Two Virtual Fingers in the Control of the Tripod Grasp

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Baud-Bovy, Gabriel and John F. Soechting. Two virtual fingers in the control of the tripod grasp. J Neurophysiol 86: 604–615, 2001. To investigate the organization of multi-fingered grasping, we asked subjects to grasp an object using three digits: the thumb, the index finger, and the middle or ring finger. The object had three coarse flat contact surfaces, whose locations and orientations were varied systematically. Subjects were asked to grasp and lift the object and then to hold it statically. We analyzed the grasp forces in the horizontal plane that were recorded during the static hold period. Static equilibrium requires that the forces exerted by the three digits intersect at a common point, the force focus. The directions of the forces exerted by the two fingers opposing the thumb depended on the orientation of the contact surfaces of both fingers but not on the orientation of the contact surface of the thumb. The direction of the thumb’s force did not depend on the orientation of the contact surfaces of the two fingers and depended only weakly on the orientation of the thumb’s contact surface. In general, the thumb’s force was directed to a point midway between the two fingers. The results are consistent with a hierarchical model of the control of a tripod grasp. At the first level, an opposition space is created between the thumb and a virtual finger located approximately midway between the two actual fingers. The directions of the forces exerted by the two fingers are constrained to be mirror symmetric about the opposition axis. The actual directions of finger force are elaborated at the next level on the basis of stability considerations.

INTRODUCTION

Grasping an object is a complicated problem that we solve with remarkable ease. It is a problem that has attracted considerable scientific attention; research has focused on topics ranging from how and when the hand is shaped to grasp the object (Jeannerod 1986; Santello and Soechting 1998; Santello et al. 1998) to how the intrinsic properties of the object and the task constraints determine the choice of a particular grasp (Cutkowsky and Howe 1990; MacKenzie and Iberall 1994). In addition, much attention has been focused on the forces generated by the digits in grasping and lifting the object, the topic of this paper.

Most of the studies on grip force have dealt with a pinch grasp in which only two digits exert force on the object. In such a grasp, the force can be decomposed into two components: the grip force (horizontal component) and the load force (vertical component). The criteria for a stable pinch grasp are simple: the sum of the load forces must equal the object’s weight and the ratio of the grip force to load force must exceed a specific value determined by the coefficient of friction between the object and the digit. It has been shown that subjects use tactile information to adjust the grip force slightly above this value (see Johansson and Cole 1994 for a review). For predictable loads, subjects adjusted the grip force in an anticipatory manner to maintain a constant safety margin (Gordon et al. 1991). When frictional conditions varied among fingers or when the surfaces were not parallel, this ratio was also adjusted at each finger independently by slightly tilting the object so as to redistribute the load between the two fingers (Burstedt et al. 1997; Edin et al. 1992; Jenmalm and Johansson 1997).

In multi-fingered grasps, the directions of the contact forces as well as the distribution of the load across fingers are only loosely constrained. For equilibrium, the sum of the forces in the horizontal plane must be zero, and these horizontal forces must intersect at a common point (the force focus). Furthermore, friction constrains the direction of the force exerted by each digit to lie within a cone. Thus neither the direction nor the magnitude of the contact forces is specified uniquely by the task. While several studies have investigated the distribution of the grip force across fingers in multi-fingered grasps (Kinoshita et al. 1995, 1996a,b; Li et al. 1998; Radwin et al. 1992; Santello and Soechting 2000), the analysis of the contact forces was limited to the normal forces. Thus little is known about how the direction of contact force is controlled in a multi-fingered grasp.

So far, only two studies have addressed this problem (Burstedt et al. 1999; Flanagan et al. 1999). In those studies, subject grasped an object with three fingers placed on flat, vertically oriented contact surfaces facing the object’s center. The combination of fingers used to grasp the object, the weight of the object, and the roughness of the contact surfaces were varied. The authors found that in all conditions the forces in the horizontal plane were directed toward the center of the object. This result can be explained by grasp stability considerations because the grasp is most stable when the contact forces are perpendicular to the contact surface (Flanagan et al. 1999). The question now arises: does this result generalize to arbitrary configurations of grasp surfaces in a three-fingered grasp?

To answer this question, we conducted experiments in which we systematically varied the orientation and location of the contact surfaces of each of the three digits. In all experiments, the contact surfaces were covered with coarse sandpaper to minimize the impact of frictional constraints on the direction of the contact forces. We found that the orientation of the contact surfaces did affect the direction of the contact forces but not in a systematic way. The actual direction of the contact forces was determined by the frictional properties of the contact surfaces and the grasping configuration.
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a way to solely maximize the stability of the grasp. In fact, the two forces opposing the thumb were coordinated in a way that is best understood in the theoretical framework of the virtual finger hypothesis developed by Arbib, Iberall, and colleagues (Arbib et al. 1985; MacKenzie and Iberall 1994). That is, the thumb’s force was generally directed so as to oppose a virtual finger located midway between the two actual fingers utilized in the grasp.

METHODS

Subjects

Six right-handed subjects participated in each experiment. Ages of the subjects ranged from 18 to 54. One person participated in all experiments, and two participated in three experiments. All subjects gave their informed consent to the experimental procedures, which were approved by the Institutional Review Board of the University of Minnesota.

