Control of Fingertip Forces in Multidigit Manipulation

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Flanagan, J. Randall, Magnus K. O. Burstedt, and Roland S. Johansson. Control of fingertip forces in multidigit manipulation. *J. Neurophysiol.* 81: 1706–1717, 1999. Previous studies of control of fingertip forces in skilled manipulation have focused on tasks involving two digits, typically the thumb and index finger. Here we examine control of fingertip actions in a multidigit task in which subjects lifted an object using unimanual and bimanual grasps engaging the tips of the thumb and two fingers. The grasps resembled those used when lifting a cylindrical object from above; the two fingers were some 4.25 cm apart and the thumb was ~5.54 cm from either finger. The three-dimensional forces and torques applied by each digit and the digit contact positions were measured along with the position and orientation of the object. The vertical forces applied tangential to the grasp surfaces to lift the object were synchronized across the digits, and the contribution by each digit to the total vertical force reflected intrinsic object properties (geometric relationship between the object's center of mass and the grasped surfaces). Subjects often applied small torques tangential to the grasped surfaces even though the object could have been lifted without such torques. The normal forces generated by each digit increased in parallel with the local tangential load (force and torque), providing an adequate safety margin against slips at each digit. In the present task, the orientations of the force vectors applied by the separate digits were not fully constrained and therefore the motor controller had to choose from a number of possible solutions. Our findings suggest that subjects attempt to minimize (or at least reduce) fingertip forces while at the same time ensure that grasp stability is preserved. Subjects also avoid horizontal tangential forces, even at a small cost in total force. Moreover, there were subtle actions exerted by the digits that included changes in the distribution of vertical forces across digits and slight object tilt. It is not clear to what extent the brain explicitly controlled these actions, but they could serve, for instance, to keep tangential torques small and to compensate for variations in digit contact positions. In conclusion, we have shown that when lifting an object with a three-digit grip, the coordination of fingertip forces, in many respects, matches what has been documented previously for two-digit grasping. At the same time, our study reveals novel aspects of force control that emerge only in multidigit manipulative tasks.

INTRODUCTION

Previous studies on the coordination of fingertip forces during manipulative tasks have revealed that one goal of the nervous system is to ensure grasp stability by controlling the ratio between forces normal and forces tangential to the grasp surfaces (see Johansson 1996; Johansson and Cole 1994; Wing 1996 for reviews). The normal forces applied are great enough to prevent slips and small enough to avoid excessive forces that are uneconomical and may impair sensitivity or damage the object and hand (Johansson and Westling 1984a). Furthermore, the engaged digits can be controlled independently in that the normal-to-tangential force ratio is tuned to the local frictional conditions observed at each digit (Burstedt et al. 1997a,b; Edin et al. 1992).

To date, work on precision grip control has focused primarily on grasps involving two digits, typically the thumb and index finger. However, many of the motor skills we associate with dexterous manipulation involve more than two digits. A three-digit grasp is inherently more stable than a two-digit grasp and provides a solid platform for dexterous manipulation. For instance, with a three-digit grasp, it is generally possible to reposition the digits to establish different grasp configurations and to disengage a digit to be used in tactile exploration or stereognostic tasks; features that represent the hallmark of skilled manipulation. Although the use of three digits promotes flexibility in manipulation tasks, it also presents the CNS with a control problem; namely, the CNS must deal with the additional degrees of freedom that arises from the fact that grasp stability can be achieved with many combinations of fingertip forces. To solve this redundancy or degrees of freedom problem, it is possible that the motor system employs one or more cost functions.

A few studies have examined precision grips in which the thumb, on one side of the object, was opposed by two or more digits (Flanagan and Tresilian 1994; Kinoshita et al. 1995, 1996). However, neither of these studies analyzed the coordination of normal and tangential forces applied by individual digits or the distribution of fingertip force across the digits. In this paper, we analyze both these aspects of coordination during a precision lift-and-hold task in which subjects used a three-digit grip. We examined three different grasp configurations, including unimanual and bimanual grips, to distinguish between neural and anatomic (grip dependent) factors influencing force control. The task chosen represents a baseline condition for further manipulation as will be addressed in subsequent reports. Specifically, we characterize the coordination of fingertip actions within and among digits during the various phases of the task and address the control of grasp stability. One of the objectives is to assess the extent to which the principles of force coordination observed in two-digit grasping extend to three-digit grasping. We also analyze force combinations used by subjects in the multidigit grasp to assess factors of potential relevance for coping with the redundancy problem.

METHODS

Subjects

Five men and three women between 19 and 45 yr of age participated in this study after giving informed consent. They were asked to

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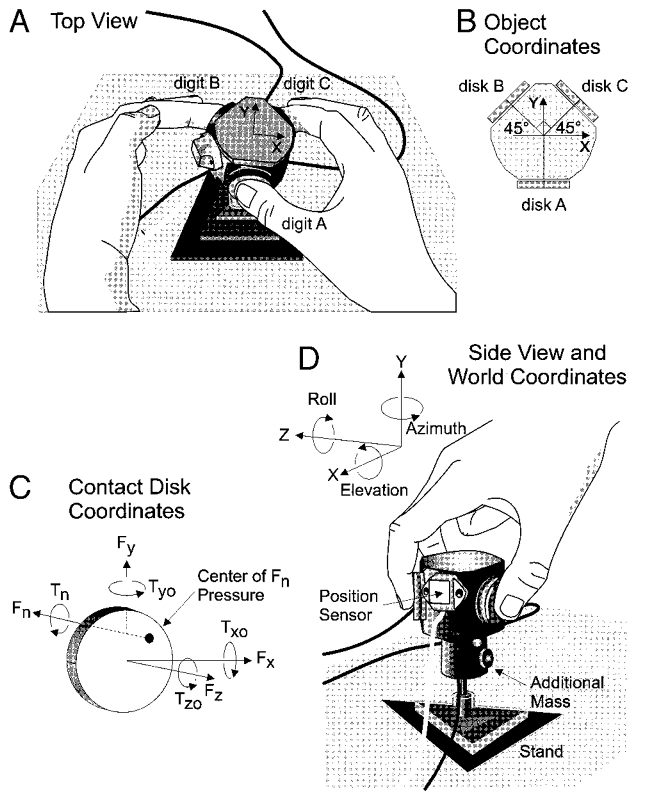

FIG. 1. Top (*A*) and side (*D*) views of the test object while being grasped with a bimanual (*A*) and a unimanual (*D*) grip. *B*: orientation of the contact disks in the horizontal plane and the *x* and *y* axes in object coordinates. Three contact disks (disks A–C) were mounted on top of force-torque sensors and were contacted by *digits A–C.* These sensors measured 3 forces and 3 torques applied at each of the disks (*C*). Object position and orientation were measured by a 6-axis position-angle sensor and described in world coordinates (*D*). A removable mass could be added to the object to change the weight (*D*).

lift a test object vertically ~5 cm and were naive with respect to the goals of the study. Subjects were asked to wash their hands before the experiment. The subjects could see the object and their digits throughout the experiment.

Apparatus

Subjects were required to grasp the test object (Fig. 1) with three digits. Each digit contacted a circular plastic disk (3 cm diameter) covered by fine grain sandpaper (No. 320). The orientations of the three grasp surfaces can be appreciated in Fig. 1, *A* and *B*, which also shows the *x* and *y* axes in object coordinates. The centers of the three vertically oriented grasp surfaces were 3 cm from the center of the object, and each contact disk was perpendicular to the vector between the center of the object and the center of the disk. The angle, in the horizontal plane, between the normal vectors of disks B and C was 90°. The angle between the normal vectors of disks A and B (or C) was 135°. This arrangement was selected for ease of grasping with one hand and because the positions of the digits resemble those used when lifting a cylindrical object from above.

Each of the plastic contact disks was attached to a six-axis force-torque sensor (Nano F/T transducers, ATI Industrial Automation, Garner, NC) that measured the forces and torques in three dimensions in disk coordinates (Fig. 1*C*). The sensing range and resolution of the two forces tangential to the grasp surface (F_x and F_y) were ±25 and 0.025 N, respectively. The range and resolution for the force normal to the grasp surface (F_z) were ±45 and 0.05 N, respectively. The range and resolution for the three torques around the three axes through the center of the grasp surface (T_{xo}, T_{yo}, and T_{zo}, see Fig. 1*C*) were ±250 and 0.125 mNm, respectively. The transducers were configured so that the forces and torques were measured in the plane of the contact surface and about the center of the contact surface. Thus the application of pure tangential forces (F_{xo} and F_{yo}) would not result in torques about the *x* or *y* axes of the contact plate (e.g., T_{xo} and T_{yo}).

