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RESEARCH ARTICLE

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Influence of object position and size on human prehension movements

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Abstract Prehension movements of the right hand were recorded in normal subjects using a computerized motion analyzer. The kinematics and the spatial paths of markers placed at the wrist and at the tips of the index finger and thumb were measured. Cylindrical objects of different diameters (3, 6, 9 cm) were used as targets. They were placed at six different positions in the workspace along a circle centered on subject's head axis. The positions were spaced by 10° starting from 10° on the left of the sagittal axis, up to 40° on the right. Both the transport and the grasp components of prehension were influenced by the distance between the resting hand position and the object position. Movement time, time to peak velocity of the wrist and time to maximum grip aperture varied as a function of distance from the object, irrespective of its size. The variability of the spatial paths of wrist and fingers sharply decreased during the phase of the movement prior to contact with the object. This indicates that the final position of the thumb and the index finger is a controlled parameter of visuomotor transformation during prehension. The orientation of the opposition axis (defined as the line connecting the tips of the thumb and the index finger at the end of the movement) was measured. Several different frames of reference were used. When an object-centered frame was used, the orientation of the opposition axis was found to change by about 10° from one object position to the next. By contrast, when a body-centered frame was used (with the head or the forearm as a reference), this orientation was found to remain relatively invariant for different object positions and sizes. The degree of wrist flexion was little affected by the position of the object. This result, together with the invariant orientation of the opposition axis, shows that prehension movements aimed at cylindrical objects are organized so as to minimize changes in posture of the lower arm.

Key words Visuomotor transformation · Coordination · Finger movements · Prehension

Introduction

The action of grasping an object is the outcome of simultaneous movements at several joints – for transporting the hand to the object, orienting the wrist or preshaping the fingers into an appropriate grip. Although these movements may differ widely in terms of their neural organization, they all concur to the same final goal: to achieve a stable grasp for holding and manipulating the object.

Several studies have dealt with the question of how the many degrees of freedom of the arm are controlled during such an action. The main experimental result was that the movements at the different joints tended to covary. For example, it was observed that altering the reaching movement (e.g., by varying the distance of the object) also affected the formation of the grip (Jakobson and Goodale 1991; Chieffi and Gentilucci 1993). Conversely, altering the grip (e.g., by varying the size of the object) affected the kinematics of the reach (Marteniuk et al. 1990; Gentilucci et al. 1991; Jakobson and Goodale 1991; Zaal and Bootsma 1993; Bootsma et al. 1994). Although they were of a relatively small amplitude, these changes were considered as reflecting the underlying coordination mechanism between movements of different joints.

Little attention, however, has been paid to the pattern of the grasp itself. In fact, because the fingers that contribute to the grasp represent the effector of the movement, their final position on the object should be the main parameter to be controlled for achieving an effi-

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cient grasp. This position will determine the opposition axis, the axis along which the opposing grip forces are exerted on the object, such that a stable grasp will ensue (Napier 1955; Iberall et al. 1986). Note that this is a very constraining definition: a grasp where the opposition axis (or the opposition space if more than two fingers are involved) does not include the center of gravity of the object would unavoidably fail because the object would slip or be dropped.

The main problem for understanding prehension is thus to describe the neural processes that serve the selection of the correct opposition axis and its achievement by the upper limb. Different types of information have to be weighted in this selection process. These include information on the properties of the object itself (shape, size, texture, etc.) and on the object's relationship to the body (its orientation and position in the workspace), but also on the current configuration of the body. Finally, information derived from former experience and the context of the action may also be important.

In most situations of daily life, object properties such as shape and size clearly define an opposition axis and the task of the motor system in the prehensile act is to bring the fingers into the appropriate position, i.e., the motor system has to define for a given opposition axis an optimal configuration of the arm. This is shown by the experiment of Stelmach et al. (1994), where a relatively small change in orientation of an object which afforded only one possible opposition axis resulted in a major reconfiguration of the arm, including wrist pronation and shoulder abduction. However, for a better understanding of the processes involved in selecting the appropriate opposition axis, it is more helpful to employ objects which allow for more than one opposition axis, such as cylinders. By analyzing prehension movements to cylindrical objects at different positions in the workspace, the limb configuration for a given object at a given position can reveal on which information the motor system predominantly relies. Will the motor system use a preferential opposition axis for all object positions, resulting in different limb postures, although other opposition axes were feasible as well? Or, alternatively, will the motor system minimize the changes in limb configuration by using different opposition axes depending on the position of the object?