Material and procedure

The object to be grasped was placed close to the edge of a table so that it could be grasped with the elbow bent at a right angle. The subject reached for and grasped the object (which had 3 flat circular vertically oriented contact surfaces 16 mm in diameter), lifted it, and held it horizontally. Data acquisition began prior to the reach and lasted 5 s, at which time the subject was instructed to put the object back on the table. The subject was free to practice placing his or her fingers on the contact surfaces between trials. Visual feedback was provided to monitor the orientation of the object throughout the trial.

Figure 1 shows a schematic drawing of the manipulandum (weight 423 g). A 6 degrees-of-freedom force transducer (ATI, sampling rate: 2,000 Hz) was placed under the index as well as the middle (or ring) finger. Each force transducer was mounted on a T-shaped aluminum frame that could be screwed in different positions on a plexiglass disk (50-mm radius) supported by three plexiglass feet. For the thumb, the force transducer was replaced by an aluminum cylinder of the same size and weight. The three vertically oriented contact surfaces were covered with coarse sandpaper (No. 60). A hemispherical mass was fixed on a shaft passing through the center of the plexiglass disk so that the object’s center of mass would be located in the plane passing through the centers of the contact surfaces. The position and orientation of the object were measured by an electromagnetic sensor (Polhemus, sampling rate: 120 Hz) located 30 mm below the plexiglass disk. Custom-designed software was used to acquire the data from the two force transducers and the Polhemus system. Visual feedback about the object’s orientation was provided by a bar whose length indicated the angle between the plexiglass disk and the horizontal plane.

The thumb, index, and middle fingers were used to grasp the object in all experiments except experiment 2, in which the ring finger replaced the middle finger. The position and orientation of the contact surfaces were varied across conditions. For each combination of positions and/or orientations of the three contact surfaces, the subject executed five consecutive trials. Trials in which the subject did not grasp the object correctly or in which the grasped object’s orientation deviated from the horizontal by 2° were repeated. The force and position data recorded during the last 0.5 s of the acquisition period were time-averaged. To ensure that these averages were representative of the (static) hold phase, we inspected the data to verify that the subject did not grasp the object before data acquisition began, that the object was horizontal (±2°) and immobile during the last 0.5 s, and that the force data had reached a plateau before the last 0.5 s. Less than three trials were discarded in each experiment. Each discarded trial was replaced by the average of nondiscarded trials conducted by the same subject in the same condition.

Arrangements of the contact surfaces

In the first two experiments, the centers of the contact surfaces were located at the vertices of an isosceles triangle inscribed in a circle (30-mm radius) centered on the center of mass (Fig. 2, top). The thumb was at the apex of the triangle, and the two fingers contacted the surfaces connected by the horizontal dashed line in Fig. 2. Each contact surface could have one of three orientations. The thumb contact surface could be parallel to the X axis or at an angle of ±22.5° relative to this axis. Accordingly, the perpendicular to the thumb contact surface pointed either to the center of mass (A: 0°) or to one of the other fingers (B and C: ±22.5°). The index and middle or ring finger contact surfaces could be parallel to the X axis (A: 0°) or at an angle such that the contact surface faced the thumb (B: 22.5°) or the center of mass (C: 45°). The combination of the three contact surface orientations yielded a total of 3 × 3 × 3 = 27 different conditions. The order of presentation of the conditions was randomized in this and the other experiments.

To further investigate the effect of the grasp geometry on the contact forces, in experiment 3 we varied the position as well as the orientation of the contact surfaces (see Fig. 2). Three thumb positions (a, b, and c) separated by 20 mm along the X axis, two index positions (d and e) and two middle finger positions (f and g) separated by 10 mm along the Y axis were combined to yield a total of 3 × 2 × 2 × 2 = 12 arrangements of finger positions. Thumb orientation was always parallel to the X axis. The contact surfaces of the index and middle fingers were set at an angle of 12.25° (A) or 45° (B) relative to the X axis. For some arrangements of finger positions, we used only two or three of the four possible combinations of the contact surface orientations to shorten the duration of the experiment. Thus only 30 of the 48 = 4 × 12 possible experimental conditions were investigated.

Finally, to evaluate the effect of the position of the center of mass on the contact forces, in experiment 4 we changed the absolute positions of the three contact surfaces while keeping their relative positions identical (see Fig. 2). We shifted the positions of the contact...
surfaces by 10 mm along the Y axis in arrangement II relative to arrangement I and by 10 mm along the X axis in arrangement IV relative to arrangement III. We also altered the relative position of the fingers in the two last arrangements by translating the position of the index and middle fingers by 20 mm along the X axis in arrangement V relative to arrangement III and in arrangement VI relative to arrangement IV. For each arrangement of finger positions, the index and middle finger contact surfaces were independently set at an angle of either 12.25° (A) or 45° (B) relative to the X axis, yielding a total of 6 × 2 × 2 = 24 conditions. Thumb orientation was always parallel to the X axis.

Contact forces

The mechanical interaction taking place between a finger and the object can be described by four parameters (Fig. 3A). Three force parameters, \( F_x, F_y, \) and \( F_z \), describe the contact force since each finger can apply a force laterally as well as perpendicularly to the surface. One parameter, the tangential torque \( M_t \), defines the moment about the axis perpendicular to the surface of the object. The normal force \( F_z \) must be positive since a finger can only push against the contact surface. Friction constraints require

\[
F_z < \lambda_{\text{lin}} F_y
\]

and

\[
M_t < \lambda_{\text{rot}} F_y
\]

where \( \lambda_{\text{lin}} \) and \( \lambda_{\text{rot}} \) are, respectively, the linear and rotational coefficients of friction. They define the minimum normal force \( F_z \) required to avoid a slip of the finger in the presence of a tangential force \( F_y = \sqrt{F_x^2 + F_z^2} \) or torque \( M_t \). The two friction constraints are generally not independent of each other, as shown experimentally by Kinoshita et al. (1997).