The test object also was equipped with an electromagnetic position-angle sensor (FASTRAK, Polhemus, Colchester, VT), which recorded the linear position and angular orientation of the object in three dimensions. The position of the object was defined in the coordinate system shown in Fig. 1*D* (world coordinates; resolution ±0.12 mm). The angular orientation of the object was recorded in Euler angles (resolution ±0.025°): azimuth, elevation, and roll. These were defined with respect to a moving coordinate frame starting with the world coordinate frame shown in Fig. 1*D* and rotated successively about the *y* (azimuth), *x* (elevation), and *z* (roll) axes. All three angles were zero when the object was resting on the table. In the present lifting task, the motion of the object was primarily in the *y* direction in world coordinates, and any tilting of the object out of the horizontal plane was measured by a combination of elevation and roll angles.

The test object was constructed out of a light-weight alloy and had a total mass of 0.2 kg corresponding to a weight of ~2 N when held stationary in air. An additional mass of 0.2 kg could be attached (see Fig. 1*D*) to bring the total mass to 0.4 kg (~4 N). The center of mass in the horizontal plane was located at the center of the object equidistant from the centers of the three grasp surfaces. The height of the center of mass was located just below the grasp surfaces but depended on whether the additional mass was attached.

Procedure

The subject sat in an office chair with the right upper arm parallel to the trunk. The test object was placed on the top of a low table and was located about 30 cm to the right and 30 cm in front of the subject's trunk, at the height of the hip. Thus the object was comfortably within reach and the lifting movement consisting mainly of flexion of the elbow.

Each subject completed six blocks of eight lift trials. The blocks of trials differed in terms of the digits used to grasp the object and the weight of the object (2 or 4 N). In the first two blocks, subjects grasped the object using the tips of the thumb, index finger, and middle finger of the right hand. This will be referred to as the ''standard grip'' (see Fig. 1*D*). In the next two blocks, the thumb, index finger, and ring finger of the right hand were used to grasp the object. This ''ring-finger grip'' (not shown in Fig. 1) was similar to the standard grip except that the ring finger was used in place of the middle finger. In the last two blocks of trials, subjects grasped the object with the ''bimanual grip'' involving the thumb and index finger of the right hand and the index finger of the left hand (Fig. 1*A*). For each grip configuration, the weight of the object was 2 N in one block and 4 N in the other.

In each trial, the subject was required to lift and hold the object in a stationary position, perform a ''fiddling'' procedure, hold the object in a stationary position again, and replace the object on the table top. No specific instructions were given regarding the orientation in which to hold the object. During the fiddle phase, the subject was required to sequentially slide the tip of each digit across the grasp surface as if they were exploring the surface texture. Subjects were free to slide the digits in any order. The primary aim of the fiddle phase was to obtain estimates of the coefficient of static friction for each digit on a trial-by-trial basis.

An auditory cue initiated each trial and prompted the subject to pick up and hold the object. A second auditory cue given 4 s after the first cue marked the start of the fiddle phase. After the fiddling phase, the subject held the object in a stationary position until receiving a third auditory cue prompting the subject to replace the object on the tabletop. This third cue was given 3 s after the experimenter had pressed a key confirming that the subject had completed the fiddle phase.

Data collection and analysis

A flexible data acquisition and analysis system (SC/ZOOM, Department of Physiology, Umeå University) was used to sample signals from the force-torque sensors (400 Hz; 12-bit resolution) and the position-angle sensor (120 Hz; 14-bit resolution). Force rates were obtained by numerically differentiating the force signals using a ±5 point (or ±12.5 ms) window.

The force tangential to the grasp surface (F_t) was computed as the vector sum of the two tangential force components: $F_1 = \sqrt{F_x{}^2 + F_y{}^2}$. The force normal to the grasp surface (F_n) was defined simply as $-F_z$ (see Fig. 1*C*).

The digit contact positions were represented by the location of the center of normal force pressure applied by the fingertip on the grasp surface. Using the torques about the *x* and *y* axes of the grasp surface (T_{xo} and T_{yo}) and F_n, the location of the center of pressure on the grasp surface (P_x, P_y) was calculated as follows: $P_x = T_{yo}/F_n$ and $P_y = -T_{xo}/F_n$. (The *x* and *y* axes used for the force vectors also were used for position in disk coordinates.) The torque about the *z* axis (T_{zo}), measured by the sensor, reflected both the true torque at the fingertip (T_z) and the off-axis torque that arose if the center of pressure was not located at the center of the sensor. To determine the true torque, we subtracted the off-axis torques as follows: $T_z = T_{zo} - F_y \cdot P_x + F_x \cdot P_y$. We then defined the torque about the normal force vector as $T_n = -T_z$. All of the torques defined in this paper follow the ''right-hand rule.''

In previous work on precision grip, the minimum normal force, or slip force (F_s), required to prevent slip in the face of a tangential force has been defined as follows: $F_{s(lin)} = F_t/\mu_{lin}$ where μ_{lin} is the coefficient of static linear friction. We have added the subscript ''lin'' because this equation is restricted to the case in which the tangential load is linear and does not apply in cases where there are significant tangential torques acting at the fingertip.

Kinoshita et al. (1997) have shown recently that F_s depends on both F_t and T_n. On the basis of data obtained from the tips of human thumbs and index fingers, these authors developed the following equation to estimate F_s from μ_{lin}, F_t and the absolute value of T_n

$$F_s = \frac{F_t + a|T_n| + bF_t|T_n|}{\mu_{lin}} = \frac{L}{\mu_{lin}} \tag{1}$$

where $a = 0.1333\ \text{mm}^{-1}$, $b = -0.0114\ (\text{mNm})^{-1}$, and F_s is the minimum normal force required to prevent any slip, linear or rotational. The variable *L* can be interpreted as a generalized load that, for a given μ_{lin}, determines the normal force required to prevent slip. Note that when T_n is zero, *Eq. 1* reduces to $F_s = F_t/\mu_{lin}$. An advantage of *Eq. 1* is that μ_{lin} can be estimated easily experimentally (see following text), allowing for good estimates of F_s with different surface materials and different subjects (Kinoshita et al. 1997). The normal force safety margin (SM) is defined as the employed normal force minus the slip force estimated using *Eq. 1*: SM = $F_n - F_s$. The relative safety margin is given by SM/F_n.

The coefficient of friction, μ_{lin}, for each digit was estimated for each trial as the inverse of the minimum linear force ratio (F_n/F_t) observed during the fiddle period. This minimum coincides with the moment at which the digit begins to slip as further described in RESULTS. For each subject and for each grip, an average coefficient of friction was computed for each digit, i.e., data were collapsed across trials and object weights. The minimum ratio is approximately constant for normal forces above ~5 N but may increase substantially when normal force drops below this level (Johansson and Westling 1984b). Therefore when computing average coefficients of friction, we excluded trials in which the minimum ratio coincided with a normal force <0.5 N. This resulted in the exclusion of ~8% of the cases. Typically at the moment of slip, the tangential torque was close to zero. The estimated coefficient of friction was independent of digit and grip. A repeated measures ANOVA indicated that neither digit ($P = 0.15$) nor grip ($P = 0.30$) had a reliable effect on the coefficient of friction and the interaction between digit and grip ($P = 0.38$) was not significant. The average μ_{lin} was 1.12.

The time at which each digit initially contacted the object (contact time) was taken as the time at which F_n first exceeded 0.1 N and remained above this level for ≥2 s. Thus contact was deemed not to have occurred if a digit briefly touched the object. The preload phase was defined as the period between the moment the leading digit contacted the object and the onset of the load phase. The latter began when the first time derivative of the total vertical force generated by the three digits last exceeded 0.5 Ns^{-1} before reaching its maximum value, i.e., when the vertical force began to increase steadily. The offset of the load phase was defined as the time at which the total vertical force reached the mean total vertical force employed during the initial hold phase. Because the latter force was defined by the weight of the object, the end of the load phase closely matched the time of lift-off. Force, torque, position, and angle measurements determined for the hold phase were computed as averages of the values recorded during the last 0.5 s of the first hold phase.

Repeated measures ANOVAs were used to assess experimental effects (e.g., grip configuration, mass, and digit), and linear regression analysis was used to examine relations among various dependent variables. A *P* value of 0.05 was considered to be statistically significant. Values reported in the text for data pooled across trials refer to means ± SD.

RESULTS

We first provide a general description of the lift-hold-fiddle-hold-replace task using an illustrative trial and then describe, in more detail, the various phases of the task. Finally, given that grasp stability can be achieved with many different combinations of fingertip forces, we analyze aspects of the variability of fingertip forces and torques across grasps and subjects.

