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RESEARCH ARTICLE

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The relation between force and movement when grasping an object with a precision grip

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Abstract When reaching out for objects, the digits' paths curve so that they approach their positions of contact moving more or less perpendicularly to the local surface orientation. This increases the accuracy of positioning the digits and ensures that any forces exerted at contact are nearly perpendicular to the surface, so that friction will prevent the digits from slipping along the surface. When lifting the object a similar force perpendicular to the surface is needed to prevent the object from slipping from one's fingers. In order to determine whether these two issues are dealt with simultaneously we let subjects pick up a cube from three different starting positions and measured the digits' movements and forces from before contact until the moment the cube started moving. The impact force was low. After impact, the digits spent about 200 ms in contact with the surface of the cube before the latter started to move. The digits first decelerated, and then they gradually built up the grip- and lift forces to move the cube upwards. We found no direct relationship between the control of the reaching movement towards the object and the force applied at the surface of the object to pick it up. We conclude that the reaching and lifting movements are quite independent.

Introduction

We reach and grasp objects many times a day. Most of the time, we perform this task very well and it does not seem very complex. However, in fact it is. We have to identify the object, to locate appropriate grasp positions on the surfaces of the object, and to move the digits to those points. When we have positioned our digits on the surface, we must exert forces in such a way that we can lift the object in a stable manner and use it for a particular goal. What is the relation between the positioning of the digits and the control of the forces?

Many studies have focused on the interaction between the digits and the contact surfaces of the object from the moment the object is contacted until the object is released again (Edin et al. 1992; Gordon et al. 1993; Johansson and Westling 1984; Kinoshita et al. 1997; Westling and Johansson 1984). Grasp stability is mainly ensured by controlling the ratio between lift forces (along the grasp surface) and grip forces (orthogonal to the surface; Reilmann et al. 2001; Westling and Johansson 1984). Coordinating grip forces and lift forces prevents the digits from slipping over the surfaces of the object without having to exert excessively large forces. The ratio between grip force and lift force depends on the friction with the grasp surface. A slippery object (for instance silk) requires a larger ratio than an object with a rough surface, such as sandpaper (Fagergren et al. 2003; Johansson and Westling 1984). While lifting an object, the ratio between grip force and lift force is not determined for the whole grip, but is controlled independently for each digit (Burstedt et al. 1997, 1999; Edin et al. 1992). Thus subjects appear to control the direction of each digit's force very accurately.

Smeets and Brenner (1999) have shown that the characteristic grip preshaping while reaching for an object can be understood as the result of the digits moving more or less independently towards their designated places of contact on the surface of the object. Obviously the digits cannot move completely independently, because they are anatomically linked. However, experiments have shown that anatomical constraints do not have much influence on grasping (Flanagan and Tresilian 1994; Smeets and Brenner 2001). Thus it would appear that both the reach to grasp movement and the build-up of the grasp forces are the result of independent control of the digits.

If you want to be able to lift the object, both digits should arrive simultaneously at opposite sides of the

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object. A number of additional requirements influence each digit's path. In order to make contact at the correct position it is advantageous to approach the surface more or less orthogonally (Smeets and Brenner 1999). The extent to which each digit will tend to approach perpendicularly depends on the properties of the surface. If accurate positioning is needed, for example, because the surface is slippery, the approach will be more perpendicular. Slippery surfaces also require a larger ratio between grip and lift forces, so there is some correspondence between the required movement before contact and the required direction of the force after contact is made with the object. Another example is a fragile object, which constrains the grip forces to be rather low. It is known that one approaches an object that looks fragile with more care than one approaches an object that looks very robust (Marteniuk et al. 1987; Savelsbergh et al. 1996).

Is the correspondence between the requirements for reaching and lifting reflected in the transition between the two, perhaps simplifying the control of the combined action? In order to find out, we examined how the force changes after the moment of initial contact, and in particular, whether this is related to how the object is approached. We varied the movement constraints by letting the subjects start their movements from different locations. We did not change the force constraints. We analysed in detail how the movements of the digits and their exerted forces changed after the digits contacted the surface.

Methods

This study is part of an ongoing research program that has been approved by the local ethics committee. Nine subjects volunteered to take part in the study after being informed about what they would be required to do.

Set-up

The cube that subjects had to lift was 5-cm high, 5-cm wide and 5-cm deep (Fig. 1a). It had two grip surfaces (5×5 cm) that were covered with sandpaper to prevent the skin from slipping over the surface, because such slipping would make the interpretation of the data more complicated. Inside the cube, the grip surfaces were each attached to a force sensor (ATI, Nano17 Ft). Each grip surface weighed 11 g. The whole cube weighed 350 g. The force (resolution 0.025 N) and torque (resolution 0.0625 Nmm) at the grasp surfaces were measured at a sampling rate of 500 Hz in all three directions. Note that we will only report forces until just after lift-off because the forces are measured in sensor coordinates, so that once the object starts moving upwards, the measured forces are no longer guaranteed to correspond with the vertical and horizontal. Two IREDs were placed on top of the cube to measure the position of the cube. IREDs were also placed on the nails of the subjects' right index finger and thumb. Positions of these IREDs were measured at 500 Hz with the Optotrak motion recording system (resolution 0.01 mm). The force sensor data were measured in synchrony with the movement data by means of the Optotrak Data Acquisition Unit. We determined the delay of the signal processing of the force sensor to be 8 ms, and corrected for this.

Subjects sat with the cube located directly in front of their right shoulder. They had to start their grasping movement from one of the three starting positions (Fig. 1b). All starting positions were 15 cm from the cube. Starting positions were in front (1), to the front-right (2) and to the right of the cube (3). A 3-cm high plateau, onto which the subjects had to place the cube, was located 2.5 cm behind the far edge of the cube.

Procedure

Before participating, subjects washed their hands with soap and water, to remove excessive oil and fat from the skin. Since the felt weight and surface texture on the previous trial may be used to plan each trial (Westling and Johansson 1984), we let subjects grasp the cube five times before beginning with the experiment. The weight and surface texture were constant throughout our study.

Subjects put their right hand at one of the starting positions with the tip of their index finger and thumb touching each other. The experimenter gave a verbal signal in response to which the subjects grasped the cube and placed it on the plateau. No instructions were given about the speed of the movement. After each trial the experimenter relocated the cube at its original position.

