual finger force, **b** index finger force, **c** middle finger force, **d** ring finger force, **e** little finger force. *Open symbols* represent supination torques, and *closed symbols* represent pronation torques



(a)

(b)

(c)

Fig. 4.

Tangential forces for different torque values, thumb positions, and handle widths. **a** Thumb force, **b** virtual finger force, **c** tangential thumb force versus virtual finger force. (*Lo*, *Mi*, and *Up* signify lower, middle, and upper thumb positions, respectively – w1=60 mm, w2=75 mm, and w3=90 mm.)

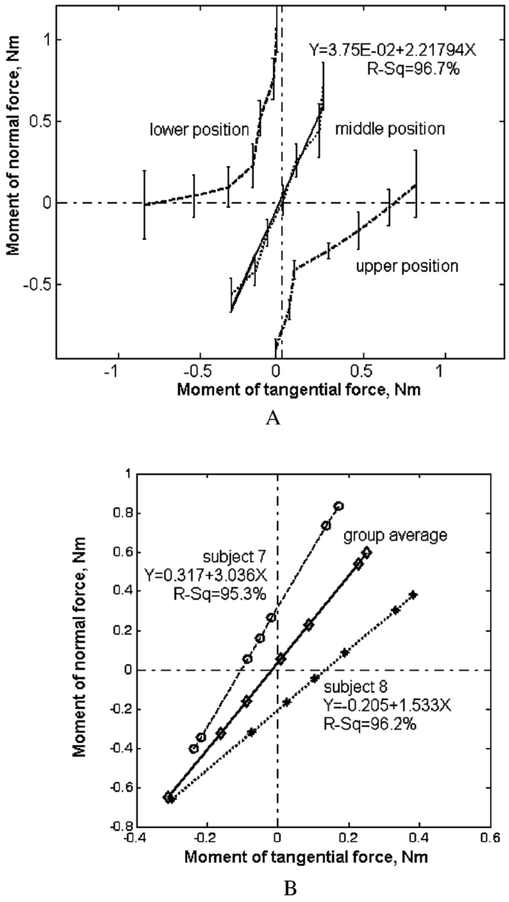


Fig. 5.

Moment of normal forces T^n versus moment of tangential forces T^t for the different torque values. Grip width 60 mm. **a** Group average at the different thumb positions. *Vertical bars* indicate standard deviations. For the middle thumb position, the regression line is also shown. **b** Representative examples for two subjects, middle thumb position. (In the regression equations, *Y* stands for the moment of normal forces, *X* is the moment of tangential forces.)

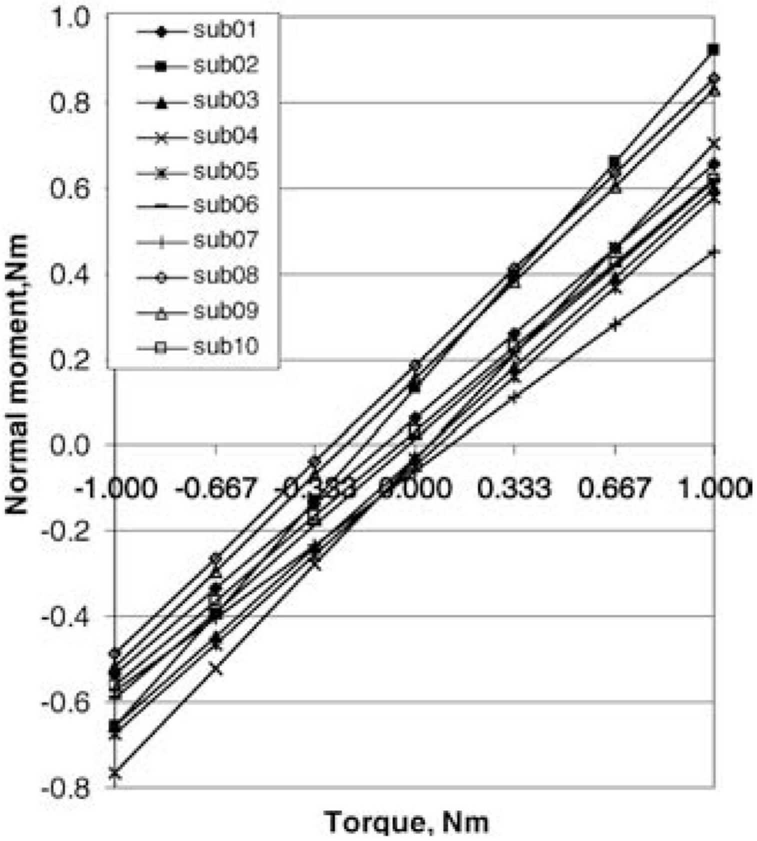


Fig. 6.