Basic description of the task

When lifting objects with the thumb and index finger at the sides, initial contact typically is followed by a preload phase when normal forces increase and a stable grasp is achieved (Johansson and Westling 1984a). The preload phase then is followed by a load phase during which upward tangential forces are developed until the total vertical force exceeds the weight of the object and lift-off occurs. An adequate safety margin against slips is preserved during the load phase by normal force increases proportional to the increases in tangential force. These phases were observed clearly in all three three-digit grips we examined.

PRELOAD AND LOAD PHASE. Figure 2 shows kinetic and kinematic records from a single trial in which the subject (*S5*) lifted the 0.4-kg object with the standard grip (i.e., right index finger, thumb, and middle finger; Fig. 1*D*). During the initial preload phase, the digits contact the object and the normal force (F_n) increases at all digits. During the subsequent load phase, the tangential forces (F_t) increase together at the three digits. The normal forces increase in parallel with the tangential forces at each digit providing for grasp stability. The increases in F_t are primarily in the vertical direction; F_y is equivalent to vertical lift force during the load phase because the object remains on the table and is not tilted. However, tangential forces in the horizontal direction (F_x) also are observed as are torques tangential to the grasp surfaces (T_n). Because these torques are relatively small (<5 mNm), the estimated total tangential load (*L*), which takes both tangential force and tangential torque into account (see METHODS), is only

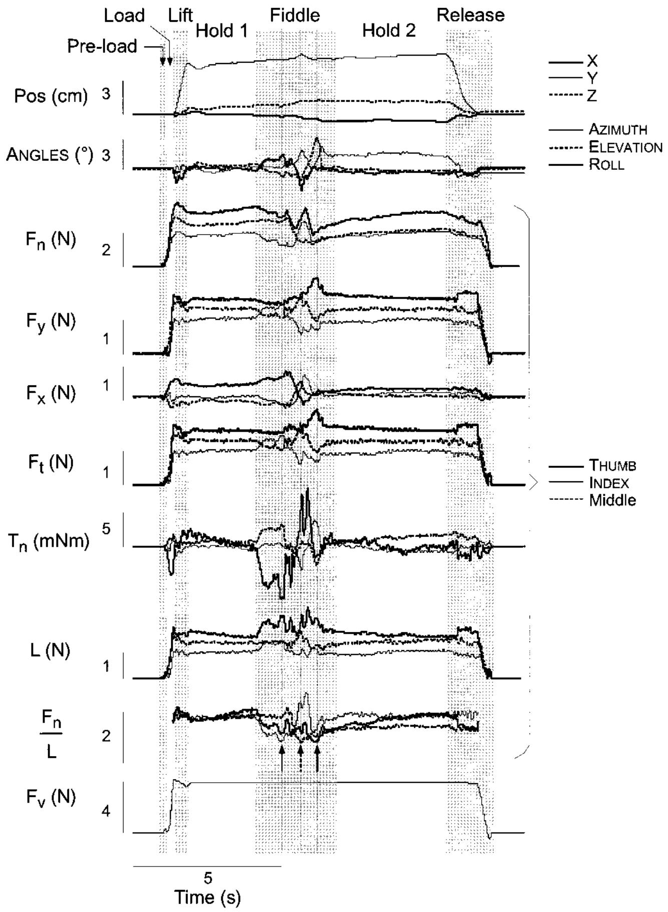

FIG. 2. Kinematic and kinetic records as a function of time from a representative single trial (*subject 5*). Shaded vertical bars mark alternate phases of the task. Subject was required to lift and hold the object and then perform a fiddling procedure in which each digit was slid across its grasp surface. Vertical dashed lines mark the times at which each digit slid, which corresponded to minima in the F_n/L ratio (arrows). After the fiddle phase, the subject was required to hold the object steady before replacing it on the tabletop.

slightly greater than the tangential forces (F_t). When the total vertical force generated by the three digits exceeds the weight of the object, lift-off occurs.

LIFT AND FIRST HOLD PHASE. The load phase is followed by the lifting of the object and the first hold phase during which the object is held in a stationary position in air (Fig. 2). Although no specific instructions (or feedback) were given regarding the orientation in which to hold the object, it was held in an extremely level orientation; both the roll and elevation angles were within ±1° throughout. Because of the geometry of the object, the thumb takes up most of the weight (see OBJECT WEIGHT) and thus it is not surprising that F_y, F_t, and L (as well as F_n) are greatest for the thumb (thick traces). Note the small tangential torques during the hold phase.

FIDDLE PHASE. During the fiddle phase, which followed the first hold phase, the subject slid each digit, in turn, across the grasp surface. The point at which each digit began to slip coincides with a minimum in the F_n/L ratio (arrows in Fig. 2). Slippage can be achieved at a digit either by increasing the load or by decreasing F_n or by combining these strategies. It is evident from Fig. 2 that the combined approach was employed. The T_n at the sliding digit is always close to zero at the points of slippage, which implies that the F_n/L ratio observed at these points provides an estimate of the inverse of the coefficient of static linear friction (μ_{lin}) at each digit, i.e., the critical normal-to-tangential force ratio (F_n/F_t) at which slip occurs. In contrast to the situation at the slipping digit, the tangential torques at the other digits tend to be relatively large at slip onset. These torques contribute to the build up of the large F_t at the slipping digit. After the slip onset, there is a small but sharp decrease in F_t at the slipping digit and increases in F_t at the other two digits. Moreover, there is an unloading of the torques at the latter two digits. A similar pattern was observed in all subjects.

SECOND HOLD PHASE AND RELEASE PHASE. The forces and torques observed during the second hold phase were similar to those seen in the first hold phase. The main difference between the two hold phases was that the digits tended to be positioned closer to the top of the grasp surface because they slid upward during the fiddle procedure. The object was still very level during the second hold phase; although the azimuth may have changed (reflecting a rotation about the vertical axis), the elevation and roll angles were close to zero. In this paper, we focus on the first hold phase because the locations of the digits on the grasp surfaces were less constrained and represented the locations initially chosen by the subjects. After the second hold phase, the subject replaced the object on the tabletop and released it. After the object contacted the tabletop during the subsequent unload phase, the vertical force (and thus the load) deceased together at the three digits (Fig. 2). Likewise, the normal forces deceased in parallel with the vertical forces at each digit as previously described for two-digit lifting tasks.

OBJECT WEIGHT. As when lifting objects with the thumb and index finger at the sides, with the heavier weight the load phase was extended and the overall force output became stronger before lift off occurs. This is illustrated in Fig. 3*A* for the standard grip and was observed in all three grips. Compared to the 2-N weight, the three vertical tangential forces (F_y) increased to higher values with the 4-N weight to counterbalance the weight of the object. Consequently, higher tangential forces (F_t) and overall loads (L) were observed at each of the digits with the 4-N weight. In addition, due to the parallel increase in normal and vertical lift force (and load) during the load phase, the normal forces (F_n) increased to higher values with the 4-N weight. However, object weight exerted no obvious influences on the balance between the normal and vertical tangential forces at any of the engaged digits (Fig. 3*B*) and the proportional increase in normal force ensured appropriate normal forces in both weight conditions.

As shown in Fig. 3*A* (and Fig. 4*A*), for all digits the rate of normal force change (the first time derivative of F_n) reached its maximum during the load phase and decreased before object lift off (see P_y). Similar rate profiles were observed for L and F_y (not shown) as expected given the in phase coupling between F_n and L and between F_n and F_y. That this occurred regardless of object weight indicates that force development during the load phase was scaled to the expected weight of the object based on previous lifting experience (Johansson and Westling 1988a).