The experiment consisted of three conditions (three starting positions) that were each presented in a separate block of 25 trials, resulting in 75 trials. The order of the blocks of trials was counterbalanced across subjects.

Data analysis

Instantaneous velocity and acceleration were computed from position samples of the IREDs. To do so we fit a second-order polynomial to seven position samples (12-ms window) around each position. Based on the three parameters of the fit polynomial we can estimate the fingers' position, velocity and acceleration at that instant. This is a convenient method for combining data smoothing and differentiation in a single procedure (Biegstraaten et al. 2003b; Smeets et al. 2002).

The beginning and end of a digit's movement to the cube were both based on the tangential velocity of the markers on that digit. The moment of lift-off was based on the upward velocity component of one of the IREDs of the cube. The onset of the movement of each digit and the moment of lift-off were defined as the last frame before peak velocity in which the velocity was smaller than that on the preceding frame. The offset of the

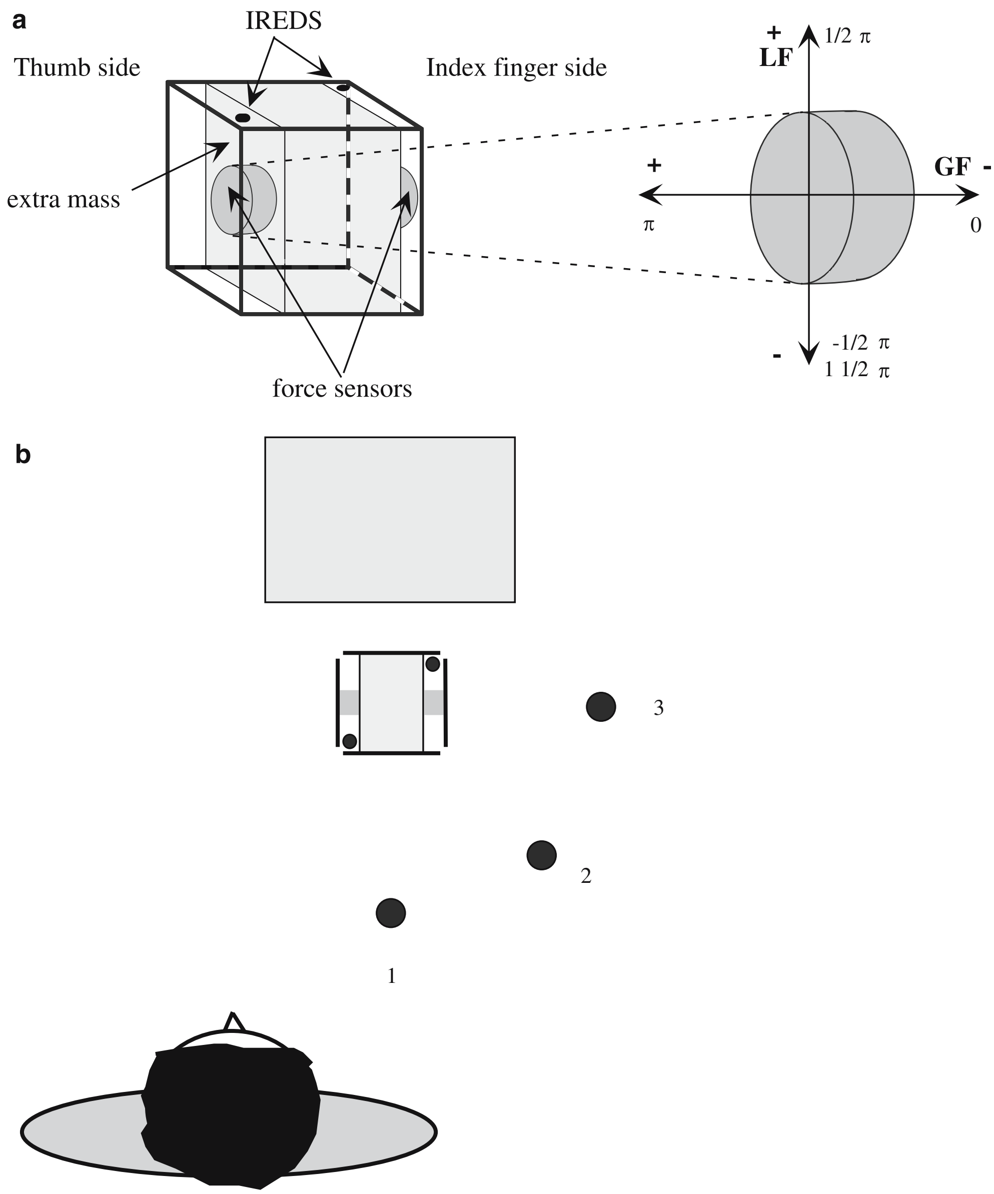


Fig. 1 **a** Drawing of the cube used in this experiment. Each force sensor inside the cube is attached both to a grasp surface (not shown) and to the extra mass inside the cube. Two IREDs were attached to the top of the cube to measure the position of the cube. **b** top view of the set-up of the experiment. The *black dots* indicate the three different starting positions. The cube is shown at its initial position. The plateau onto which subjects had to place the cube is indicated by a *grey square*. Drawing not to scale

movement of each digit was defined as the first frame after peak velocity in which the velocity was smaller than that on the following frame (Biegstraaten et al. 2003b). The total movement time (MT) was calculated as the time between the onset and offset of the movement for each digit. This total MT was divided into the time from movement onset of the digit until its initial contact with the cube (MT before contact) and the time from initial contact of the digit until its movement offset (MT after contact). The period between movement offset and lift-off of the cube is referred to as late contact.

The horizontal forces perpendicular to the surface (grip force), the vertical forces applied to the cube (lift force) and the torques in all directions were analysed. The definition of the coordinate system is given in Fig. 1a. In this article we only consider the movements and forces in the grip direction and the lift direction. The moment of initial contact (initial contact time) of a digit with the cube was determined on the basis of the grip force. It was defined as the first frame in which the grip force was more than two times the standard deviation of the noise and remained above that value until maximum force.