The contact forces at the fingers were measured by the two force transducers, while the contact force at the thumb was derived from the contact forces at the two fingers by the equilibrium conditions. For each finger, the contact force \([F_x, F_y, F_z, M_x, M_y, M_z]\) was initially measured in a reference frame having its origin at the center of the corresponding contact surface (Fig. 3A). In this reference frame, the moments \( M_x \) and \( M_y \) along the x and z axes can be different from zero if the fingertip touches the contact surfaces off the center.

For each finger, the center of pressure (the position of the fingertip on the contact surface) and the tangential torque (the position of the contact surface) were independently set at an angle of 0° and 24°, respectively. We also asked subjects to lift the object and then to let it slip. From the ratio of \( F_y \) and \( F_z \) (Eq. 1) at incipient slip, we estimated \( \lambda_{\text{lin}} \) to be 1.2 for each of the digits.

Since four parameters are necessary to specify the contact force applied by each finger, controlling the contact forces while grasping an object with three digits requires the control of 12 parameters. Equilibrium conditions reduce the number of independent degrees of freedom from 12 to 6. In particular, equilibrium in the horizontal plane for a tripod grasp requires that the directions of the contact forces must intersect and that the three contact forces drawn tip-to-tail must form a triangle (Flanagan et al. 1999; Yoshikawa and Nagai 1990). The intersection point, called the force focus, can be located anywhere in the intersection of the three friction cones (hatched area in Fig. 3C). This latter constraint insures that the friction constraints \( F_y / F_z < \lambda_{\text{lin}} \) are satisfied. The force focus together with the size of the force triangle constitutes a parametrization of the horizontal forces in the tripod grasp.

Statistical analysis

To determine the extent to which the force direction of each of the fingers depended on the orientation of the contact surfaces, we performed a multiple regression analysis. For this purpose, the direction of contact forces was defined by the angles \( \beta \), and the orientation of the contact surfaces was defined by the angles \( \alpha \), (see Fig. 3B). We
because the contact forces intersected very far from the center of the object when the contact forces were almost parallel and because small variations in their directions could yield large variations in the positions of the force foci. Thus we used a different coordinate system to analyze the position of the force foci, defining this parameter by two angles ($\eta$ and $\theta$) defined in Fig. 3C.

**RESULTS**

**Time course of the contact forces**

The temporal evolution of the grip forces in our experimental situation was similar to what has been described by others for two- or three-fingered grasps (Flanagan et al. 1999; Johansson 1991). Figure 4 shows the results from five trials from one subject for one experimental condition (all contact surfaces facing the object’s center). The subject began to grasp the object at about 2.5 s, increasing the horizontal and vertical (lift) forces until the object was lifted from the table. This subject required about 0.5 s to lift the object approximately 25 mm above the table (Fig. 4, top). The average distance for all trials was $16 \pm 5$ mm for this subject ($\text{mean} \pm \text{SD}$ for all subjects: $14 \pm 7$ mm). The object was maintained in a horizontal orientation throughout the hold phase. The magnitude and direction of the finger contact forces at the end of the lift phase remained stable throughout the hold phase and were similar across trials. Data collection ended before the object was replaced on the table. The results shown in Fig. 4 are typical and illustrate that the subjects grasped and lifted the object in a stereotypical manner. Tangential torques were typically $<5$ Nmm in magnitude and never more than 10 Nmm. In the rest of this paper, we focus our attention on the horizontal forces in the hold phase.

**Center of pressure**

The magnitude and direction of the horizontal contact forces are shown in Fig. 5 for 12 combinations of contact surface orientations for the same subject as in Fig. 4. Short thick solid lines denote the position and orientation of the contact surfaces, and the thin solid lines emanating from the contact surfaces represent the time-average of the contact forces during the hold phase of individual trials. The points at which the contact forces touch the contact surfaces indicate the location of the center of pressure in the horizontal plane. Although the contact forces touch the contact surfaces, and the mean horizontal position, $p_x$, of the center of pressure was close to the center of the contact surfaces for this subject, it did vary by several millimeters from trial to trial ($-1.0 \pm 1.5$, $0.5 \pm 2.0$, and $0.45 \pm 2.0$ mm for thumb, index and middle finger, respectively). Variations of the center of pressure along the vertical direction were of the same order of magnitude.) The mean position depended on the subject and on the orientations for the same subject as in Fig. 4. Short thick solid lines denote the position and orientation for two- or three-fingered grasps (Flanagan et al. 1999; Johansson 1991). Figure 4 shows the results from five trials from one subject for one experimental condition (all contact surfaces facing the object’s center). The subject began to grasp the object at about 2.5 s, increasing the horizontal and vertical (lift) forces until the object was lifted from the table. This subject required about 0.5 s to lift the object approximately 25 mm above the table (Fig. 4, top). The average distance for all trials was $16 \pm 5$ mm for this subject ($\text{mean} \pm \text{SD}$ for all subjects: $14 \pm 7$ mm). The object was maintained in a horizontal orientation throughout the hold phase. The magnitude and direction of the finger contact forces at the end of the lift phase remained stable throughout the hold phase and were similar across trials. Data collection ended before the object was replaced on the table. The results shown in Fig. 4 are typical and illustrate that the subjects grasped and lifted the object in a stereotypical manner. Tangential torques were typically $<5$ Nmm in magnitude and never more than 10 Nmm. In the rest of this paper, we focus our attention on the horizontal forces in the hold phase.