Contact phase

TEMPORAL COORDINATION AMONG THE DIGITS AT INITIAL TOUCH. In the standard grip (see Fig. 1*D*) and bimanual grip (see Fig. 1*A*), subjects initiated contact with the object more

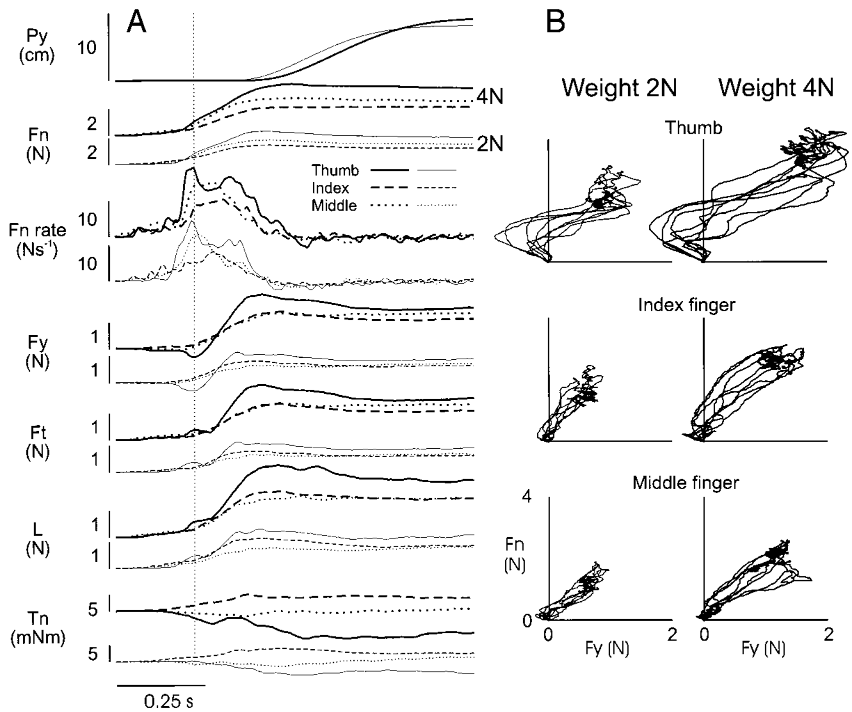

FIG. 3. *A*: averaged records from a single subject (*3*) illustrating the coordination of fingertip forces in the standard grip during the preload, load, and lift phases and the initial part of the hold phase. Thin and thick lines refer to 0.2- and 0.4-kg object weight, respectively. During averaging, single trial records were aligned to the start of the load phase (vertical dashed lines). *B*: plots of normal force (F_n) versus vertical force (F_y) for each digit over the time period from contact to the end of the lift phase. Each trace represents a single trial.

frequently with some digits than others ($\chi^2 = 9.89$ and 9.34, respectively; $P < 0.01$ for both grips). In the standard grip, the middle finger most often contacted the object first (46% of all trials from all subjects), followed by the thumb (32%) and index finger (22%). In the bimanual grip the thumb most often contacted the object first (44%) followed by the left index finger (36%) and the right index finger (20%). In the ring-finger grip, the frequencies with which the thumb, index finger, and ring finger first contacted the object were not reliably different from chance ($\chi^2 = 1.68$; $P = 0.43$). The mean and standard deviation of the time lag between the first and last digit to contact the object was similar across the three grips. The means ranged from 94 to 96 ms and the standard deviations ranged from 64 to 68 ms.

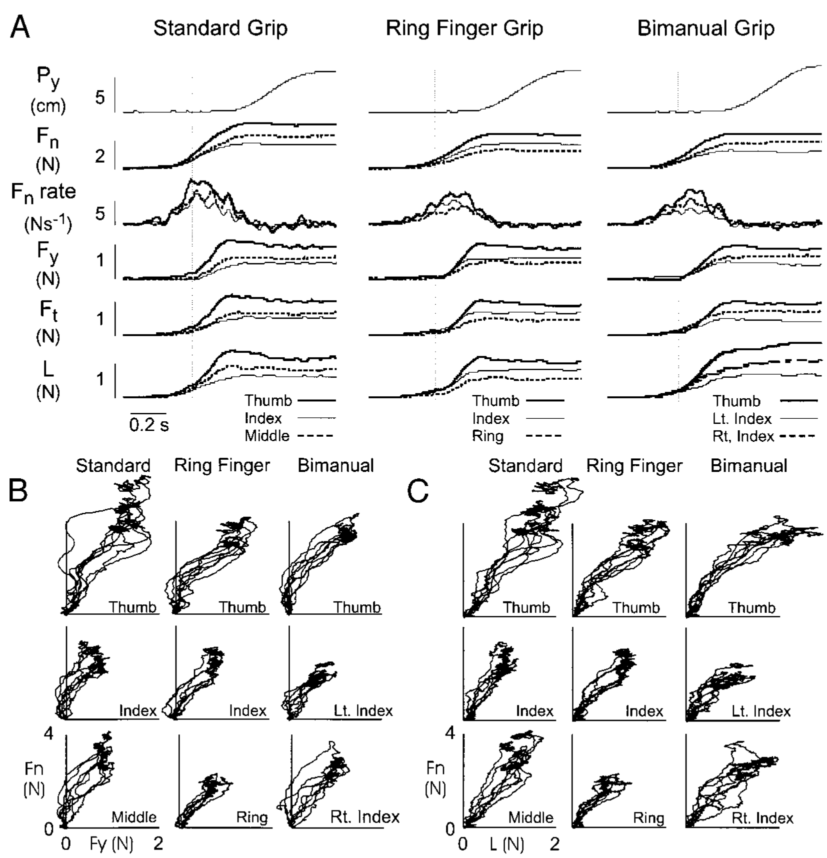

FIG. 4. Initial part of the lift for each of the 3 grips. *A*: averaged records, based on 8 trials by *subject 7* when lifting the 0.2-kg object. In each panel, the records have been aligned at the start of the load phase (vertical dashed lines). *B* and *C*: relationship between normal force (F_n) and vertical force (F_y) for each digit and between normal force and tangential load (L). Each trace represents a single trial. Same data as in *A*.

PRELOAD PHASE. During this phase, normal forces increased before a consistent increase in vertical lift forces. The average duration of this phase (beginning when the leading digit contacted the object) was 157 ± 116 ms and was not affected by the mass of the object, the type of grip, or their interaction ($P > 0.05$ in all 3 cases).

A three-way repeated measures ANOVA (contact disk by mass by grip) revealed that the normal force at the end of the preload phase depended on the location of the contact disk ($P < 0.001$) but not on object mass or grip. (None of the 2-way interactions was significant.) The average normal forces at the end of the preload phase were 0.71, 0.42, and 0.48 N for digits contacting *disks A, B,* and *C,* respectively (cf. Fig. 1*B*). Thus the thumb (*digit A* in all grips) generated considerably more normal force than the other two digits already during the preload phase.

Despite the fact that there were no consistent increases in vertical tangential forces during the preload phase, the total load (L) tended to increase (Figs. 3 and 4). In addition to some horizontal tangential forces and tangential torques, the three digits often generated small downward tangential forces (negative F_y values) that contributed to the total load (L). We extracted the minimum (most negative) value of F_y for each digit during the preload phase. On average, the minimum F_y values for the thumb and the two fingers were −0.19, −0.11, and −0.10 N, respectively. Subjects tended to generate the greatest downward force in the standard grip (mean = −0.20 N; data pooled across the 3 digits) followed by the ring-finger grip (−0.12 N) and the bimanual grip (−0.09 N). These downward forces may have been related to the manner by which the object was approached before contact. With the standard and ring-finger grips, a downward hand movement grasped the object from above. A failure to fully break this downward motion before contact would produce downward forces. Although the object was approached more obliquely with the bimanual grip, there still tended to be a small downward force following contact.

Load phase

COORDINATION BETWEEN NORMAL FORCES AND TANGENTIAL LOAD AT INDIVIDUAL DIGITS. Regardless of grip configuration, F_n increased in parallel with F_y (and L) at all digits throughout the load phase. As illustrated in Figs. 3*B* and 4*B*, the relationship between F_n and F_y is approximately linear after the initial increase in F_n during the preload phase when F_y either remained close to zero or decreased slightly. Correlations between F_n and F_y during the load phase were computed for each digit on each trial. Average coefficients then were computed for each subject, mass, and grip yielding 48 values for each digit. The means ± SDs were 0.95 ± 0.03, 0.96 ± 0.02, and 0.97 ± 0.02 for *digits A, B,* and *C,* respectively. These values indicate that there was a strong linear relationship between normal force and vertical tangential force at all three digits during the load phase. The same procedure was used to assess the relationship between normal force and load (tangential force and torque combined) at each of the three digits. In this case, the correlations were slightly lower but still high, implying a strong linear relationship between normal force and overall load at all three digits. The means ± SDs (based on 48 coefficients) were 0.87 ± 0.17. 0.89 ± 0.10, and 0.92 ± 0.12 for *digits A, B,* and *C.* In contrast to the vertical force, the load showed an approximately linear relationship with the normal force throughout the period of normal force increase, including the preload phase (Fig. 4, *B* and *C*).

DIGIT-SPECIFIC SCALING OF FORCE OUTPUT. During the load phase, the rate of force increase could differ considerably across the digits (Fig. 4*A*); this resulted in different final forces (F_n, F_y, and F_t) during the hold phase. Accordingly, for each digit, the peak force rates were roughly proportional to the final forces. (This is shown for normal force in Fig. 4*A* but was observed for all forces). This variance, across digits, in force output reflects neural control and does not depend solely on mechanical or anatomic constraints. First, during the load phase, the object remained on its support and therefore the vertical forces were not constrained by the object's weight and mass distribution. Second, the digit-specific scaling of force output was observed in all grip configurations including the bimanual grip. Third, the orientation of the fingertips in the bimanual grip was vastly different from in the unimanual grips (compare Fig. 1, *A* and *D*).

