

Grasping trapezoidal objects

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Abstract When grasping rectangular or circular objects with a precision grip the digits close in on the object in opposite directions. In doing so the digits move perpendicular to the local surface orientation as they approach opposite sides of the object. This perpendicular approach is advantageous for accurately placing the digits. Trapezoidal objects have non-parallel surfaces so that moving the digits in opposite directions would make the digits approach the contact surfaces at an angle that is not 90°. In this study we examined whether this happens, or whether subjects tend to approach trapezoidal objects' surfaces perpendicularly. We used objects of different sizes and with different surface slants. Subjects tended to approach the object's surfaces orthogonally, suggesting that they aim for an optimal precision of digit placement rather than simply closing their hand as it reaches the object.

Introduction

Since the pioneering work of Jeannerod (Jeannerod 1981, 1984), grasping research has concentrated on the

question of how the hand opens and closes during a precision grip (e.g. Marteniuk et al. 1990; Tresilian and Stelmach 1997; Zaal et al. 1999). There are two lines of interpretation of grasping behaviour. One line considers grasping as emerging from the co-ordination of transport and grip, which in turn are guided by extrinsic and intrinsic object properties, respectively, (Jeannerod 1999). The other line of interpretation considers grasping as emerging from the constraints imposed on the individual digits' movements (Smeets and Brenner 1999; Rosenbaum et al. 2001).

The issue of where to make contact with the object has received relatively little attention. The choice of positions should ensure that the digits do not slip and that the object does not turn or move laterally while it is being lifted. In order to prevent the digits from slipping, the force should be more or less perpendicular to the surface, because any force along the surface has to be counteracted by friction with the surface. In order to prevent gravity from rotating the object around the line connecting the digits, without having to exert large grip forces, the forces should go through (or above) the centre of mass. In order to prevent the object from moving laterally, the horizontal components of the forces should be equal but in opposite directions. All three requirements can be fulfilled if the line connecting the positions at which the digits contact the object passes through the object's centre of mass and is perpendicular to the object's surfaces at the places of contact. Experiments have shown that subjects choose pairs of contact positions that are close to this ideal: contact positions that are connected by a line that both passes close to the centre of mass (Goodale et al. 1994; Lederman and Wing 2003) and is approximately perpendicular to the surface at the contact positions (Cuijpers et al. 2004).

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An interesting situation arises if one asks subjects to grasp objects at sub-optimal positions: for instance to grasp trapezoidal objects by their non-parallel sides. The movement towards these sub-optimal contact positions can reveal whether grasping mainly consists of controlling grip closure, or mainly of placing the digits optimally. If the grip simply closes on the object, then the digits will approach the surfaces along the line connecting the contact positions, irrespective of the local surface orientation. An approach perpendicular to the surfaces will improve the precision of placing the digits (less variability in contact position for a given variability in the trajectory) and make it less likely that the digits will slip across the surface when they make contact (Smeets and Brenner 1999). However, when grasping trapezoidal objects by their non-parallel sides, approaching the surfaces perpendicularly increases the danger of the whole object slipping across the support surface. Approaching the surface along the line connecting the contact positions is a better way to make sure that the object does not move laterally at contact. Thus if subjects consider all the constraints (as opposed to controlling grip closure) the approach direction will be a compromise between the direction of a line through the contact positions and the direction of the surface normal.

In this study subjects were asked to grasp isosceles trapezoidal objects of varying base angle α by their non-parallel surfaces (we define the top left angle as α , see Fig. 1). We define an approach angle β in the horizontal plane, whereby an angle of zero is an approach from the right and an angle of $\pm 180^\circ$ is an approach from the left.

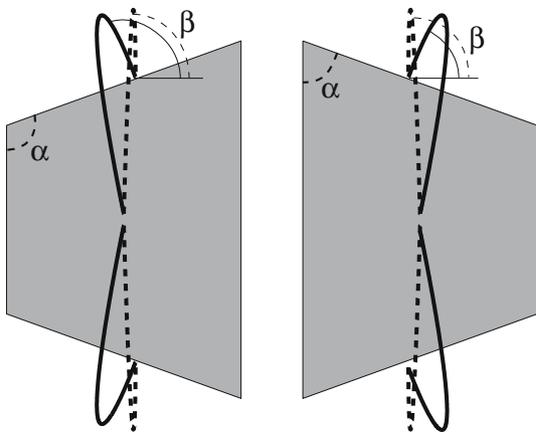


Fig. 1 Horizontal components of modelled trajectories of the digits towards optimal grasp positions on non-parallel sides. We modelled minimum jerk trajectories (Smeets and Brenner 1999), assuming that the digits either both approach perpendicular to the surface (*solid curves*) or that they approach in opposite directions (co-linear approach; *dotted curves*). The definition of the trapezoid angle α and of the approach angle β are indicated