**Force magnitude**

The length of the line denoting the contact forces in Fig. 5 was very similar from trial to trial and across different conditions, suggesting that the magnitude of the contact forces was...
relatively constant. Statistical analyses confirmed that the orientation of the contact surfaces had almost no effect on the magnitude of the horizontal forces [repeated measures ANOVAs: $F(26,130) = 2.64, \epsilon = 0.11, P = 0.09$ for the thumb; $F(26,130) = 6.15, \epsilon = 0.11, P = 0.01$ for the index; $F(26,130) = 2.78, \epsilon = 0.10, P = 0.09$ for the middle finger]. However, there were large variations in the magnitude of the horizontal forces exerted by different subjects. In fact, the sum of the forces in the horizontal plane ranged by a factor of 3 from 5.5 to 15.0 N (12.5 N for the subject illustrated in Fig. 5). As much as 84% of the variability of the magnitude of the contact forces was explained by inter-subject differences. Despite the large differences among subjects in the amount of force used to grasp the object, the relative magnitude of the horizontal force of each digit was remarkably similar. For all subjects, the thumb force was larger than the index or middle finger force (48 to 24 or 29 ± 1% of the total force).

### Force direction

The direction of the index and middle finger forces varied considerably across conditions (Fig. 5). For example, when the contact surfaces were parallel (condition AAA, top left), the directions of the three contact forces were also almost parallel and were close to being perpendicular to the contact surfaces. In contrast, when the contact surfaces were oriented so as to yield an arrangement similar to a cylinder (ACC, top right), the contact forces were directed toward the center of the object [in agreement with the results of Flanagan et al. (1999) who studied this configuration]. Repeated measures ANOVAs confirmed that, unlike the force magnitude, the direction of the contact forces depended on the orientation of the contact surfaces [$F(26,130) = 9.57, \epsilon = 0.14, P < 0.005$; $F(26,130) = 31.48, \epsilon = 0.11, P < 10^{-4}$; and $F(26,130) = 45.82, \epsilon = 0.14, P < 10^{-4}$, for the thumb, index, and middle finger, respectively].

The orientation of the contact surfaces affected the direction of the thumb and of the index or middle finger forces in different ways. For example, changing the orientation of the contact surface under the middle finger changed the direction of the contact force of the index finger (compare panels in the 1st and 2nd columns) as did changing the orientation of the contact surface under the index finger (compare 1st and 3rd columns). In short, the direction of the index and middle finger forces depended on the orientation of both contact surfaces. In contrast, the direction of the thumb force seemed to be influenced only by the orientation of the thumb contact surface for
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TABLE 1. Multiple regression analysis of the direction of horizontal contact forces

<table>
<thead>
<tr>
<th>Digit</th>
<th>$c_0$</th>
<th>$c_1$</th>
<th>$c_2$</th>
<th>$c_3$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experiment 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Index</td>
<td>6.8 ± 2.8**</td>
<td>−0.02 ± 0.08</td>
<td>0.33 ± 0.07**</td>
<td>0.32 ± 0.07**</td>
<td>0.74</td>
</tr>
<tr>
<td>Middle</td>
<td>10.0 ± 4.4***</td>
<td>−0.04 ± 0.03*</td>
<td>0.26 ± 0.03**</td>
<td>0.32 ± 0.06**</td>
<td>0.73</td>
</tr>
<tr>
<td>Thumb</td>
<td>2.3 ± 3.1</td>
<td>−0.16 ± 0.09***</td>
<td>−0.02 ± 0.05</td>
<td>0.06 ± 0.03**</td>
<td>0.56</td>
</tr>
<tr>
<td><strong>Experiment 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Index</td>
<td>6.2 ± 4.0*</td>
<td>0.02 ± 0.07</td>
<td>0.30 ± 0.07**</td>
<td>0.28 ± 0.05**</td>
<td>0.73</td>
</tr>
<tr>
<td>Ring</td>
<td>5.9 ± 5.7</td>
<td>−0.05 ± 0.06</td>
<td>0.25 ± 0.08**</td>
<td>0.36 ± 0.06**</td>
<td>0.75</td>
</tr>
<tr>
<td>Thumb</td>
<td>0.8 ± 2.0</td>
<td>−0.17 ± 0.03***</td>
<td>−0.07 ± 0.06*</td>
<td>0.05 ± 0.03*</td>
<td>0.70</td>
</tr>
</tbody>
</table>

Force direction: $\beta_i = c_0 + c_1\alpha_i + c_2(\alpha_2 - 180) + c_3(\alpha_3 - 180)$. Values are means ± SD. * $P < 0.05$; ** $P < 0.01$. 

This subject, not by the orientation of the index and middle finger contact surfaces (compare panels in row). Altogether these observations suggest that the direction of the index and middle finger contact forces is coordinated, keeping the direction of the thumb force independent of the orientation of the index and middle finger contact surfaces.

The equilibrium conditions for an object held immobile in the horizontal plane require that the directions of the three contact forces intersect. The intersection point (force focus) for each trial is indicated by a solid square in Fig. 5. The location of the force foci along the Y axis was strongly affected by the orientation of the contact surfaces. Their location along the X axis varied much less. For example, when the index and middle finger contact surfaces were at an angle of 45° relative to the X axis, the force foci were located close to the center of the object (Fig. 5, right column). As the angles between index and middle finger contact surfaces and the X axis decreased, the force foci moved away from the center of the object and could even be located outside the object (Fig. 5, left columns).