COORDINATION FORCE OUTPUT ACROSS DIGITS. Changes in normal force (F_n) and vertical tangential force (F_y) during the load phase were well synchronized across the three digits. This was also true for tangential load (L). The parallel coordination across digits of normal forces and vertical tangential forces is demonstrated in Fig. 5, *A* and *B*, respectively. Each plot shows, for single trials, the relationship between normal force (or vertical force) generated by either *digit A* or *digit C* against the normal force (or vertical force) generated by *digit B.* The relationships among the three normal forces and among the three vertical tangential forces are close to linear in all cases. We computed, for each trial, the correlations between normal forces at *digits A* and *B*, *digits A* and *C*, and *digits B* and *C.* Average correlation coefficients (based on 8 trials) then were computed for each subject, mass, and grip. The means ± SDs of the 48 coefficients for each pair of digits were 0.98 ± 0.01 for *digits A* and *B*, 0.98 ± 0.01 for *digits A* and *C*, and 0.99 ± 0.01 for *digits B* and *C.* The same procedure was used to assess the correlations among the vertical tangential forces (F_y) at the three digits. The means ± SDs were 0.96 ± 0.02 for *digits A* and *B,* 0.97 ± 0.01 for *digits A* and *C,* and 0.97 ± 0.01 for *digits B* and *C.* The corresponding correlations for the loads (L) were slightly lower (0.86 ± 0.18 for *digits A* and *B*, 0.86 ± 0.17 for *digits A* and *C*, and 0.89 ± 0.09 for *digits B* and *C*).

Hold phase

TANGENTIAL LOAD AT INDIVIDUAL DIGITS. The bar graphs in Fig. 6*A* show the distributions, across the three digits, of vertical forces (F_y, ▤), tangential forces (F_t, □), and estimated total tangential loads (L, ■). Separate distributions are given for each grip and for both object weights. We used F_y as a measure of the vertical lift force because the object was close to level (see following text).

The total tangential forces (F_t) were only slightly greater than the vertical tangential forces (F_y), indicating that subjects did not generate large horizontal tangential forces (F_x) in this task. The estimated total tangential loads (L) were clearly greater than the tangential forces (F_t) at all three digits in all grips and for both object weights (Fig. 6*A*). That is, the magnitudes of torques tangential to the grasp surfaces (Fig. 6*B*) were large enough to significantly increase the load at the fingertips. Overall, L was 23% greater than F_t. Although tan-

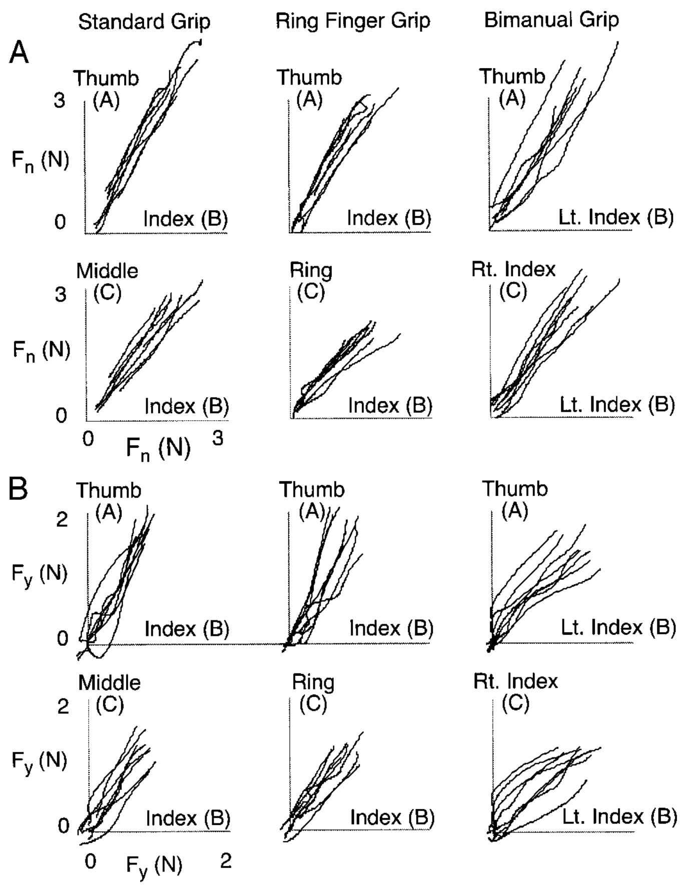

FIG. 5. Force coordination across the 3 digits for each grip during the load phase. *A*: coordination between normal forces (F_n). *B*: coordination between vertical forces (F_y). *A* and *B*: each trace represents a single trial and data from *subject 5* when the weight of the object was 4 N. *Left*, *middle*, and *right*: data from the 3 grips. *Top*: coordination between thumb and the finger contacting disk B; *bottom*: coordination between the 2 fingers (contacting disk B and C; see Fig. 1*B*). Relationship among the normal forces at the different digits was approximately linear, as were the relationships between the vertical forces.

gential torques are not required to lift the object, nontrivial torques are nevertheless applied.

FACTORS THAT POTENTIALLY INFLUENCE THE DISTRIBUTION OF TANGENTIAL LOAD ACROSS DIGITS. The differences in vertical tangential force taken up by the thumb and by the fingers largely accounted for the difference in tangential load across the digits. A higher vertical tangential force at the thumb than at the fingers was expected based on the geometric relationship between the center of mass of the object and the locations of the grasp surfaces. The arrows pointing at the light gray bars in Fig. 6*A* (showing F_y) represent the vertical forces expected if subjects applied the forces at the centers of the grasp surfaces, applied no tangential torques, and held the object level. Although the distributions of vertical force among the digits roughly matched the expected distribution, there were small deviations that varied across the grips. These deviations could be accounted for by four factors: the positions of the applied fingertip forces in the horizontal plane, differences among digits in the vertical position of the applied forces (leading to torques, tending to tilt the object, that could be counteracted by differences among vertical forces), object tilt, and presence of tangential torque at any digit (Fig. 6*C*). We analyzed these factors focusing mainly on the heavier (4 N) object.

Figure 6*D* shows the distribution of digit contact positions (defined as the center of normal force pressure) for each grip. The circles within each disk represent the mean contact positions for each subject. The variance in height of contact (P_y) was much greater in the unimanual grips than in the bimanual grip and most of the variance can be attributed to differences among subjects. That is, individual subjects tended to grasp the object with the three digits at more or less the same height. Nevertheless, there were small but reliable differences in P_y among digits. On average, *digit C* was positioned lower than the average of the other two digits for all three grips ($P <$ 0.001; planned comparisons). Concerning digit contact positions in the horizontal plane of the object (P_x), there was no overall effect of grip but a reliable digit by grip interaction ($P < 0.001$). The fingers (*digits B* and *C*) contacted the grasp surfaces closer to the midline of the object in the standard grip than in the other two grips combined ($P < 0.05$ in both cases). As for object orientation, the mean elevation and roll angles, computed for each subject and grip and averaged across object weights (n = 24), never exceeded ±2.8 and ±2.2°, respectively, and the corresponding SDs never exceeded 2.9 and 1.5°. The corresponding values for mean absolute elevation and roll angles were 3.2 and 2.2°, respectively, and the SDs were 2.3 and 1.3°. Finally, regarding tangential torques, a comparison between the signed values shown in Fig. 6*C* and the corre-