In a previous experiment where subjects grasped cylindrical objects, we had noticed that the variability of the spatial paths of index finger and thumb tended to decrease sharply while the fingers approached the object (Paulignan et al. 1991). This suggested that the fingers were aiming at a predetermined locus on the object surface. However, because the object positions in that experiment were grouped within a small portion of the workspace, no firm conclusion could be drawn as to which factors this final position depended on. In the present experiment we have systematically varied object position and size across the workspace, and demonstrate the predominant role of motor factors in selecting the opposition axis.

Subjects and methods

Subjects

Four healthy right-handed subjects (1 male, 3 females) participated in the experiment. None of them had a history of neurological disorder. They all gave their informed consent. Before the experi-

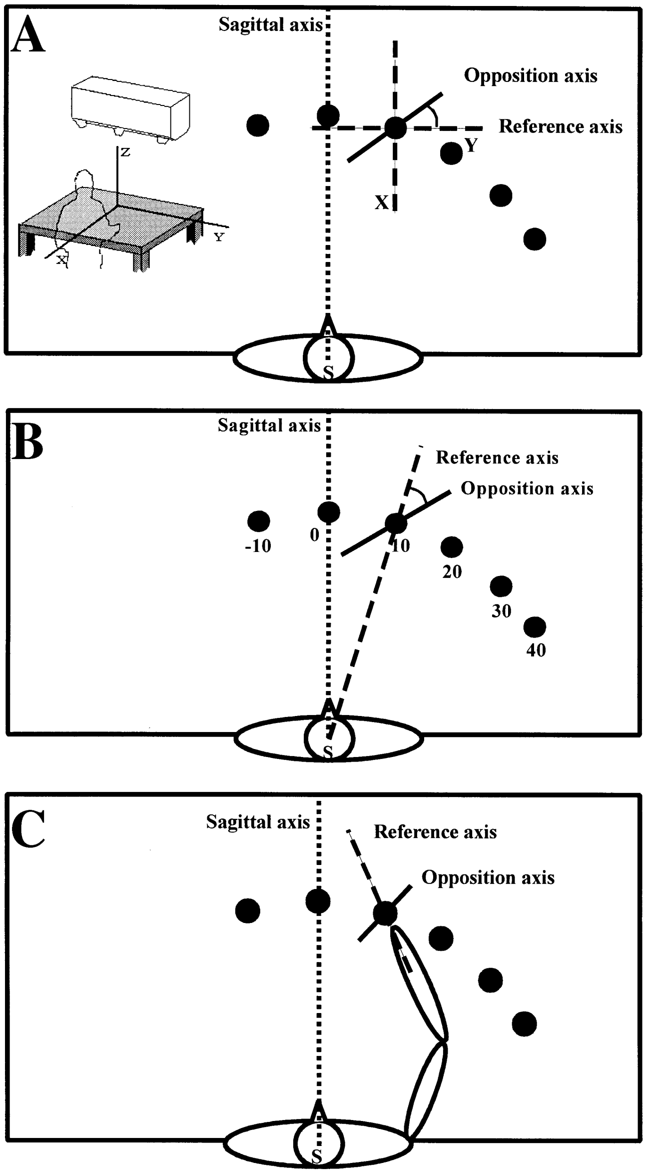


Fig. 1A–C Schematic representation of the different reference frames used in the calculation of the orientation of the opposition axis. The schemas represent the camera view from above the table (**A**, *insert*). The subject (*S*) is comfortably seated in front of a table. Six objects locations are used from –10° to 40°, centered on the subject's body axis. The orientation of the opposition axis is defined by the angle between the line joining the fingers and a reference axis. In the object-centered reference frame (**A**) the center of space is defined for each movement as the center of the target object. The reference axis is the *Y* axis of the measurement system. In the head-centered reference frame (**B**) the reference axis is the line crossing the vertical head axis and the center of the object. In the forearm-centered frame (**C**) the reference axis is represented by the forearm at the end of the movement

ment, they received explanations of the methods used, and after the experiment an explanation of the purpose of the study.