Statistically, the within-condition variability of the force directions did not differ across conditions ($P > 0.05$). On average, this variability was 2.2, 4.0, and 4.4° for the thumb, index, and middle finger forces, respectively. This small variability of the force directions was nevertheless sufficient to produce a scatter of the force foci along the average direction of the thumb force. This scatter was particularly noticeable when the contact forces were almost parallel (conditions AAC and BCA for example).

In the following paragraphs, we examine in more detail the effect of the orientation of the contact surfaces on the direction of the forces and on the position of the force foci. We will show that direction of the thumb force was only slightly affected (if at all) by the orientation of the index and middle finger contact surfaces. Then we will show that the index and middle fingers contact forces were controlled in such way that any variation in the force direction of one finger was compensated by a variation in the force direction of the other finger so as to keep approximately the same direction of the thumb force across trials.

To detail the effect of the orientation of the contact surfaces on the orientation of the contact forces for each subject, we regressed the angle $\beta_i$ between the Y axis and the contact force of each digit against the angles $\alpha_i$ defining the orientation of the three contact surfaces (Fig. 3B). The results of this analysis are summarized in Table 1, which reports the average results for the six subjects. For both the index and middle fingers (Table 1, top 2 rows), the coefficients for the corresponding contact surfaces ($c_2$ and $c_3$) were much larger than the coefficient for the thumb contact surfaces ($c_1$). Furthermore the coefficients $c_2$ and $c_3$ were consistently positive and similar to each other. An equality between these coefficients would imply that the direction of the index and middle finger contact forces are symmetrically and reciprocally affected by the orientation of the finger contact surfaces (see Fig. 3B). The intercept terms ($c_0$) for index and middle fingers differed among subjects and were correlated ($r = 0.84$, $P = 0.03$), indicating that some subjects tended to direct the index and middle finger contact forces closer to the center of the object than others. The direction of the force exerted by the thumb depended minimally on the orientation of the index and middle finger contact surfaces (small $c_2$ and $c_3$ values) but, in half of the subjects, it did depend ($c_1 < -0.20$) on the orientation of the thumb contact surface. The intercept term for the thumb did not differ significantly from zero, indicating that the thumb force pointed toward the center of the object.

To interpret these results, it is convenient to consider the simplification that the $c_2$ and $c_3$ coefficients for the two fingers are equal and that finger forces do not depend on the orientation of the thumb contact surface ($c_1 = 0$). If so, the index and middle fingers contact forces would always intersect along the Y axis of the object and the thumb force would be directed along this axis. This simplified interpretation is consistent with the large effects reported in Table 1. However, there were small deviations of the coefficients from the idealized values and this simplification does not take into account the variations of the position of the centers of pressure. To address these issues, it is useful to consider the force foci.

For each orientation of the thumb contact surface, the force foci of individual trials fell along the line defined by the average direction of the thumb force, passing through the average center of pressure of the thumb. This is illustrated in Fig. 6, which shows the positions of the force foci and the average direction of the thumb force of one subject (same as in Figs. 4 and 5). The alignment of the force foci along the average direction of the thumb’s contact force was striking because each force focus could have been located anywhere in the intersection of the three friction cones (see METHODS). As a measure of the goodness of fit of the data to a straight line, we computed the percentage of the variance in the position of the force foci explained by their projection onto the line. For this subject, this value exceeded 99% for each of the three orientations of the contact surface of the thumb. This finding was representative of the results for all subjects (mean 99.5%). The results illustrated in Fig. 6 reinforce the conclusions of the regression analysis (Table 1): the direction of the thumb con-
closer to the index finger (43°). When the thumb contact surface was tilted toward the index finger, the thumb force was directed to a point midway between the centers of pressure of the index and middle fingers.

The force of the thumb was directed to a point midway between the centers of pressure of the index and middle fingers. The force of the thumb was directed to a point midway between the centers of pressure of the index and middle fingers. The direction of the thumb’s contact force depends on the orientations of the contact surfaces of the two fingers. Figure 7 shows the across-subject average position of the force focus for each condition, and it is clear that the ordering of conditions is consistent for the three orientations of the thumb contact surface. For example, when the index and middle finger contact surfaces faced the center of the object (CC), the force foci were always close to the center of the object. Similarly, when the index and middle finger contact surfaces were parallel to the X axis (AA), the contact forces intersected far away from the center of the object.

If the force foci vary mostly along the direction defined by the average thumb force, then the directions of the index and middle fingers forces must be coordinated to keep the direction of the thumb force invariant. To determine whether the directions of the index and middle finger forces were indeed coordinated on a trial-by-trial basis, we computed the coefficient of correlation between the directions of the index and middle finger forces after subtracting the mean for a given subject and orientation of the contact surfaces. The coefficient of correlation between these residual variations ($r = 0.50$) was highly significant [2-tailed Pearson correlation test: $r(808) = 16.4$, $P < 0.01$] and the slope (0.89) was close to one. By contrast, the coefficient of correlations between the residual variations of the thumb and of the index or middle finger directions were lower ($r = -0.17$ and 0.18).