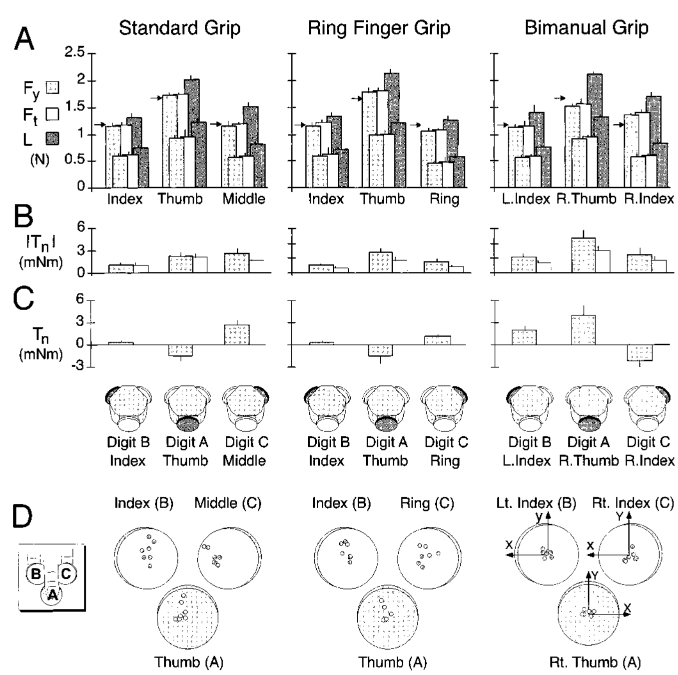

FIG. 6. Fingertip load and digit contact positions during the hold phase. *A*: average vertical force (F_y), tangential force (F_t), and estimated total tangential load (L) shown for each grip and object weight. Bars in the background and foreground represent the 0.4- and 0.2-kg objects, respectively. →, vertical force (F_y) expected for the 0.4-kg object mass in the absence of tangential torques and horizontal tangential forces and if all digits contacted the centers of the contact plates (see text for details). Averages are based on subject means and vertical lines represent standard errors. *B*: corresponding average absolute tangential torque (189 Tn 189) for each digit for both the 0.4-kg (▩) and 0.2-kg (□) objects. c: average signed tangential torque (Tn) for each digit given for the 0.4-kg object. As a reminder, the locations of the digits on the object are indicated *below C*. Disk contacted by a given digit is darkened. *D*: centers of normal force pressure for each digit and grip. Object mass is 0.4 kg. Outside surface of contact disk A and the inside surfaces of disks B and C can be seen (see *inset*). ○, subject means. ← and → and ↑ overlaid on the contact disks shown for the bimanual grip, positive x and y directions in disk coordinates (see Fig. 1*C*).

sponding absolute values in Fig. 6*B* indicates that, for some combinations of grasp and digits, subjects systematically applied torques in certain directions but not in other combinations.

We further analyzed these factors in terms of their potential influences on the distribution of vertical force across the digits and observed that each factor could, in principle, significantly influence the distribution. For example, with an elevation angle of 2°, the change in F_y at the thumb (*digit A*) compared with when the object is level was estimated to be 0.14 N for the 4-N object (assuming that the grasp surfaces were contacted at their centers). However, no single factor could account for the details of the force distributions as expressed in the means across subjects. Therefore we conclude that the observed distributions of F_y values across the digits, as such, were influenced by all four factors, but that these factors interacted by partly canceling each other. We also conclude that subjects can satisfactorily perform the present three-digit lifting task with the digits in different locations on the grasp surfaces and with different patterns of fingertip forces/torques.

NORMAL FORCES AT INDIVIDUAL DIGITS AND SAFETY MARGINS AGAINST SLIP. To assess the control of normal forces, it is useful to consider the minimum normal force, or slip force (F_s), required to prevent slip and compare this with the normal force (F_n) that is employed (Johansson and Westling 1984a; Westling and Johansson 1984). Figure 7*A* shows the average normal forces (based on subject means) applied by the three digits for each grip and for both object weights. The corresponding slip forces also are shown. Both normal force and slip force varied across digits and the distributions of both closely approximated the distribution of tangential loads described earlier (Fig. 6*A*). A proportional relationship between slip force and load was expected because the coefficient of friction was independent of digit and grip (see METHODS). Recall that the slip force is the ratio between total tangential load (L) and the coefficient of friction (μ_{lin}) (see *Eq. 1*).

Safety margin. The mean normal force safety margin ($F_n - F_s$), represented by the gray part of the columns in Fig. 7*A*, ranged from 0.42 to 1.5 N and tended to be proportional to normal force. Thus the safety margin tended to be greater for the thumb (*digit A*) than for the other digits and it tended to be greater for the 4-N object than for the 2-N object. However, the relative safety margin, expressed as a fraction of the normal force (Fig. 7*B*), was fairly stable across digits, grips, and object weight.

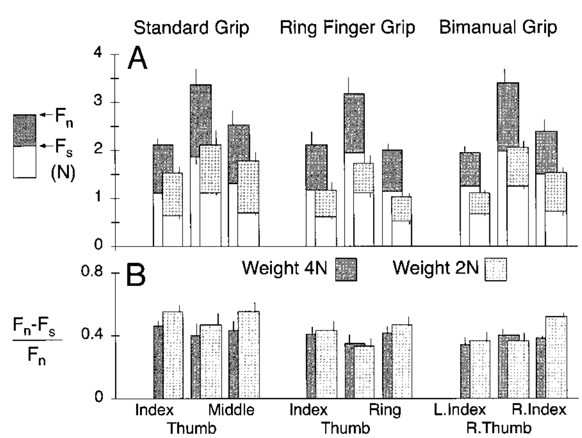

FIG. 7. Normal force and safety margin against slippage during the hold phase. *A*: average normal forces (based on subject means) applied by the 3 digits for each grip and for both the 0.2-kg (foreground) and 0.4-kg (background) object weights. Height of each bar represents the normal force (F_n); the open part represents the slip force (F_s) and the gray part represents the normal force safety margin ($F_n - F_s$). *B*: corresponding relative safety margins defined as the safety margin as a proportion of the normal force. Vertical bars in the figure represent standard errors.

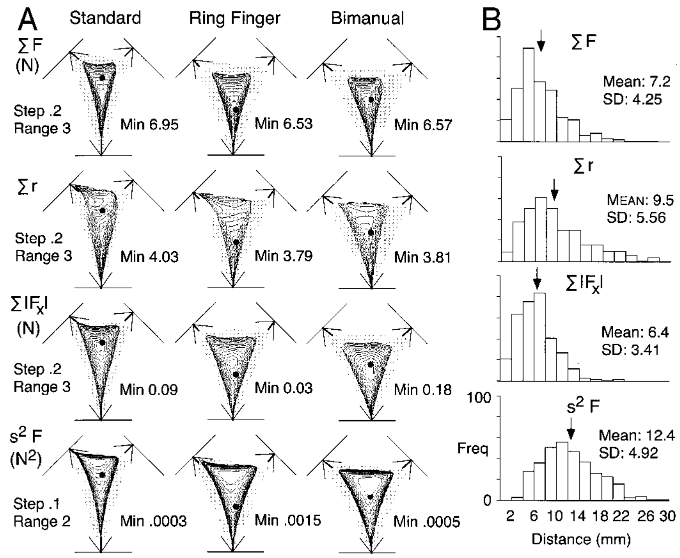

FIG. 8. Force coordination in the horizontal plane of the object illustrated on a schematic top view of the object: stability zone of intersection points and examples of ''cost'' functions estimated for the 3 grips based on hold phase data obtained with the 0.4-kg object weight. *A*: contour plots for 4 different ''cost'' functions superimposed on a top view of the object showing the 3 grasp surfaces. All contour plots are bowl-shaped. Thick lines emerging from the grasp surfaces represent the mean force vectors produced by a single subject (*2*) for a given grip. Large dot in the center of the object represents the intersection of the mean force vectors. Cone formed by the lines on either side of each force vector represents a stability cone; the digit would slip if the force vector pointed outside this cone. Shaded area is the region of possible intersection points. Step, or distance, between contour lines and the range between the lowest and highest contour lines are constant across grips and are given for each cost function. Minimum is within the white region and may vary from plot to plot. *B*: histograms showing the distribution of distances, in the horizontal plane of the object (see *A*), between the intersection points coordinated by the subjects and the minima of the contour plots for the 4 cost functions, i.e., the intersection point that would be obtained if the cost function was minimized. Each histogram includes data from all single trials obtained from all subjects and all grasp conditions (n = 333; 3 trials were omitted because the subject mishandled the object). Mean (arrows) and SD of each histogram is shown.

COORDINATION OF FINGERTIP FORCES IN THE HORIZONTAL PLANE OF THE OBJECT. *Force vectors and stability zone.* In the present multidigit task, subjects may achieve stable grasps with different combinations of forces in the horizontal plane of the object. However, the force vectors generated by the three digits always intersected, approximately, at a single point in the horizontal plane because the total force and torque acting on the object were always close to zero (see APPENDIX). We used this intersection point to examine the subjects' choice of coordination of forces among the three digits during the hold phase.

The gray triangular zone in each of the top view schematics of the object shown in Fig. 8*A* illustrates, for a single subject, the region of possible intersection points (i.e., force vector orientations compatible with a stable grasp). The cones defined by the thin lines at each grasp surface are the frictional cones estimated for each digit-object interface as the arc tangent of the measured coefficient of friction. Force vectors outside these cones would lead to slip. However, the union of the three stability cones does not alone define the stability zone. The latter also is constrained by the three digit contact positions; if the intersection point lies outside the triangle defined by the contact positions, the net force acting in the horizontal plane could not be zero as required for holding the object stationary in air.