Procedure

The objects used as targets in the experiment were white plastic cylinders 9 cm high of three different diameters (3, 6 and 9 cm). Their weight was 100, 200 and 300 g, respectively. The cylinders were placed upright on a horizontal table at which the subject was comfortably seated. They were presented one at a time at six fixed locations centered on the subject's head, starting from 10° on the left of subject's sagittal axis (–10°), 0° (along the sagittal axis), and 10°, 20°, 30° and 40° on the right (Fig. 1). The subject's right hand rested on the table immediately to the right of the sagittal body axis, so that the tips of the thumb and index finger were positioned on that axis. This position approximately corresponded to a distance of 25 cm from the center of the body. The distance between the resting hand position and the object locations, as measured by a light-emitting diode (LED) placed on the wrist, was 52 cm for the –10° location and 48.6, 46.3, 44.9, 44.9 and 45.8 cm, respectively, for the others. The presentation of objects was randomized for both position and size. Subjects were instructed to reach, grasp and lift the objects using a precision grip. They were asked not to move their trunk and to make fast and accurate movements. The GO signal for each movement was given by the illumination of a red LED embedded in the table in front of each object position. The recording was continued for 2 s after the GO signal. Ten movements were recorded for each object position and size.

Movement recording

The movements of the right arm were recorded by means of an Optotrak 3020 system. The spatial position of active markers was sampled at 250 Hz by a camera composed of three linear infrared sensors. The camera was fixed 2.5 m above the work space with its optical axis aligned with the vertical (Fig. 1A, insert). Two markers were stuck on the nails of the index finger and the thumb, respectively. Another one was placed at the wrist level on the styloid process of the radius. These markers were used for measuring the two main components of prehension, namely the grasping component (the change over time of the distance between the index finger and thumb markers) and the transport component (the change over time of the position of the wrist marker). Two additional markers were used for measuring the wrist angle: one on the dorsal aspect of the hand immediately proximal to the metacarpophalangeal joint of the index finger, and the other on the forearm.

To evaluate the dynamic accuracy of the system (Haggard and Wing 1990), the position of three markers mounted on a rigid structure was recorded when the structure was displaced with pseudo-planar movements parallel to the table or was rotated in space. The distances between the three markers were computed in each condition over 2500 frames. The maximum range obtained for the mean distances was 0.7 mm, and the maximum standard deviation obtained for each condition was 0.1 mm. This dynamic measurement confirms the nominal precision of 0.1 mm given for the Optotrak 3020 system. In this study, we considered as relevant only those differences which were greater than this value, in spite of the fact that statistical significance can appear for smaller differences.

Data processing

Kinematic parameters

After acquisition, the position data were filtered with a second-order Butterworth filter with a forward and reverse pass. A cutoff frequency of 10 Hz was used.

Movement onset was determined visually as the first increasing value of a sequence of at least seven points on the recording of thumb position. The movement endpoint was similarly determined on the curve of the interfinger distance, as the point where the interfinger distance stopped decreasing.

Kinematic parameters were also measured on the trajectories of markers. For the transport component, the tangential velocity of the wrist marker was measured. For the grasping component, the values of the maximum interfinger distance (maximum grip aperture) and the time to maximum grip aperture were measured. Finally, the wrist angle at the end of the movement was measured.

Spatial parameters

The spatial paths of the three main markers and their variability over repeated trials were measured in three dimensions. The spatiotemporal variability of these spatial paths was quantified after time normalization of the data. The standard deviations of the mean X, Y and Z positions of each marker were calculated for each of the 100 normalized frames (Georgopoulos et al. 1981). Variability was expressed as the square root of SD X^2+SD Y^2+SD Z^2.