### Coordination between index and ring fingers

The results presented so far suggested that the directions of the index and middle finger contact forces were coordinated so that the direction of the thumb force was impervious to the orientation of the contact surfaces of the two fingers. The contact force of the thumb was directed to a point approximately midway between the two fingers, with a slight tendency for the thumb’s force to be perpendicular to its contact surface. The second experiment tested whether this pattern still existed when a different combination of fingers was used. Thus we repeated the experiment with the subjects grasping the object with the thumb, index, and ring finger instead of the middle finger.

The results of this experiment were very similar to those of the first. The results of this experiment are summarized in Fig. 8 and in Table 1. The direction of the contact forces of the index and ring fingers depended on the orientations of the three contact surfaces in the same symmetrical and reciprocal manner as was found for the index–middle finger combination.
(Table 1). The coefficients $c_2$ and $c_3$ for the index and ringer fingers were large, positive, and about equal in magnitude. The direction of the thumb force depended slightly on the orientation of the thumb contact surface ($c_1$ negative). Figure 8 shows the position of the force foci for each of the three orientations of the thumb contact surface. As in the first experiment, the force foci were aligned along the direction of the average thumb force for each orientation of the thumb contact surface, and the thumb’s force was directed approximately midway between the centers of pressure of the ring and index fingers (average for all subjects and conditions $48 \pm 8\%$). Over $98\%$ of the variance in the positions of the force foci was explained by their projection along the average direction of the thumb force. Finally, the ordering of the force foci along the direction of the average thumb force in Figs. 7 and 8 is remarkably similar.

Asymmetric arrangements of the contact surfaces

In the two first experiments, where the three contact surfaces were arranged with an axis of symmetry passing through the thumb, the force foci tended to lie along this axis of symmetry. In the third experiment, we also consider asymmetric arrangements of finger positions. Specifically, we tested arrangements in which the thumb’s contact surface was opposite to the contact surface of one of the two fingers. In this arrangement, we found that the force foci still tended to be aligned along the average direction of the thumb’s force; this direction passing approximately midway between the two contact surfaces of the fingers (Fig. 9). The examples in Fig. 9 also show, in agreement with the results of the first two experiments, that the direction of the index and middle finger forces clearly depended on the orientation of the index and middle finger contact surfaces. Furthermore the contact forces intersected away from the center of the object when the contact surfaces of the index and middle fingers were almost parallel with the X axis (top left) and close to the center of the object when these contact surfaces faced it (bottom right).

Figure 10 shows the average positions of the force foci for each condition in this experiment. For each arrangement of finger positions, the force foci were along the line defined by the average direction of the thumb force. On average, $99\%$ of the variance was explained by their projection on this line. Moreover, for all arrangements of finger positions and subjects, the average direction of the thumb force approximately bisected the line connecting the index and middle finger contact surfaces ($50 \pm 6\%$). The location, as well as the orientation of the contact surfaces of the two fingers affected the location of the force foci. This can be ascertained by comparing the two top panels in Fig. 10; in the top right panel, the two fingers are further away from the thumb. Each of the force foci in the right panel has also been displaced away from the thumb when compared with the analogous result in the left top panel.

Influence of the location of the center of gravity

In the final experiment, we translated the location of the contact surfaces relative to the center of mass to ascertain the influence of this parameter on the direction of the contact forces. As in the other experiments, the force foci were aligned. This is demonstrated in Fig. 11, which shows the average position of the force foci for each arrangement of finger positions. In each row, the contact surfaces have been shifted in one direction: along the Y axis (top row), along the X axis (middle row), and in a mirror reversal (bottom row). In the middle column, the results from the...
two columns have been superimposed by aligning (or flipping) the locations of the fingers’ contact surfaces. For all finger arrangements, we found that the force foci were aligned along the direction defined by the average thumb force. As in the previous experiments, the thumb force was directed toward a point located approximately midway between the index and middle fingers (mean = 52 ± 8%).

The plots in the middle column of Fig. 11 demonstrate that the location of the center of mass had no effect on the locations of the force foci. The average direction of the thumb force and the locations of the force foci for any particular orientation of the contact surfaces are almost coincident. In general, statistical analysis showed that the location of the center of mass did not affect the direction of the contact forces. The sole exception was a small influence of the center of mass on the direction of the force exerted by the middle finger \(F(3,15) = 8.55, \epsilon = 0.61, P = 0.01\), but this effect was much smaller than the effect of the orientations of the contact surfaces \(F\) ratio equaled 60.13 for the effect of orientation. In this experiment, as in the previous ones, the orientation of the index and middle finger contact surfaces did not affect the direction of the thumb force.

A model to account for the location of the force foci

As noted in the Introduction, grasping an object is an under-constrained task. Because the contact surfaces were covered with a sandpaper having a large friction coefficient, the direction of the contact forces could have varied over a wide range. In this section, we examine whether our results can be explained by a strategy maximizing the stability of the grasp. The safety margin can be defined as the tangent of the angle between the force direction and the border of the friction cone (Fig. 3C). Thus the safety margin is the largest when the direction of the force in the horizontal plane is perpendicular to the surface. In a multi-fingered grasp, one may suppose that the forces in the horizontal plane are directed so as to maximize the safety margin of all fingers. However, generally the normals to the contact surfaces do not intersect. Therefore the overall safety margin will be the largest when all three contact forces are as close as possible to being perpendicular to the respective contact surfaces and compatible with the constraints of equilibrium. This translates into a criterion that minimizes the sum of the absolute values of the tangents of the angles between the force directions and the normals. We used this criterion to predict the force focus for each of the arrangements of the contact surfaces in the first series of experiments.