Implications of choice of intersection point. To learn about some consequences of the choice of intersection point, we calculated the values of the following variables as a function of the location of the intersection point within the stability zone: the total force produced by the digits (ΣF, i.e., the vector sum of the force applied by each digit), the sum of the three normal-to-tangential force ratios (Σr), the sum of the absolute values of the horizontal tangential forces ($\Sigma|Fx|$), and the variance of the magnitudes of the three-dimensional force vectors (s^2F). The contour plots in Fig. 8*A* show typical results. All plots were bowl-shaped such that the smallest contour region is the minimum. Thus if the subject coordinated the fingertip forces so as to minimize the total force output (ΣF), for example, the intersection point should be close to the minimum in the plots referring to ΣF in Fig. 8*A*. For other locations, the total force requirements would increase. Note that the values of all variables shown in Fig. 8*A* tend to increase sharply as the intersection point moves off the *y* axis (in the *x* direction in object coordinates; Fig. 1*B*), whereas changes along the *y* axis would be associated with a relatively small increases in ΣF, Σr, and $\Sigma|F_x|$.

We generated these contour plots using the following constraints: the total force and total torque acting on the object are zero, the object is level, the three digits contact the object at the same height, the tangential torques at the three digits are zero, and the normal-to-tangential force ratio at each digit is equal to or greater than a specified minimum value. All these constraints, or assumptions, are reasonably consistent with the results described earlier. Using these constraints, the three force vectors corresponding to any intersection point within the stability zone can be determined and, hence, the chosen functions can be computed. To find the three force vectors for a given intersection point, we first determined the vertical force components for each digit based on their actual contact positions in the horizontal plane of the object. Given the constraints listed above, these three unknown vertical forces were determined from the geometry, mass, and center of mass of the object. The intersection point gives the directions of the force vectors in the horizontal plane and, therefore, for each vector we know the ratio of the normal force (F_n) to the horizontal tangential force (F_x). To find the magnitudes of the horizontal force vectors, we used an iterative procedure whereby the magnitude of one of the vectors was gradually increased until the force ratios (F_n/F_t) for all three digits were equal to or greater than specified minimum values. (On each iteration, once the magnitude of 1 vector is set, F_n and F_x are fully determined for all 3 vectors.) The minimum ratio values used were the mean force ratios measured for a given subject, digit, grip, and object weight.

Subjects' choice of intersection points. The question now arises as to which intersection points the subjects actually selected. For the subject exemplified in Fig. 8*A*, the dots superimposed on the contour plots represent the mean of the intersection points chosen in single lift series and the thick lines at each of the three grasp surfaces represent the corresponding force vectors. The distances between the intersection points and the minima of the contour plots may provide an indication of the ''cost'' of the coordination chosen by the subject in terms of ΣF, Σr, $\Sigma|F_x|$ and s^2F. For the subject exemplified in Fig. 8*A*, this distance was, on average, shortest for $\Sigma|Fx|$ and ΣF. We computed, for each trial and for all subjects, these distances. Figure 8*B* shows that the intersection points chosen were rather close to the minimum of the $\Sigma|F_x|$ and ΣF functions. We observed the largest distances for the s^2F function, i.e., subjects did not generate similar force magnitudes across all digits.

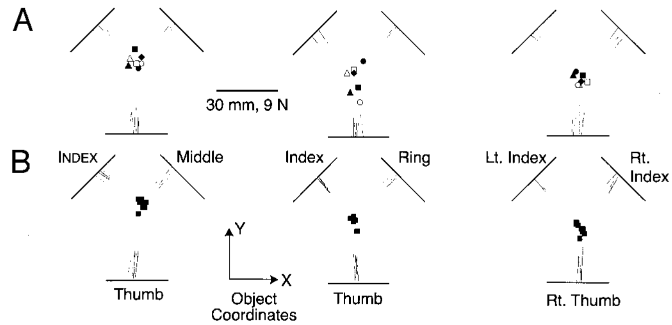

FIG. 9. Orientation of force vectors in the horizontal plane of the object chosen by subjects during the hold phase and corresponding intersection points illustrated on a schematic top view of the object. *A*: each line represents the mean force vector generated by a single subject and digit and emerges from the contact disk at the mean *x* position of the center of normal force pressure. Calibration line is provided to the *right* of the plot for the standard grip. Dots in the center represent the intersection for the 3 mean force vectors from single subjects coded by separate symbols. To estimate the coordinates of the intersection point, we calculated the average of the 3 closely located intersection points formed by the 3 pairs of 2 vectors. *B*: force vectors and intersection points for a single subject (*subject 7*). Each line represents a force vector for a given trial and digit and emerges from the disk at the *x* position of the center of normal force pressure. Scale factor is the same as in *A*. *x* and *y* axes in object coordinates are shown to the *right* of the plot for the standard grip.

Figure 9*A* further illustrates the location of the intersection points for each subject based on data averaged across the series of eight trials for each grip with the 4-N object. The origins of the corresponding mean force vectors are located at the mean contact positions (P_x) on the disks. Again, it is clear that subjects tended to avoid generating appreciable horizontal tangential forces. The average angle of the force vectors, relative to the normal of the contact surface (0.004°) was not reliably different from zero ($P = 0.99$) and was not influenced by digit, mass, or grip. However, there was appreciable spread in the intersection points both across grips and subjects (Fig. 9*A*). This spread was greatest in the *y* direction in object coordinates (see Fig. 9*B*, *inset*) and can be attributed, at least in part, to variance in the mean contact positions of the digits (indicated by the force vector origins). We correlated the *y* position of the intersection point in object coordinates and the average *y* position of the digit contact positions of *digits B* and *C* (in object coordinates) using data from individual trials. Separate correlations run for each subject, collapsing across grips and weights, yielded correlation coefficients between 0.51 and 0.87 ($P < 0.001$ in all cases). We also correlated the *x* position of the intersection point with the average *x* position of all three digit contact positions in object coordinates and obtained positive coefficients that were reliable ($P < 0.05$) in six of the seven subjects. There was also variation of the intersection point across trials within subjects and grips as illustrated by the single trial data in Fig. 9*B*. However, this intertrial variation depended on variability in the orientation of the force vectors and not on variability in the contact positions.

DISCUSSION

We have shown that when lifting an object with a three-digit grip, the coordination of fingertip forces, in many respects, matches what has been documented previously for two-digit grasping (see Johansson 1996 for a review). At the same time, our study reveals novel aspects of force control that emerge only in multidigit manipulative tasks.

Coordination within digits

During the load phase of the lift, the normal force at each digit increased in phase with, and thus anticipated, the increase in tangential load at that digit. This basic coordination between normal force and load has been documented for two-digit precision grip tasks during a variety of loading conditions, including lifting and moving hand-held objects under inertial, viscous, and elastic loads (Flanagan and Wing 1993, 1997; Johansson and Westling 1984a, 1988a,b). A tight coupling between normal force and tangential load also has been reported for a variety of two-contact grasps including bimanual grips and ''inverted'' grips (or pirgs) (Burstedt et al. 1997b; Flanagan and Tresilian 1994). Furthermore in two-digit grips this coordination is observed at each individual digit (Burstedt et al. 1997b; Edin et al. 1992; Jenmalm et al. 1998). The present experiment extends this principle to multidigit grips; a close link between normal force and tangential load was observed at the separate digits in all three grips involving different digits and one or both hands.

In the current experiments, the tangential loads at the digits included both a linear (tangential force) and a rotational (tangential torque) component. In agreement with the recent results of Kinoshita et al. (1997) and Goodwin et al. (1998), the sensorimotor mechanisms engaged in the control of normal force appear to take into account the combined effect of these load components. On average, the largest of the tangential torques was relatively small (<5 mNm). Nevertheless, the torques appreciably increased the normal force required to prevent (rotational) slip compared with the normal force that would have been needed to prevent (linear) slip had torques been absent.

The coordinated action of normal force and tangential load at the fingertips provides for grasp stability by ensuring that the normal force at any given load exceeds the minimum normal force needed to prevent slippage by a certain safety margin. To achieve this control goal, the balance between the normal force and tangential load is adjusted to the current frictional conditions (Johansson and Westling 1984a). In the present experiments, the coefficients of friction at each digit were similar and so were the normal forces at any given load (e.g., Fig. 4*C*). Thus the present results are consistent with the view that subjects adjusted the normal forces at all digits so as to preserve adequate but not excessive safety margins (Burstedt et al. 1997b; Edin et al. 1992). Indeed, we found that the fraction of the normal force constituting the safety margin during the hold phase was rather stable across digits and across grips.

Coordination among digits

We found that the average delay between the time the first digit contacted the object and the time all digits contacted the object was 96 ms. This value is considerably greater than the corresponding delay in unimanual (36 ms) and in bimanual (26 ms) two-digit lifting tasks with the hand and object in view (Burstedt et al. 1997b; see also Lemon et al. 1995). Thus establishing contact with all digits takes a longer time when the grasp includes three digits compared with two digits. Furthermore for three-digit grasps, the temporal coordination across hands (bimanual grip) was similar to the coordination across digits within a hand (unimanual grips).