We calculated the points of force application for each digit and each sample using the relation between the measured forces and torques. The direction of the applied force was determined at each instant from the lift force and the grip force (for a definition see Fig. 1a). Similarly, we calculated the direction of the velocity of each digit from the horizontal and vertical velocity components at each instant.

For each variable the median value for each subject and condition was used for further statistical analysis. Using the median value makes the data less sensitive to outliers. For each variable a separate repeated measures ANOVA was used to evaluate whether there were consistent differences between the starting positions and between the digits (across subjects). The variables that we considered were the MT, the total contact time, the time between initial contact and movement offset and the grip and lift forces of the individual digits at the moment of lift-off. To further analyse the difference in timing between the digits we determined the difference in initial contact time between the two digits, and subjected these differences to a repeated measures ANOVA for the factor starting position. Reported standard errors are all between subjects.

Results

Figure 2 shows example traces of one trial of one subject. Figure 2a shows the grip force and the lift force of index finger and thumb and Fig. 2b shows the direction of these applied forces. In this trial the index finger contacts the surface before the thumb does (Fig. 2a). Grip force and lift force are not equally distributed over the digits near the moment of lift-off, which means that the object did not only move upwards. The direction of

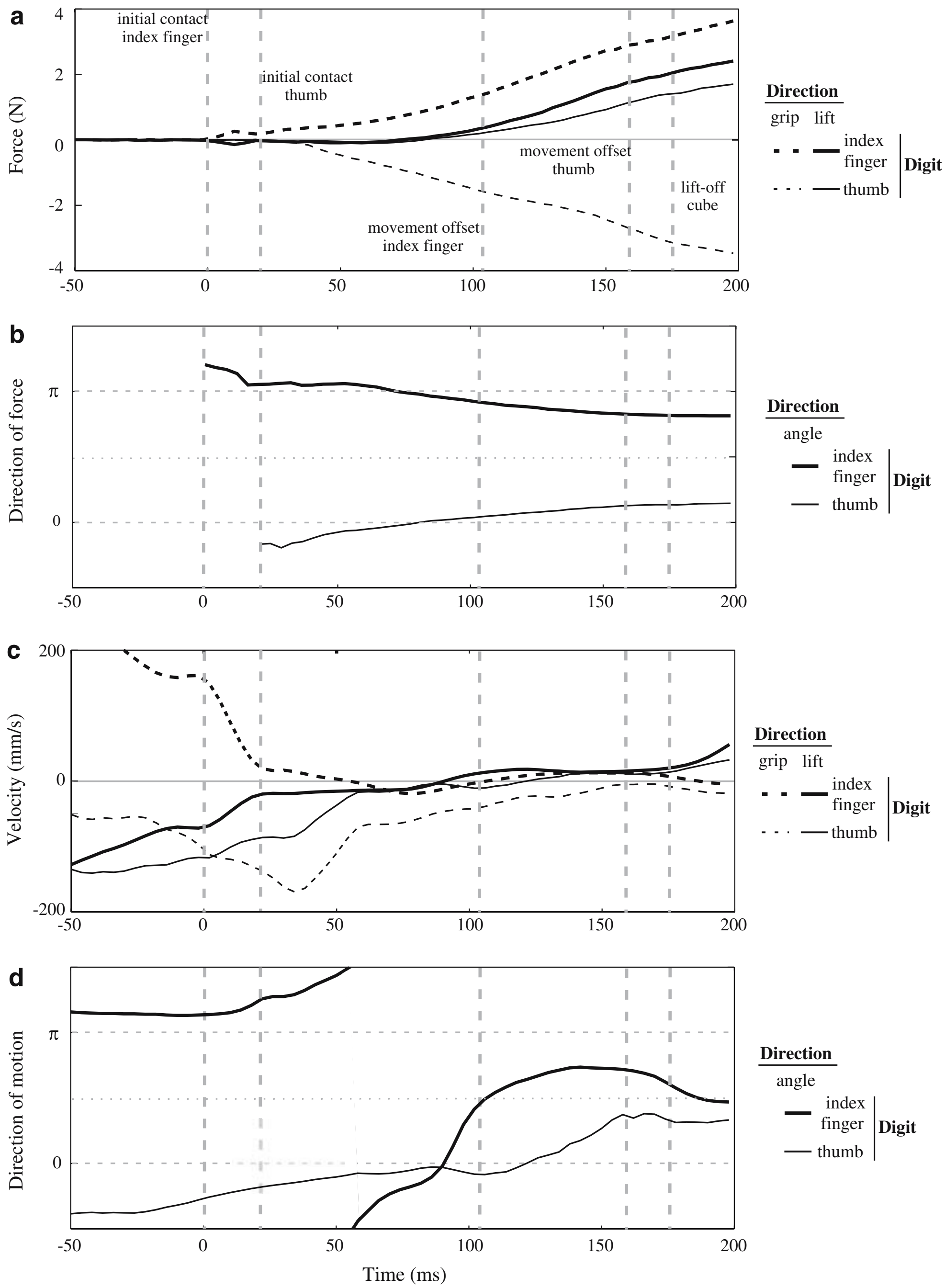


Fig. 2 A single trial of one subject. *Thick lines* indicate traces of the index finger; *thin lines* indicate traces of the thumb. If there are two curves for a digit, *dashed lines* indicate the grip component and *solid lines* indicate the lift component. *Vertical dashed lines* indicate the timing of initial contact and movement offset (for each digit) and the moment of lift-off (of the cube). *Horizontal dashed lines* indicate the grip force direction and *dotted lines* the lift force direction. Time zero is the moment of initial contact with the surface. **a** Grip force and lift force for each digit. **b** The direction of the applied force. **c** The two components of each digit's velocity. **d** The direction of the velocity

force changes gradually from the moment of initial contact until it reaches the value that is maintained after lift-off (Fig. 2b).