Regardless of how one chooses the final contact points at the target object, a surface-normal approach path will have an approach angle β of either α (top) or $-\alpha$ (bottom) at the end of the movement. For an approach path along the line connecting the contact positions, the direction of approach for each digit depends on the contact positions of both digits. However, by definition the difference between the two approach angles is 180° for such an approach. Thus, when grasping trapezoidal objects by their slanted surfaces an approach perpendicular to the surface is different from a co-linear approach whenever the angle α is not 90° .

To illustrate these predictions we used the model of Smeets and Brenner (1999) to produce minimum jerk trajectories for both the co-linear and the perpendicular approach (Fig. 1). This model uses a vector (of which the length is called the “approach parameter”) to describe the final deceleration towards a chosen contact position. Since we had subjects grasp the trapezoids starting with their digits above the trapezoid’s centre (see Method and Fig. 2b), both digits started midway between the parallel sides of the trapezoid in the horizontal projection shown in Fig. 1. The digits’ contact positions with the trapezoid’s surfaces were chosen such that the line connecting them passes through the object’s centre of mass, so they were slightly away from the centre of the non-parallel surfaces. We used a value of 1.2 m for the approach parameter in order to make the peak grip aperture of the modelled movements comparable with the value found in the measured movements. The only difference between the two pairs of trajectories is whether the approach vectors are perpendicular to the surface (continuous curves) or along the line connecting the two contact positions (grip closure, dotted curves). The grip closure clearly predicts different paths for the

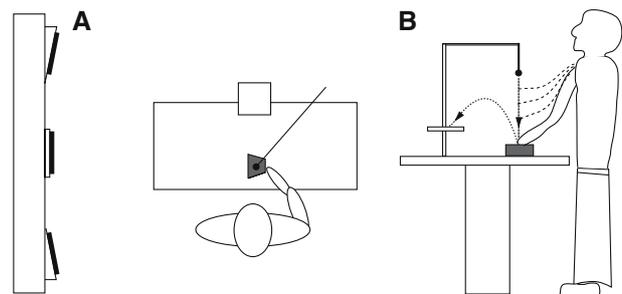


Fig. 2 The experimental set-up as seen from above (**a**) or from the side (**b**). Subjects stood upright behind a horizontal surface and performed vertical (*downward*) grasping movements starting from the end of a downward pointing bar (indicated by the *black sphere*). They had to lift the grey object and place it onto a small platform. The Optotrak camera on the left in the *top view* (**a**) was just above eye height, and is therefore not shown in the *side view* (**b**)

digits than does a perpendicular approach, so we can discriminate between the two ways of approaching experimentally.

Method

Subjects and apparatus

Twenty-three subjects (13 females and 10 males, with an average age of 30 years) participated in the study. All subjects reported being right-handed. They performed the grasping movements while standing behind a horizontal surface with the starting position, object and target position all in their sagittal plane (see Fig. 2). An iron bar that was mounted 45 cm above the centre of the object served as the starting point. Subjects were to pick up the object by its non-parallel sides and place it on a small platform that was behind the object (at a height of 12.5 cm).

The movements of the index finger and thumb of the right hand were recorded at a sampling rate of 300 Hz using an Optotrak 3020 infrared tracking system. The Optotrak camera unit was mounted 2.4 m from the setup at a height of 1.8 m. An infrared marker on the horizontal surface to the left of the object emitted light to the right in such a way that the Optotrak camera registered its reflection by the object. This allowed us to accurately determine the very first movement of the object (Franz et al. 2005). Movements of the digits were determined from the positions of two sets of three infrared markers on a small aluminium holder that were attached to the digits' nails with reusable adhesive pads.

Trapezoidal shaped blocks of grey plastics were used as target objects. The trapezoidal angle of the blocks varied from 70° to 110° in steps of 5°, with 90° being a rectangular block (see Fig. 1). The shapes were arbitrarily characterised by the angle of the upper left corner, so angles of less than 90° indicate that the wide side was on the left. The distance between the blocks' parallel sides was always 40 mm (width), and their upper surface was always 25 mm above the support surface (height). The distance between the centres of the non-parallel sides by which the blocks had to be lifted was either 40 or 50 mm (there was a full set of objects for each of the two sizes). The mass was 55.2 g for the smaller (40 mm) blocks and 69.0 g for the larger (50 mm) ones.