To reconstruct the opposition axis, the position of the tips of the thumb and index finger was sampled at the end of the movement. The opposition axis was defined as the line connecting these two points. Its orientation was measured, for each object position and size, with respect to several different reference frames originating from the object center (object-centered frame) or from a body part (body-centered frame):

1. *Object-centered frame*. The workspace was defined by the X, Y and Z axes of the Optotrak system. The Y axis was used as the reference for calculating the angle of orientation of the opposition axis (Fig. 1A, insert). To compare the values of this angle for movements directed at objects of different positions and sizes, the object center for each trial was considered as the center of the workspace. In this way, the X and Y coordinates of the finger positions on the objects (and thus the opposition axes) for all trials were referred to the same point.
2. *Body-centered frame*. The reference axis was the line connecting the center of the head and the object center (Fig. 1B). The orientation of the opposition axis was calculated with respect to this reference axis. To compare orientations of the oposition axis for movements directed at objects of different positions and sizes, the reference axis was rotated around the subject's head, so that oppositions axes for all trials were superimposed.
3. *Forearm-centered frame*. The reference axis was the line connecting the forearm and the wrist LEDs at the end of the movement (Fig. 1C).

A within-subject 3 (Sizes)×6 (Target positions) repeated measures ANOVA was conducted for each parameter. A significance level of 0.05 was chosen. A Newman-Keuls test was used as a post-hoc test.

Results

Transport component

Movement time

There was a significant effect of object position on movement time [$F(5,25)=7.07$; $P<0.0003$]. The post-hoc analysis showed a tendency for movement time to covary with movement amplitude. It was longer for object positions which involved longer distances between the hand and the object (Fig. 2A). Object size had no influence on movement time.

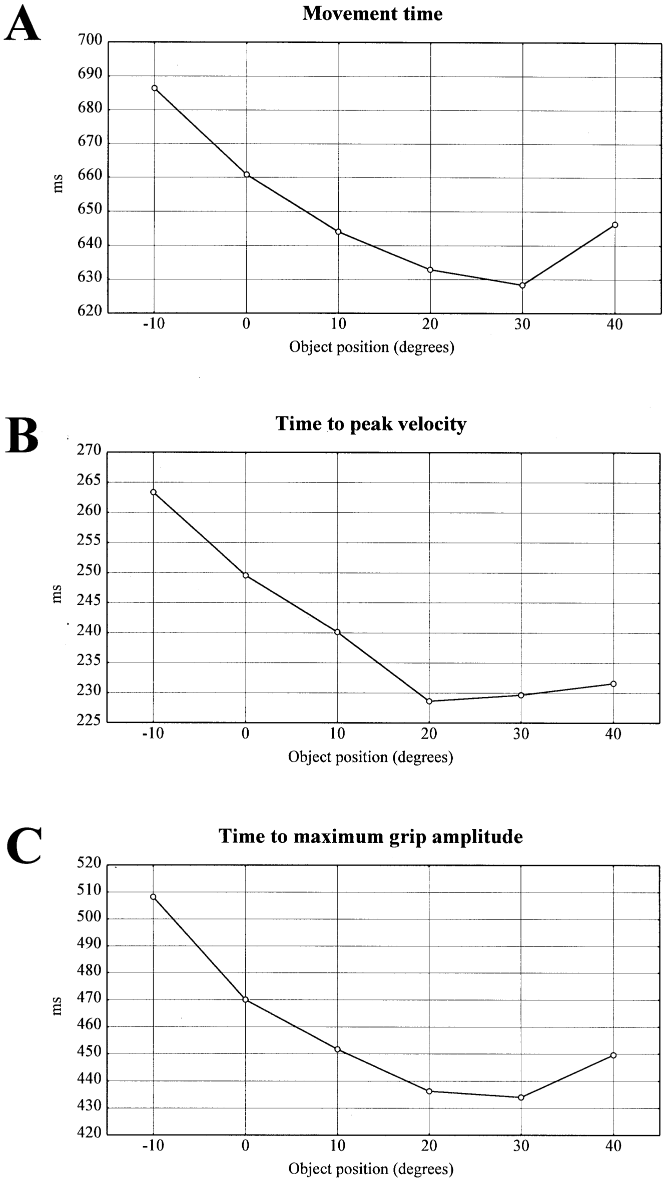


Fig. 2A–C Effect of object location on temporal parameters of the movements. Movement time (**A**), time to peak velocity (**B**) and time to maximum grip amplitude (**C**) are plotted as a function of object position