Figure 2c shows the velocity in the grip direction and in the lift direction for each digit. The velocity and acceleration of the finger at lift-off is larger than that of the thumb, which corresponds with its larger lift force shown in Fig. 2a. Figure 2d shows the direction of these velocities. After the surface is contacted ($t = 0$) there is still a considerable amount of movement of both the digits (Fig. 2c). The thumb even has a peak in the velocity component orthogonal to the surface (grip) just after contact, illustrating the fact that the movement cannot be considered to have ended at contact. However, although the initial direction of force is a nice continuation of the direction of motion just before contact, the force generated by the contact itself is very modest. The most rapid increase in force occurs after motion offset (Fig. 2a). There are also considerable intentional or accidental shifts and rotations of the digits while in contact with the object. The direction of motion of the digits changes much more than the direction of force (Fig. 2d). One reason for this could be that part of the perpendicular force is transformed into compression of the skin. However, the index finger and thumb did not even stand totally still at the moment of their own movement offsets (Fig. 2c; with movement offset defined on the basis of the individual digit's tangential velocity as described in the Methods section).

Timing

Figure 3 shows the percentage of all trials that reached a certain event at a certain time relative to lift-off (a) or relative to the end of the reaching movement of the index finger (b) or thumb (c). For instance, at about 100 ms before lift-off (vertical dashed line in Fig. 3a), both digits had contacted the cube in 80% of the trials. The index finger had stopped moving in 25% of the trials and the thumb in about 8% (see horizontal dashed lines). The figures look more or less the same for the other two starting positions (not shown). In almost all trials both digits stopped moving (according to our criterion) before the cube was lifted from the table (a). The movement offset of the index finger was usually earlier than the movement offset of the thumb (b, c).

Figure 4 shows the median time (per subject and then averaged across subjects) that each digit spent in each stage of the movement, from the digit's movement onset until lift-off of the cube. We distinguish between three stages: the MT before contact, the MT after contact and the late contact. The MT before contact was significantly larger for the thumb (675 ± 20 ms) than for the index finger (640 ± 23 ms; $P < 0.05$). The average MT after contact was also larger for the thumb (141 ± 13 ms) than for the index finger (130 ± 14 ms), but this difference was not significant. The thumb spent less time in late contact (32.5 ± 2.7 ms) than the index finger (65.4 ± 4.7 ms; $P < 0.001$).

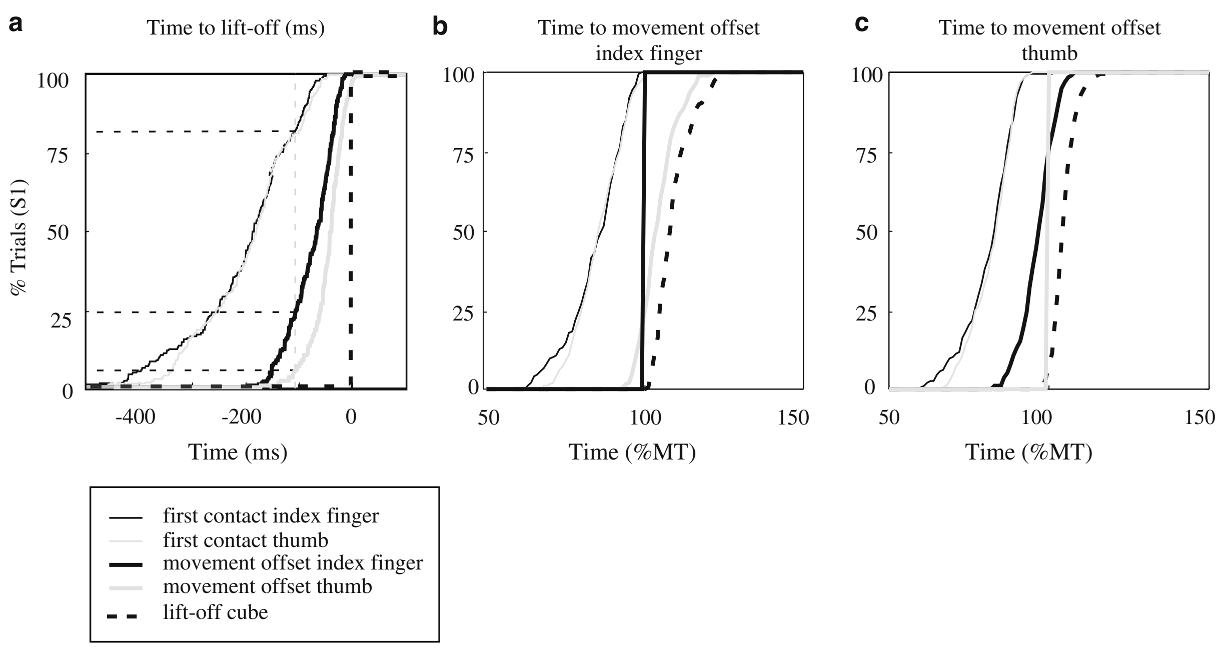


Fig. 3 Distribution of the timing of events in trials starting from position. Percentage of all trials in which an event has occurred as a function of the time to lift-off in milliseconds (**a**) or of the time to movement offset of the index finger (**b**) or thumb (**c**) as a percentage of the total MT. Data are only shown for starting position 1, but similar results were found for the other two starting positions. *Each curve* denotes a certain event, as described in the legend. For example, the *dashed lines* indicate that at about 100 ms before lift-off, both digits had contacted the cube in 80% of the trials. The index finger had stopped moving in 25% of the trials and the thumb in 8%

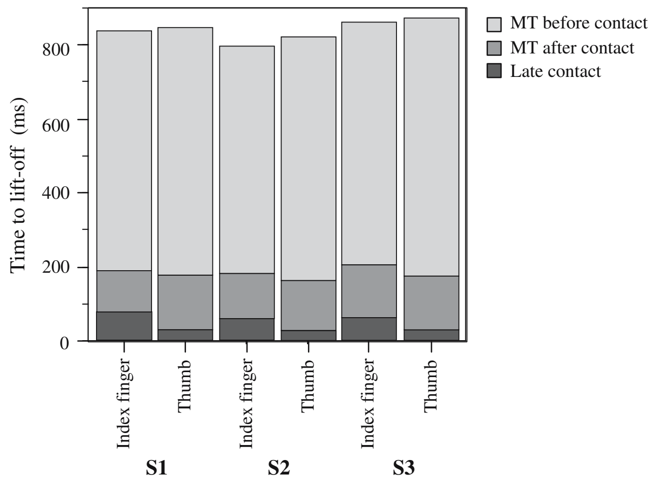


Fig. 4 Timing of the three stages of each digit's movement from each of the three starting positions. For details see text