FIG. 10. Average location of the force foci for different arrangements of digit contact surfaces. Each panel groups the data for combinations of 3 thumb positions with a particular set of the index and middle finger positions. For each arrangement of finger positions, a line was fitted through the force foci corresponding to different combinations of orientation of the index and middle finger contact surfaces. □, the average locations of the center of pressure. Note that the force foci fall on the lines and that the lines bisect the (---) line connecting the contact surfaces of the index and middle fingers.

FIG. 11. The average direction of thumb force does not depend on the location of the center of mass. Left and right columns: plots depict average results for trials in which the relative arrangement of the contact surfaces is the same but differs with respect to the location of the manipulandum’s center of mass. Top and middle row: the locations have been shifted along the Y and X axes, respectively. Bottom row: the arrangements are mirror symmetric with respect to each other. The center of mass is at the intersection of the vertical and horizontal dotted lines. As in previous plots, the location of the average force foci is indicated by solid circles, and the direction of the average thumb contact force for each arrangement is denoted by the solid line. The data for the right and left columns have been superimposed in the middle column by shifting (and flipping, bottom row) the data so that the contact surfaces for the digits coincide.
The predictions of this criterion for four arrangements are shown in Fig. 12. The shaded regions indicate permissible solutions, i.e., force directions for each of the three digits that are within the safety margin. The experimentally determined locations of the force foci are indicated by filled circles and the open circles denote the predictions of the stability criterion. Contour lines denote different levels of stability. The position of the predicted force focus corresponds to the intersection of the three normals if they intersect (ACC and CCB). When the three contact surfaces are parallel (AAA), the predicted force focus is at ±∞ on the Y axis. For ACA (bottom left), the predicted force focus is on the line perpendicular to the middle finger contact surface. For ACC (top row), the actual and predicted position of the force focus were close. For AAA, even though there was a large difference between the predicted and actual locations of the force focus, the predicted directions of each of the three contact forces were in close agreement to the actual values. However, the predictions for the other two conditions (bottom row) were not in accord with the experimental data even when there is a well-defined minimum as in CCB. Specifically, for the two examples shown in the bottom row, the optimal solution did not lie on the axis of symmetry (Y axis). In ACA, the thumb’s force is predicted to be toward the index finger’s contact surface; in CCB, it is predicted to be toward the middle finger’s contact surface.

Maximizing the safety margin thus fails to account for the finding that the force foci tended to be aligned. This model predicted that the direction of the thumb contact force should depend significantly on the orientation of the contact surfaces of the two fingers. We then tested two models where the force foci had to be on a line passing through the thumb contact surface. In the first (partially constrained) model, the direction of the line was a free parameter. This model failed in that, for asymmetric configurations of finger positions, the line passed through the thumb and the finger facing the thumb (see Fig. 9). Furthermore in this model, the direction of the line was very sensitive to the orientation of the thumb contact surface.

We next constrained the force foci to lie along a line passing through the thumb contact surface and a point midway between the index and middle finger. The positions of the force foci on this line were optimized to maximize the safety margin. The results of this model were more satisfactory albeit not perfect. Its predictions are shown in Fig. 13, where we plot the angular coordinates (η, θ) of the actual and predicted positions of the force foci for the fully constrained model. Each data point corresponds to a different combination of contact surface orientations and/or arrangement of finger positions. Actual data were obtained by averaging the force foci across subjects for all conditions of experiments 1 and 4.
force foci (defined in Fig. 3C). Data are shown for the results of the first (Fig. 7) and the fourth (Fig. 11) experiments. The values of the correlation coefficients of this third model (0.89 and 0.92 for $\eta$ and $\theta$) were significantly better than the results of the same analysis performed on the unconstrained and partially constrained models (0.75, 0.74 for $\eta$ and 0.71, 0.71 for $\theta$). The average angular distance errors were 14.6, 13.1, and 7.7° for the unconstrained, partially constrained, and totally constrained models, respectively.

**DISCUSSION**

**Summary of the results**

In multi-fingered grasps, the contact forces are only partially constrained by the task. Nevertheless we found that the directions of the contact forces had a consistent and repeatable pattern. First, the index and middle finger contact forces were directed so that they intersected at a force focus located on a line that passed from the center of pressure of the thumb to a point close to midway between the centers of pressure of the two fingers. Consequently the direction of the thumb force, which must also intersect the force focus, varied little across a large set of experimental conditions. As a secondary effect, we found that the direction of the thumb’s force shifted slightly when the orientation of the thumb contact surface changed (Figs. 6 and 7). Finally, the location of the force focus along the line could be predicted by stability considerations (Fig. 13).

This general pattern held true for a grasp involving the thumb coupled to the index and middle fingers and also for the index–ring finger combination. It held true when the contact surfaces of the two fingers were arranged symmetrically with respect to the thumb (as in experiments 1 and 2), as well as when the locations of the three contact surfaces were shifted with respect to each other (experiment 3) and when they were shifted with respect to the location of the center of mass (experiment 4). Finally, the magnitudes of the finger forces were minimally affected by the orientation of the contact surfaces and/or the positions of the fingers. This is in contrast to the weight of the object (Flanagan et al. 1999) and to the texture of the contact surfaces (Burstedt et al. 1999), which do affect the magnitude of the contact forces.