Procedure

Before starting the experiment subjects adjusted the height of the horizontal surface in front of them so that they could comfortably perform the task. This was

followed by a simple calibration procedure that allowed us to infer the fingertips' positions from the positions of the three markers attached to each digit. Subjects were instructed to grasp the blocks with index finger and thumb only. They were to avoid grasping the corners or the left and right sides of the trapezoid. The hand had to leave the starting point, grasp the block, and place it on the platform, within 3 s. Two sound signals indicated the time period during which the movement was to be made. Three seconds was long enough to allow subjects to move at a leisurely pace, but ensured that they performed the whole sequence as a single action. The experimenter removed the block from the platform and placed a new block on the surface with the centre of its axis of symmetry exactly below the starting point. The different blocks were presented in a random order. Subjects grasped each block eight times. Six training trials were given before the experiment started.

Data analysis

The trajectories of the index finger and thumb were determined from the measured positions of the three infrared markers that were attached to each digit. Before the actual experiment started, subjects had placed the tips of their digits onto two calibration points with known coordinates. By measuring the relation between the three markers and these calibration points (for each digit), we could convert the positions of the three markers to a position of the digit's tip (i.e. the part of the digit that contacted the calibration marker). We defined the end of the grasping movement as the first contact with the block, as judged from the motion of the reflection (by the block) of the infrared marker attached to the horizontal surface. This is a very sensitive method to determine the very first contact of the digits with the object (Franz et al. 2005).

To get an idea of the average trajectories of the grasping movements, we used linear interpolation (between the points that were closest in time) to determine the position along the movement path after various proportions of the movement time, and averaged these positions across movements towards the same object. We are most interested in the last part of the trajectory; in particular, the angle at which the digits approach the surface (approach angle β , see Fig. 1). We defined this angle on the basis of the orientation of the horizontal projection of the line connecting the digit's position at object contact with its position when it was 4 mm away from the position of contact. To examine whether the grasp axis passed close to the object's centre of mass, we determined the intersection point of the grasp-axis (the line connecting the digits at

the moment of contact) with the object's axis of symmetry. We will refer to this intersection point as the "grasp centre". We determined mean values for each subject and object shape, and used two way repeated measures ANOVAs (9 shapes \times 2 sizes) to evaluate whether the mean approach angle (for each digit) and the mean grasp centre depend on the object's shape.

Results

On average, it took subjects 821 ± 108 ms (mean \pm standard deviation across subjects) to move from the starting position to the object. The movement time was 10 ms longer for the 50 mm objects than for the 40 mm objects ($P < 0.005$), independent of trapezoid angle α ($P > 0.05$). The average maximal grip aperture was 71 ± 7 mm when reaching for the 40 mm objects and 78 ± 7 mm when reaching for the 50 mm objects. Figure 3 shows the average measured trajectories for the targets for which model predictions are shown in Fig. 1. It is clear that the trajectories do not exactly correspond with either of the predictions: the paths are less smooth than predicted, perhaps partly because of having to release the bar at movement onset. We are mainly interested in the direction in which the digits move just before reaching the surface. It is evident that this direction depends on the surface orientation, rather than subjects simply closing their grip on the object. In Fig. 3 the trajectories appear to end before the digits contact the surface. The gaps between the ends of the trajectories and the contact surfaces probably arise from several factors, including the subject not touching the target object exactly with the part of the fingertip that was used for calibration,

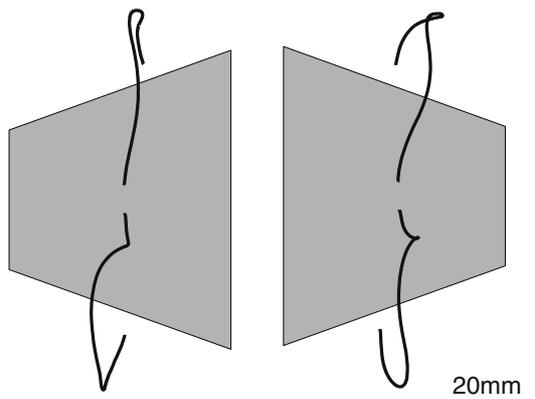


Fig. 3 Horizontal projection of the average of all subjects' trajectories of the thumb (*upper curves*) and the index finger (*lower curves*) for grasping 40 mm trapezoidal objects with angles of 110° (*left*) and 70° (*right*). Note that the main movement direction was vertical, and is thus not visible in this projection

the movement being considered to have ended when the digit touched the surface more lightly than during the calibration, and the movement being considered to have ended when the first digit touched the surface even if the second digit had not yet done so.