Importantly, the development of normal force and load force before object lift-off reflected both the magnitude and the distribution of forces across the digits during the hold phase, which in turn largely reflected object geometry, center of mass, and weight. With regard to the object's weight and mass distribution, this predictive behavior must have been based on sensorimotor memory because there is no explicit information available about mass and its distribution until the object begins to move. Indeed, it has been demonstrated previously for two-digit lifts that force development in the load phase is predictive of the final forces required to lift the object and that this prediction is based on sensorimotor memory built up from object weight experienced in previous lifts (Johansson and Westling 1988a). Because the weight and mass distribution of the test object was kept constant in series of lifts in the present experiments, the subject could have exploited efficiently a similar anticipatory control strategy. In the case of object geometry, it has been documented that people can use tactile cues as well as visual geometric cues to adapt fingertip forces for object shape (Jenmalm and Johansson 1997). In general terms, the brain appears to rely on feedforward control mechanisms and takes advantage of predictable physical properties of objects that we handle to parametrically adapt the motor commands before their execution and in anticipation of the upcoming force requirements (Johansson 1996). Both visual and somatosensory inputs are used to intermittently update the relevant sensorimotor memory systems (internal models) that specify the various motor coordination parameters.

To maintain the object level when in air, *digit A* would take up 41.4% of the total vertical force and the other two digits would each take up 29.3% if one assumes that all digits contact the centers of their respective grasp surfaces and that the tangential torques are zero (black bars in Fig. 8*A*). To keep the object stationary in the horizontal plane under these conditions, the ratio of normal forces generated by *digits A–C* also would have to be 41.4:29.3:29.3 but only if the horizontal tangential forces are zero. However, the forces recorded in the hold phase were not exactly distributed in this manner. Although the coordination of vertical and normal forces applied to the object primarily reflected intrinsic object properties (geometry, center of gravity, weight, and friction in relation to the skin), superimposed on these forces were subtle actions exerted by the digits. In all three grasps, these included horizontal forces, small object tilts, and significant tangential torques at one or more of the digits. It is not clear to what extent the brain explicitly controlled these various additional actions or whether they reflected secondary phenomena related to the implementation of the control and the mechanics of the task. However, some of these actions could, for instance, have compensated for deviations in digit contact positions from the centers of the grasp surfaces.

Comments on control strategies

The present three-digit lifting task can be performed satisfactorily with the digits in different locations on the grasp surfaces and with many different patterns of fingertip force application. To address this ''degrees of freedom problem,'' we analyzed in some details the choice of force vectors in the horizontal plane of the object. One way the CNS might select those force vectors is to minimize certain costs. Previous work on precision grip control suggests that subjects attempt to minimize (or at least reduce) fingertip forces (ΣF) while at the same time ensure that grasp stability is preserved. In the present study, we examined this cost function and three others and found that ΣF appeared to a good predictor of subjects' behavior together with the total horizontal tangential force ($\Sigma|F_x|$). However, the analysis of the cost functions studied is incomplete in several respects. For example, it did not take account the actual vertical contact positions of the digits, object orientation, or observed tangential torques. However, given the magnitude of these factors in relation to the major determinants of the force coordination (center of mass and geometry of the object), the omission of those factors may not be that severe. Furthermore apart from the cost functions analyzed one easily can conceive other important cost functions, e.g., minimizing tangential torques and choice of exact grasp sites. The possibility that the CNS may solve the degrees of freedom problem (in this case the problem of selecting specific force vectors) by combining several differently weighted cost functions recently has been suggested by Rosenbaum et al. (1993) in the context of selection of hand trajectories in reaching. One attraction of this approach is that it can account for differences across individuals and contexts by adjusting the weights applied to the cost functions.

Arbib, Iberall, and colleagues (Arbib et al. 1985) have suggested that grasping is controlled in terms of opposition spaces and virtual fingers. In their model, a variety of grips can be characterized by a single opposition axis between two virtual fingers where a virtual finger may comprise a single digit, a group of digits, the palm, etc. For two or more digits to be considered as a virtual finger, they must generate forces in approximately the same direction. We question whether this notion is useful when humans perform three-digit grasping task of the type described in this report. The forces exerted by the three digits were all in different directions and did not directly oppose one another, i.e., there were no opposition axes.

APPENDIX

Consider three forces applied to a rigid body in a plane (see Fig. A1). We will show that if $\Sigma F = 0$ and the three forces intersect at a common point, C (Fig. A1*A*), then $T_z = 0$ and if $\Sigma F = 0$ and the three forces vectors do not intersect at a single point (see Fig. A1*B*), then $T_z \neq 0$ where the z axis is normal to the plane.

Part 1

The torque normal to the plane about point C, T_c, will be zero because all three forces pass through C

$$T_c = F_1 \times (P_1 - C) + F_2 \times (P_2 - C) + F_3 \times (P_3 - C) = 0$$

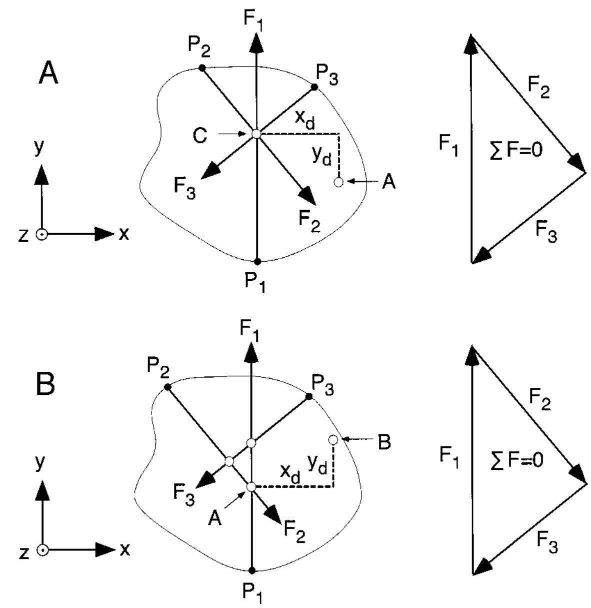

FIG. A1. *A*: schematic showing 3 forces (F_{1-3}) applied to an object in a horizontal plane at 3 points (P_{1-3}). Force vectors intersect at point *C*. *B*: same as *A* but the 3 force vectors do not intersect at a single point.

where P_i is the point of application of F_i.

Now consider the normal torque about any given point A displaced from C by line D such that $D = A - C$

$$T_a = F_1 \times (P_1 - A) + F_2 \times (P_2 - A) + F_3 \times (P_3 - A)$$

therefore

$$T_a = F_1 \times (P_1 - C - D) + F_2 \times (P_2 - C - D) + F_3 \times (P_3 - C - D)$$

factoring out T_c we have

$$T_a = T_c - F_1 \times D - F_2 \times D - F_3 \times D$$

which simplifies to

$$T_a = T_c - (\Sigma F_i) \times D = 0$$

Because A can be any point in the plane, it follows that $T_z = 0$ regardless of the location of the z axis.

Part 2

Let point A be the intersection of forces F_1 and F_2 such that the torque normal to the plane about A will be

$$T_a = F_3 \times (P_3 - A)$$

If the magnitude of $F_3 \neq 0$ and F_3 does not pass through A, then $T_a \neq 0$.

Consider the normal torque about a given point B displaced from A by line D such that $D = B - A$ or $B = D + A$ (see Fig. A1*B*). The torque about B is

$$T_b = F_1 \times (P_1 - B) + F_2 \times (P_2 - B) + F_3 \times (P_3 - B)$$

therefore

$$T_b = F_1 \times (P_1 - A - D) + F_2 \times (P_2 - A - D) + F_3 \times (P_3 - A - D)$$

factoring T_a we have

$$T_b = T_a - F_1 \times D - F_2 \times D - F_3 \times D$$

which simplifies to

$$T_b = T_a - (\Sigma F_i) \times D = T_a$$

Because the torque is constant about all points in the plane, it follows that $T_z \neq 0$ regardless of the location of the z axis. It also follows that the torques exerted by each force vector about the intersection of the other two are equivalent.

Note that *Part 1* is a special case of *Part 2* because the torque exerted by any one of the vectors about the intersection of the other two will be zero.

Finally, the proofs provided above do not apply when all of the forces are parallel because no intersections can be defined.

This study was supported by Swedish Medical Research Council Project 08667, Department of Naval Research, Arlington, VA Grant N00014–92-J-1919, the Göran Gustafsson Foundation for Research in Natural Sciences and Medicine, and the Canadian Natural Sciences and Engineering Research Council.

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Received 27 August 1998; accepted in final form 16 December 1998.

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