Our results suggest that the horizontal forces in a tripod grasp are governed by two factors, the second being subordinate to the first. The first factor is a geometrical one—the directions of the forces exerted by the two fingers tend to be mirror symmetric about an axis that passes between the two fingers. Given this constraint, the forces are directed so as to maximize the safety margin. In the following, we will take up these two factors in reverse order.

**Task constraints and safety margin**

Frictional constraints require that the force focus should be located within the intersection of the friction cones of the three contact surfaces. We purposely used coarse sandpaper on the contact surfaces. Accordingly, the friction cones spanned 50° on each side of the normal to the contact surface. Thus our task was relatively unconstrained. For example, the center of mass of the object was always within the intersection of the friction cones. Therefore a result in which the contact forces were always directed to the center of mass would have been compatible with stability. Had we used surfaces that were more slippery, we would have introduced additional constraints on the solution. It is conceivable that our results will not generalize to experimental conditions in which the friction of the contact surfaces is varied over a wide range. Our results do represent the minimally constrained solution for a tripod grasp.

We did examine whether our results were in accord with a model in which the directions of the contact forces were adjusted to maximize grasp stability (Fig. 12). Grasp is most stable when each of the contact forces is perpendicular to the contact surface. However, this solution generally is not compatible with the requirement that the three contact forces intersect at a force focus. Thus we used a criterion according to which the three contact forces were as close to perpendicular as possible, consistent with the constraint of equilibrium. This criterion failed to account for the experimental data, since there were many instances in which the thumb’s force was not directed to a point located between the two fingers (Fig. 12).

However, a model in which the force foci were constrained to lie along a line bisecting the contact surfaces of the two fingers was able to account for much of the data (Fig. 13). In fact, the correlation coefficients between the predicted and experimentally determined force directions were high (0.89 and 0.92).

The fact that the direction of the thumb’s force rotated slightly when the orientation of the thumb’s contact surface changed is also in accord with the supposition that stability constraints influence the direction of the contact forces. For the thumb, this effect was small. On average the rotation of the force direction represented only 16% of the rotation of the orientation of the thumb’s contact surface. However, it was in a compensatory direction such as to keep the thumb force closer to the perpendicular to the thumb’s contact surface.

**Virtual finger hypothesis**

The most striking finding of this study was that the direction of the force exerted by the thumb did not depend on the orientation of the surfaces contacted by the two fingers. In most of the experiments, this force was directed along an axis midway between the two fingers. Consequently, the directions of the force exerted by the two fingers were mirror symmetric about this axis. This was true not only in an average sense, but also on a trial-by-trial basis. Small variations in the direction of the force exerted by one finger tended to be accompanied by similar variations in the force exerted by the other finger. In functional terms, it is as if the action of the two fingers were replaced by an equivalent finger, located close to midway between the two actual fingers. Our results suggest that the control of a tripod grasp may be simplified as the equivalent of a pinch grasp, the thumb opposing a single virtual finger rather than two independent real fingers.

Our results are reminiscent of the theoretical framework developed by Arbib, Iberall, and colleagues who suggested that grasping is controlled in terms of virtual fingers and opposition spaces. They defined a virtual finger as “a group of fingers which acts as a single functional unit,” and they suggested that grasping involves the opposition of pairs of virtual fingers (Iberall et al. 1986). According to this theory, virtual fingers can be used to characterize different types of grasps in an abstract way and, as such, provide an organizing principle at a
higher level of planning and control. The mapping to actual fingers would occur at a lower level (Arbib et al. 1986).

Although this theory provided important suggestions about how to control artificial hands and was useful to classify the large variety of ways objects can be grasped (MacKenzie and Iberall 1994), to date the hypothesis has not been stated precisely enough to make it testable experimentally. Part of the difficulty stems from the fact it was originally developed to deal with kinematic aspects of grasping (Iberall et al. 1986). Furthermore the notion of a virtual finger has usually been taken to be a group of adjacent fingers (a kinematic definition). However, our study shows that two or more finger forces can be coordinated to act as a single functional unit even if the fingers are not located closely together.

Disagreements about how to characterize a tripod grasp in the context of the “virtual finger” hypothesis further illustrate the problem. Originally, the tripod grasp was classified as a two virtual finger grasp with one opposition axis (Iberall and MacKenzie 1990; Iberall et al. 1986; MacKenzie and Iberall 1994). Later, because there are three independently controllable contact locations, Cutkowsky and Howe (1990) argued that the tripod grasp was a three-virtual-finger grasp. They also argued that from a practical point of view, there were only two oppositions between the thumb and each of the two opposing fingers. Finally, the question has been raised whether the notion of virtual fingers was useful in the tripod grasp because “for two or more digits to be considered as a virtual finger, they must generate forces in approximately the same direction” (Flanagan et al. 1999).

Our results suggest that the tripod grasp can indeed be viewed as a two-virtual-finger grasp involving one opposition axis as originally suggested by Iberall and colleagues. Our results can be well explained if one assumes that the two fingers opposing the thumb correspond to a virtual finger. We found that the sum of the index and middle finger forces always acts in the same direction independently of the orientation of the index and middle contact surfaces. Therefore the index and middle fingers could be replaced by a single virtual finger placed approximately at mid-distance between the two real fingers. The position of the virtual finger would depend on the position of the index and middle fingers and, to a limited extent, on the orientation of the thumb contact surface. At a lower level in the control hierarchy, the direction and magnitude of the index and middle finger forces would then be determined to maximize the safety margin. The relative importance of these two levels would depend on the functional properties of the object and the behavioral context of the grasping movement.

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