The bars in Fig. 4 are synchronised at the moment of lift-off, which (by definition) is the same for both digits. Thus the differences in bar length give an impression of the differences in movement onset between the digits. However the actual differences in movement onset are slightly different, because the durations of the three stages are not independent and normally distributed, so the median times for the three stages of the movement do not simply add up to give the overall time. In fact, the thumb starts to move 13.8 ± 4.6 ms earlier than the index finger (median difference in movement onset; $P < 0.01$). The total MT was also significantly ($P < 0.001$) larger for the thumb (817 ms) than for the index finger (769 ms). The only significant difference between starting positions (for any of the timing variables) was that the difference between the moment of initial contact of the digits depended on the starting position ($P < 0.01$). This difference is 5.2 (± 10.1) ms when starting from position 1, 16.8 (± 10.6) ms when starting from position 2 and 37.4 (± 9.1) ms when starting from position 3, with the index finger always contacting the surface first. These asymmetries correspond with the asymmetries in movement distance (see Fig. 1b).

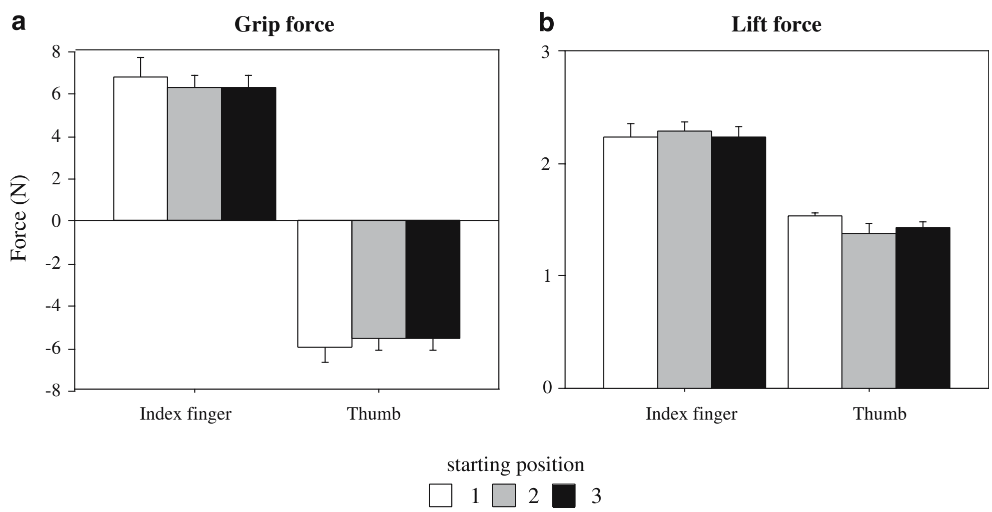
Force

As in the example in Fig. 2, the average grip force exerted by the index finger at the moment of lift-off was higher (6.40 ± 0.40 N) than that exerted by the thumb (5.76 ± 0.33 N; $P < 0.001$; Fig. 5a). The total lift force at the moment of lift-off was 3.70 ± 0.05 N, which was larger than the weight of the cube (3.5 N), as it must be able to lift the cube. The lift force produced by the index finger was significantly larger (2.25 ± 0.05 N) than the lift force produced by the thumb (1.45 ± 0.04 N, $P < 0.0001$; Fig. 5b). A higher lift force of the index finger corresponds to a higher acceleration of the cube at that side. This means that the cube must have tilted severely when leaving the surface of the table, with the edge at the side of the thumb longer in contact with the table. An analysis of the movements of the markers on the cube showed that the side of the cube near the index finger was lifted about 3 mm higher during the first 20 ms after lift-off. There were no significant differences between conditions for any of the force variables.

Velocity

As already shown in Fig. 2c for a single trial, on average the digits did not totally stand still at movement offset. This is possible because the movement offset was defined by a local minimum in the tangential velocity. The average velocity of the index finger at its movement offset was −4.6 (± 1.7) mm/s in the lift direction and 14.2 (± 2.5) mm/s in the grip direction. For the thumb the velocities were respectively −10.2 (± 2.4) mm/s and −42.8 (± 4.2) mm/s. Only the velocity in the grip direction differed significantly between the digits (obviously

Fig. 5 Average grip (**a**) and lift (**b**) forces at the moment of lift-off. Data for movements of the index finger and the thumb from each of the three starting positions



tested after inverting the sign of the velocity of one digit; $P < 0.001$). All values were significantly different from zero and none differed between starting positions.

Direction of force and velocity

Figure 6 shows the vector averages across trials, subjects and conditions for the applied force, velocity and acceleration of each digit when starting at position 1. Averages are shown for each 2 ms from 30 ms before contact until 70 ms after contact (thus synchronised at the initial contact of each digit separately). Only trials in which the time between initial contact and the movement offset of that digit was more than 70 ms (454 trials for the index finger; 544 trials for the thumb; out of a total of 675 trials) were included. At initial contact, the acceleration of the digit clearly changes amplitude and direction. Just after initial contact the acceleration is directed against the direction of motion of the digit, leading to a reduction of speed without a major change in movement direction. The applied force (on the surface of the cube) is small and is initially directed in the same direction as the digit's motion. This force gradually changes direction (upwards) as it becomes larger. The change in the direction of the force during the first 70 ms after contact is not reflected in a change in the direction of velocity or acceleration.