Figure 4 shows the average approach angle for each target, as determined from the last 4 mm of displacement before contact. The approach angle clearly depends on the trapezoid's shape (index finger: $F_{(8,176)} = 27.44$, $P < 0.001$; thumb: $F_{(8,176)} = 21.63$, $P < 0.001$). It was also significantly different for the two target sizes for the thumb ($F_{(1,22)} = 73.76$, $P < 0.001$), but not for the index finger ($F_{(1,22)} = 0.80$, $P = 0.38$). For

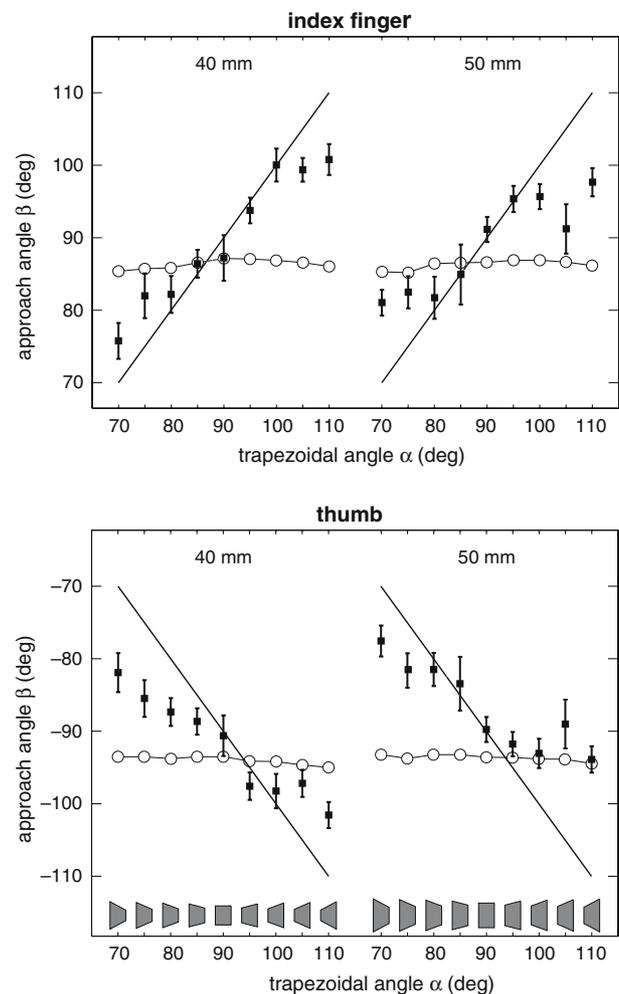


Fig. 4 Average approach angle β of index finger and thumb. *Solid squares* indicate the average approach angle for each kind of target (with the standard error across subjects). The *continuous line* and the *open circles* indicate the angle predicted by an approach perpendicular to the surface and by an approach along the line connecting the contact points (grip closure), respectively. Grip closure does not predict angles of exactly $\pm 90^\circ$ because the finger and thumb did not contact the object at exactly symmetrical positions (the prediction is based on the actual contact positions)

the index finger there was a significant interaction between trapezoidal angle and size ($F_{(8,176)} = 2.18$, $P = 0.03$). If one assumes that the approach angle variation is a constant fraction of the variation in trapezoid angle, this fraction equals 0.44 for the thumb and 0.54 for the index finger (averaged over both object sizes).

Figure 5 shows the position of the grasp centre (as defined in the [Data analysis](#)). A grasp centre at 0 mm means that the line connecting the contact points passes half way between the object's parallel sides. The lines show how changing the target's shape shifts the centre of mass over the object's symmetry axis. It is clear that subjects take the distribution of mass into account (there is a significant effect of trapezoidal angle: $F_{(8,176)} = 19.03$, $P < 0.001$), but they grasp to the right of the centre of mass for all but the largest trapezoidal angles. The shift of the centre of mass as a function of trapezoidal angle depends on the object's size, so one could expect an interaction between size and trapezoidal angle (the slopes of the lines in the two panels of Fig. 5 differ), which was indeed found ($F_{(8,176)} = 2.30$, $P = 0.02$). We also found a main effect of size ($F_{(1,22)} = 60.08$, $P < 0.001$) on the grasp-centre: subjects grasped further to the right for small objects.