Moments of normal forces T^n versus total torque. The thumb is in the middle position. Grip width is 60 mm. Individual data of ten subjects

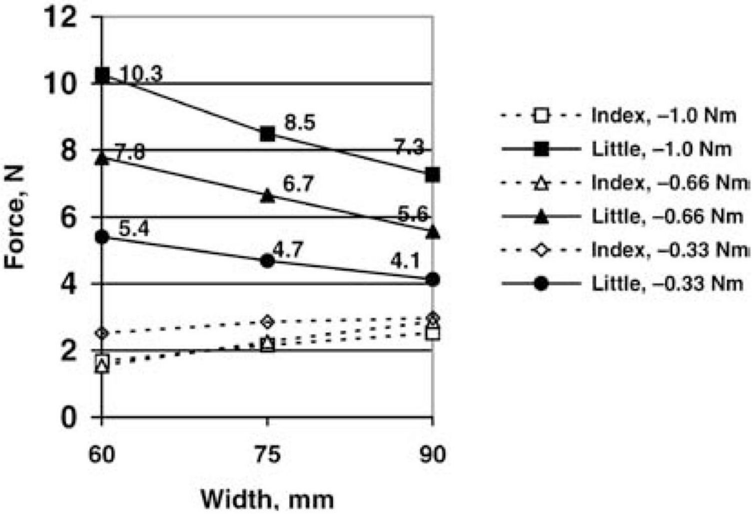


Fig. 7.

Normal index and little finger forces at different handle widths during supination efforts. When the width increases the little finger force decreases and index finger force. As a result, the moment of normal forces decreases. Forces of the ‘central’ fingers (middle and ring) that have smaller moment arms do not change systematically. To avoid a messy picture, these forces are not shown

Table 1

ANOVA results. Degrees of freedom for torque = 6, for width = 2, for thumb position (ThuPos) = 2, for errors = 52. Total = 62

Source	**Normal forces**				**Tangential forces**			
	SS	**MS**	**F**	**P**	**SS**	**MS**	**F**	**P**
Thumb								
Torque	1905.41	317.57	20.15	0.000	934.68	155.78	81.87	0.000
Width	0.50	0.25	0.02	0.984	0.02	0.01	0.00	0.996
ThuPos	105.01	52.50	3.33	0.044	1006.38	503.19	264.45	0.000
Error	819.65	15.76	–	–	98.94	1.90	–	–
Total	2830.58	–	–	–	–	–	–	–
Index finger								
Torque	1298.47	216.41	92.20	0.000	36.91	6.15	11.65	0.000
Width	0.04	0.02	0.01	0.992	0.46	0.23	0.44	0.649
ThuPos	152.57	76.29	32.50	0.000	97.53	48.76	92.34	0.000
Error	122.05	2.35	–	–	27.46	0.53	–	–
Total	1573.13	–	–	–	162.37	–	–	–
Middle finger								
Torque	160.75	26.79	82.63	0.000	163.92	27.32	124.07	0.000
Width	1.68	0.84	2.60	0.084	0.12	0.061	0.28	0.760
ThuPos	17.17	8.59	26.49	0.000	70.88	35.44	160.93	0.000
Error	16.86	0.32	–	–	11.45	0.220	–	–
Total	196.47	–	–	–	246.37	–	–	–
Ring finger								
Torque	67.62	11.27	11.34	0.000	82.25	13.71	49.90	0.000
Width	1.61	0.80	0.81	0.450	0.691	0.346	1.26	0.293
ThuPos	3.21	1.60	1.61	0.209	93.72	46.86	170.59	0.000
Error	51.67	0.99	–	–	14.28	0.275	–	–
Total	124.11	–	–	–	190.94	–	–	–
Little finger								
Torque	187.42	31.23	29.60	0.000	28.35	4.72	18.03	0.000
Width	14.18	7.09	6.72	0.003	0.002	0.001	0.00	0.996
ThuPos	2.50	1.25	1.19	0.314	41.27	20.63	78.73	0.000

Source	**Normal forces**				**Tangential forces**			
	SS	**MS**	**F**	**P**	**SS**	**MS**	**F**	**P**
Error	54.88	1.06	–	–	13.63	0.26	–	–
Total	258.98	–	–	–	83.25	–	–	–