Figure 7 shows the relationship between the direction of the force applied by each digit and the direction of its velocity. This is shown for each trial from initial contact until 70 ms after contact (35 data points per trial). The

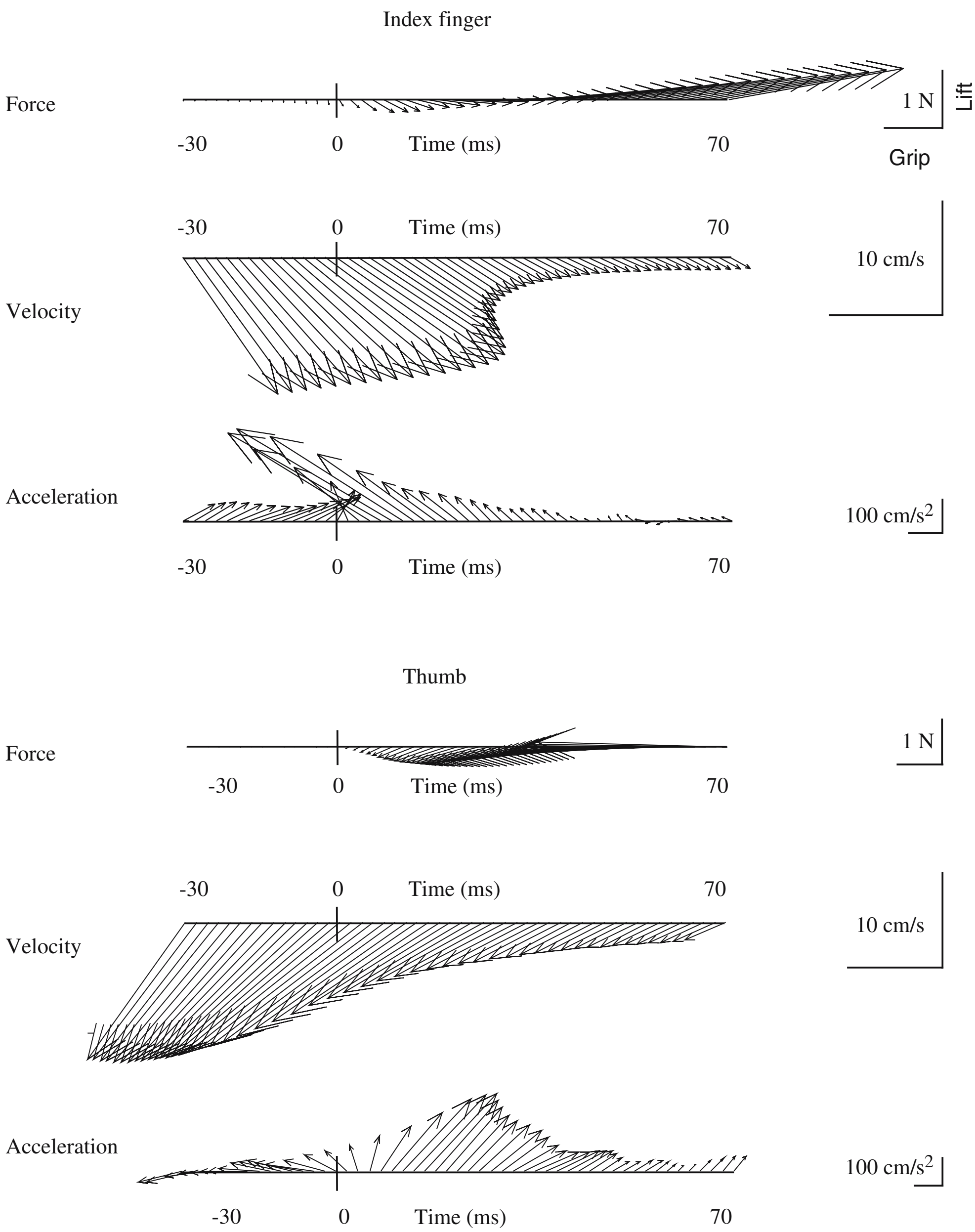


Fig. 6 The progress of the average force applied to the cube's surface and of the average velocity and acceleration of the digit around initial contact. Vector plots (showing both directions and amplitudes) are presented for both the index finger and the thumb. Data are averaged over subjects and synchronised at initial contact. Only trials in which the time between the digit's initial contact and movement offset was more than 70 ms are included. The data is for starting position 1. The *origins of the arrows* indicate the time relative to initial contact, in steps of 2 ms. The drawing is to scale

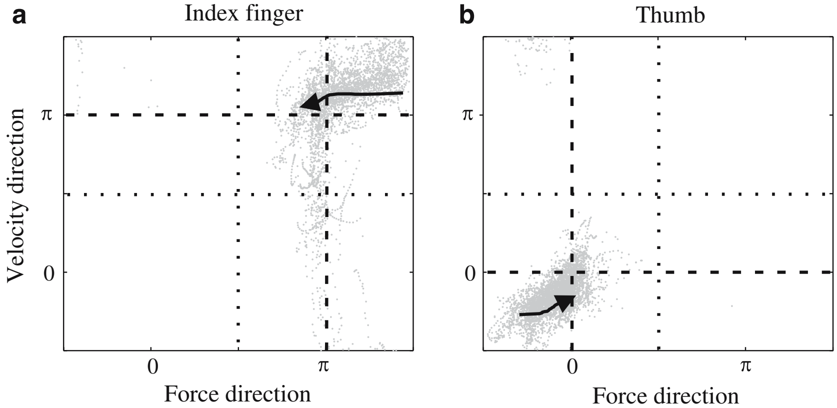


Fig. 7 Relation between the direction of the force (*horizontal axis*) and the direction of the velocity (*vertical axis*) from the moment of initial contact until 70 ms after initial contact. *Each dot* represents an instant of a single trial. The *arrow* indicates the change in direction of the vector average shown in Fig. 6. Only trials in which the time between the digit's initial contact and movement offset was more than 70 ms are shown. The data is for starting position 1. *Dashed lines* indicate a horizontal approach (*horizontal line*) and the direction of the grip force (*vertical line*). *Dotted lines* indicate an upward motion (*horizontal line*) and the direction of the lift force (*vertical line*)

directions of the average force and velocity (as depicted in Fig. 6; i.e. not the average of the directions on individual trials) are represented by the arrows. The applied force at contact is directed a bit downwards for both index finger and thumb (above an angle of π and below 0 for index finger and thumb, respectively; Fig. 7). After contact, as the applied force gradually increases, it also shifts to being perpendicular to the surface (towards π and 0), while the digits keep moving slightly downwards.

Figure 8 shows similar average vectors to those in Fig. 6 for the same trials, but for the period from 70 ms before until 30 ms after movement offset. In this figure the values for each digit are synchronised at that digit's movement offset rather than at the moment of its initial contact. The same data points contribute to Figs. 6 and 8 for fast trials but not for slow trials. Note that although the average is taken after synchronisation at a local minimum ($t=0$) for each individual trial, this does not necessarily lead to a minimum in the average velocity at the same point in time. If the increase in velocity after the minimum is in different directions for different trials, the average velocity does not have to increase. When averaged in this manner, the direction of the force hardly changes as its amplitude gradually becomes larger. In particular, there is no evident change at each digit's movement offset. The direction of the velocity and of the acceleration does change as the reaching movement gradually becomes a lifting movement.