Discussion

The analysis of the approach angle shows that people do not approach objects' surfaces by simply moving the digits in opposite directions. Instead they move the hand towards the objects in a way that makes each digit tend towards approaching its contact surface

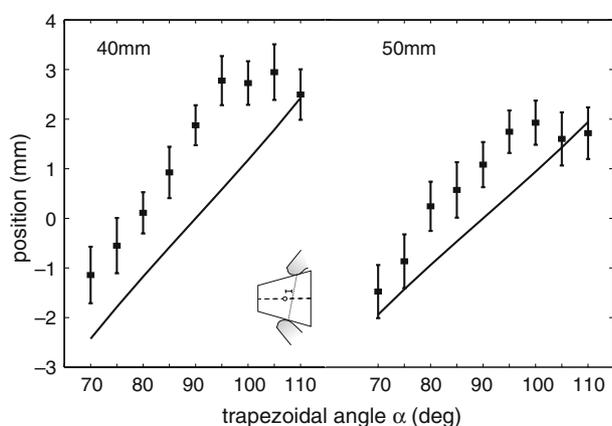


Fig. 5 The position of the grasp centre for the various objects (with the standard error across subjects). The grasp centre is the intersection of the grasp-axis (dotted line in inset) with the object's symmetry axis (dashed line). Positions are relative to the centre of the object's symmetry axis (open circle in inset; positive is to the right). The continuous lines indicate the position of the trapezoids' centre of mass relative to the centre of the symmetry axis

perpendicularly, thereby improving the placement precision. The range of angles that were used in the present study extends to the limits of the easily graspable. Considering the whole range of trapezoidal angles, the shift towards a more perpendicular approach is only about 54% of the shift that is required to achieve a surface-perpendicular approach for the index finger, and only about 44% of the required shift for the thumb. However, the shift towards a more perpendicular approach seems to be the largest for small deviations from parallel surfaces (trapezoid angles near 90°), for which the chance of the object slipping laterally at contact is the smallest. Thus human performance seems to rely on a trade-off between the various constraints near the moment of contact, considering both the forces at and after contact, and placement precision.

The present results show that digits even tend to approach their contact surfaces perpendicularly when this means that they are not moving in opposite directions, providing the first direct evidence that the individual digits' previously observed perpendicular approach during grasping is planned that way, rather than emerging from the grip closing on the object. This result is particularly important in relation to the 'new view on grasping' (Smeets and Brenner 1999), a model based on independent smooth movements of the digits that has been successful in describing many experimental phenomena in grasping (Smeets and Brenner 1999; Smeets et al. 2002, 2003), because taking the surface orientation into account is fundamental to the model. Whether surface orientation influences the approach in grasping had not previously been tested directly.

The final approach is not entirely perpendicular to the surface: there is also a tendency for the digits to move in opposite directions. As indicated in the introduction, this is probably because not all the task constraints favour an orthogonal approach. In particular, moving the digits in opposite directions is more adequate for preventing the object from moving laterally at contact. After contact, the forces applied by the fingers should also be in opposite directions if the object is not to move laterally. For circular or rectangular objects all constraints favour a perpendicular approach. In the model (Smeets and Brenner 1999) the approach parameter (a scalar) by definition led to a tendency to a perpendicular approach (rather than moving along a straight line). The results of the present study suggest that the deviation from a straight-line approach need not always be towards the surface normal, because it takes all constraints at contact into account. We cannot be more precise because we did not measure the contact forces, and it is known that contact forces can build up in a different direction

than the direction of motion in the last part of the movement (Biegstraaten et al. 2006).

Although the centre of mass was never more than 2.5 mm from the object's centre, the relationship between the grasp centre and the objects' centre of mass supports the notion that subjects adjust their grip with respect to the centre of mass. However, they did not do so for objects with the largest trapezoidal angles. The adjustments to the approach angle also appeared to be particularly weak for these objects. Perhaps the position of the centre of mass is misjudged for such objects, possibly because the hand hides the right side of the object during our right-handed subjects' grasping movements. Another possibility that would also explain the observed systematic error is that subjects effectively exert the grip force with a part of the digit that is 1 mm to the right of what we defined as the location of the tip, and that this point of force application shifts back to the position used during the calibration for large trapezoidal angles, when the fingers have to bend further to make sure to avoid hitting the extending corners on the right. The latter explanation is consistent with a strategy that considers all the constraints for successfully grasping the object.

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