Figure 9 shows the relationship between the direction of the applied force and the direction of the velocity during the same period as in Fig. 8. The direction of the velocity changes from perpendicular (0 and π) to upwards (0.5π) as it should do to lift the cube. The direction of the force is mainly directed perpendicular to the surface of the cube (0 and π). The individual trials (dots) show roughly the same behaviour as the average (arrows).

When discussing the motion of the digits during contact, one should keep in mind that we measured the motion of the IREDs on the nail, not the actual contact point between the digit and the surface of the cube. We have seen that the digits (i.e. the IREDs) move considerably during contact. As the IREDs first move downward and subsequently upward (see Fig. 2c), the net displacement between initial contact and lift-off is rather small (on average -1.3 ± 0.3 mm; Fig. 10a). For the control of the cube the point of force application is more important than the position of the nail (i.e. the IRED). This point only moves downward, leading to a net vertical displacement of $-5.5\pm0{,}7$ mm (Fig. 10b), much more than that of the IREDs. The net displacement of the points of force application does not differ significantly between the digits (Fig. 10 b). However, the net displacement of the IRED on the tip of the index finger is smaller than that of the thumb (Fig. 10 a). Thus the digits do not move in exactly the same manner during contact with the surface.

Discussion

How does a reaching movement towards an object change into a lifting movement? Smeets and Brenner (2001) showed that the digits move more or less independently towards their designated places of contact on the surface of the target object. The subsequent build-up of forces has also been shown to be controlled separately for each digit (Burstedt et al. 1997, 1999; Edin et al. 1992). In the present study we examined whether the final approach and the initial applied forces are somehow related. We let subjects reach for and grasp a cube starting their movement from different positions. We expected to find an effect of the starting position relative to the cube on the movement of each digit. If the movement and force are

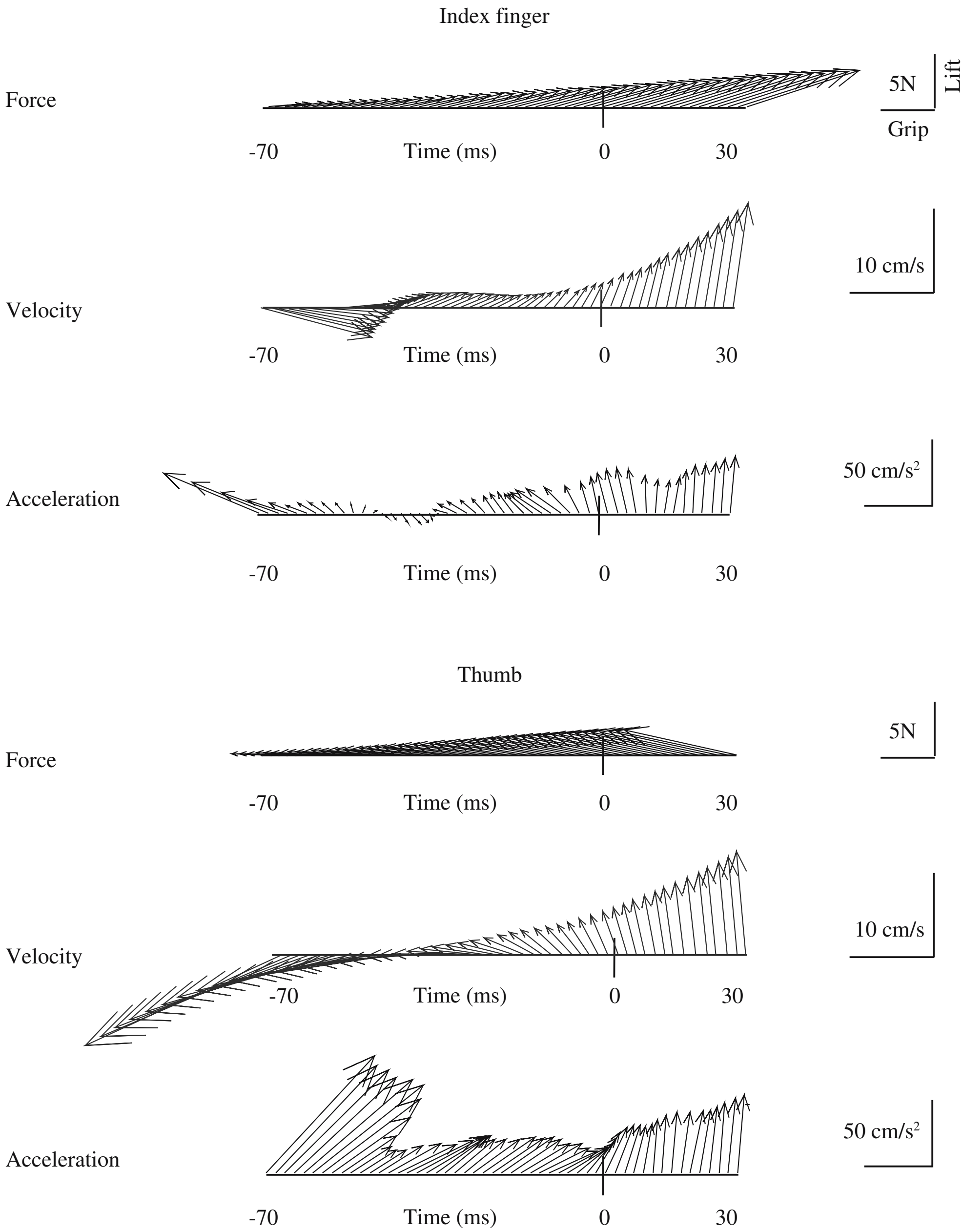


Fig. 8 The progress of the average force applied to the cube's surface and of the average velocity and acceleration of the digit around initial contact. *Vector plots* (showing both directions and amplitudes) are presented for both the index finger and the thumb. Data are averaged over subjects and synchronised at movement offset. The *origins of the arrows* indicate the time relative to movement offset. All other details as in Fig. 6. Note the difference in scales between Fig. 6 and 8

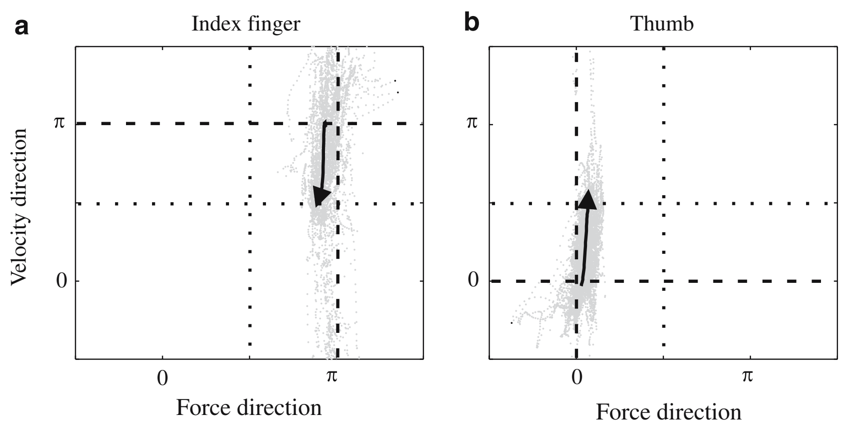


Fig. 9 Relation between the direction of the force (*horizontal axis*) and the direction of the velocity (*vertical axis*), from 70 ms before until 30 ms after each digit's movement offset. The *arrow* indicates the change in direction of the vector averages shown in Fig. 8. Other details as in Fig. 7

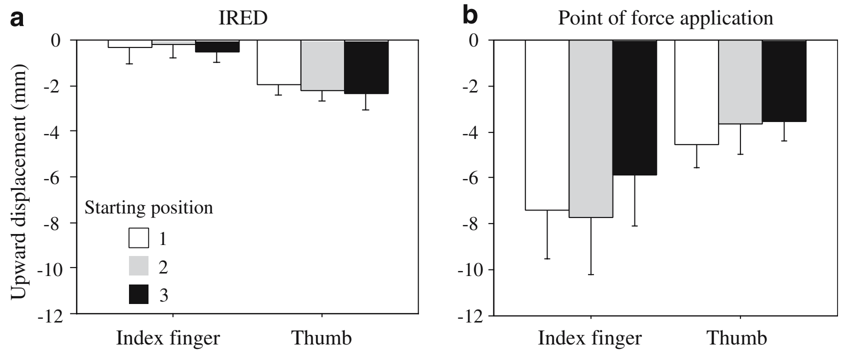


Fig. 10 Average vertical displacement of each digit between initial contact and lift-off. Displacement of the IREDs (**a**) and of the points of force application (**b**) for movements from each of the three starting positions

related, this effect should extend to the way in which the forces build up for lifting. We analysed the movements of the digits and the applied forces and torques during contact with the cube.

In our experiment, the applied forces during the first 20 ms of contact with the cube are small compared to the forces needed to pick the cube off the table. The forces required to lift the cube build up gradually from the moment of initial contact. Nevertheless, the force during the first 20 ms after initial contact is large enough to bring the digit to an almost complete standstill. The high deceleration (see Fig. 6c) and the change in direction of motion during this period, indicates that contacting the surface of the cube helps to stop the digits' movement.

A movement can be stopped actively by muscle forces, or passively by impact with the target. In the latter case one expects high contact forces, whereas in the former the contact forces can be quite low. In our experiment the contact force is relatively small, but it is clearly not negligible. The use of contact force to help stop movements has already been demonstrated for pointing movements towards single and multiple targets (Adam et al. 1997; Biegstraaten et al. 2003b). Those experiments showed that contact forces help to stop movements, but that this is independent of whether another movement will follow. The force at a target was not larger when subjects could stop at that target than when they had to move on to a second target. The similarity with the present results, in terms of the contact force not appearing to be related to the subsequent action, supports the idea that the control of the grasping movement is relatively independent of the forces that are exerted on the object when picking it up.

As shown previously (Flanagan et al. 1999; Forssberg et al. 1991), the forces just after initial contact are directed slightly downwards (see Fig. 6a), opposite to the direction required to lift the cube. This is no problem since the table supports the cube. The fact that the force is initially directed downwards also suggests that the initial contact is part of the reach-to-grasp movement, rather than of the lifting movement, because a downward force helps to stop the digit, but does not help to lift the object.

The time between initial contact with the cube and the start of the lifting movement is rather large and variable. Since both the force and the velocity of the digits gradually change during that time, we can conclude that after contact the reaching movement gradually turns into a lifting movement. Part of the initial contact with the object is presumably used for gathering tactile information (initial preload phase; Johansson and Westling 1984; Westling and Johansson 1984). Part of the variability probably arises because the time to start the lifting movement depends on how the reach to grasp was executed.

The fact that an apparently fragile object is approached with more care than an apparently robust object (Marteniuk et al. 1987; Savelsbergh et al. 1996), was one of the arguments to hypothesize a tight coupling between the reaching and lifting phase. As we found that the forces at contact are small and are not optimized for the lifting movement, there must be another explanation for the careful approach of fragile objects. Probably, the fragility leads to the selection of different grasping points on the surface of the object or makes people take more care to move exactly to these positions because they cannot compensate for inadequate positioning by higher grip forces.

We see systematic differences in timing between the thumb and the index finger. These differences are probably related to the starting position of the reaching movement. Movements started earlier (and ended later) if the digit had to move a longer distance (compare starting position 1–3; Fig. 4). The same was found by Boessenkool et al. (1999) in simultaneous bimanual pointing movements to a single target. This supports the assumption in the model of Smeets and Brenner that the movements of the index finger and the thumb are controlled independently.

We see smooth changes in force (Figs. 6 and 8) and a clear transition in the relationship between the velocity and the force as the grasping movement becomes a lifting movement (compare Figs. 7 and 9). Together with the fact that the digits are moving downwards when they initially contact the object, which is advantageous for grasping but not for lifting, this suggests that the two components (grasping and lifting) are controlled separately. The transition between them is gradual, but it appears that the grasping movement is optimized for achieving a stable grip posture before the lifting movement really starts.

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