Velocity

There was a significant effect of object position on the time to peak velocity [$F(5,25)=11.44$; $P<0.0001$]. Again, the longer the distance to be travelled by the hand, the later the peak velocity occurred (Fig. 2B). An effect of object position was also observed on the amplitude of the velocity peak [$F(5,25)=4.50$; $P<0.046$]. The velocity peak was higher for movements directed at the objects located at –10°, 30° and 40° than for movements directed at objects located in the central zone of the display. This difference, however, did not exceed 10% of the value of the peak.

Grasp component

Effect of object size on grip aperture

The usual effect of object size on maximum grip aperture was observed, i.e. the bigger the object, the larger the maximum grip aperture [$F(2,10)=151.91$; $P<0.0001$]. There was also a significant main effect of object size on the time to maximum grip aperture [$F(2,10)=7.58$; $P<0.01$]. The post-hoc analysis revealed that this effect was mostly due to movements directed at the larger object, for which the time to maximum grip size was longer (by 40 ms) than for the smaller objects.

Effect of object position on grip aperture

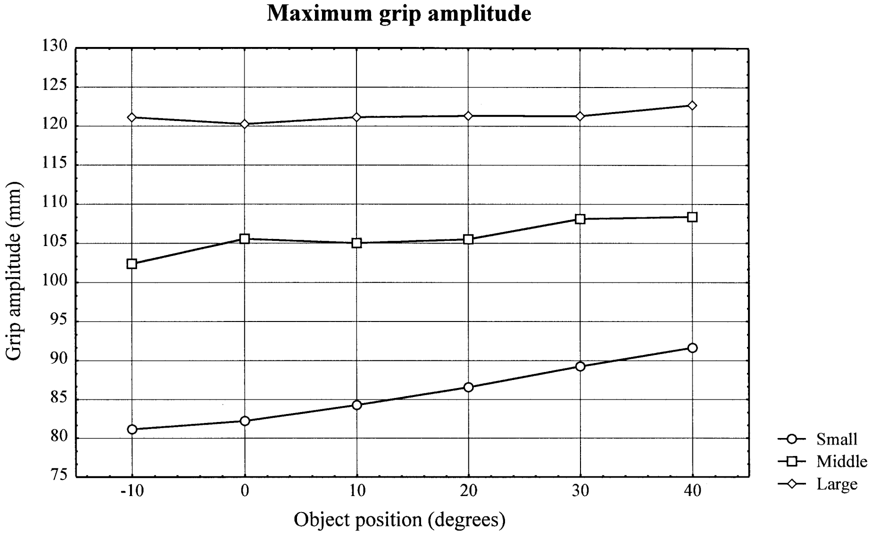
The time to maximum grip aperture was affected by object position [$F(5,25)=13.94$; $P<0.0001$]. It was longer for movements directed at the object located at –10° (i.e., placed at a greater distance from the hand) than for movements directed at objects located at the other extremity of the display (Fig. 2C). The amplitude of the maximal grip aperture was smaller when the movements were directed at an object of a given size located at –10° than at 40° [$F(5,25)=14.79$; $P<0.0001$]. This effect was more marked for the smaller objects and tended to "saturate" for the larger one (Fig. 3). It is important to note that the differences measured in this experiment were up to 10 times greater than the spatial resolution of the recording system.

Effect of object position and size on orientation of the opposition axis

A striking difference was observed according to whether the orientation of the opposition axis was expressed with respect to an object-centered or a body-centered frame of reference. In the object-centered frame, the orientation of the opposition axis varied monotonically as a function of object position. The difference from one object to the next was almost exactly 10° (Fig. 4A). By contrast, in the body-centered frame the total variation in orientation between the object located at –10° and that located at 40° did not exceed 10° (Fig. 4B). The same was true for all three object sizes. A similarly small (<10°) variation of the opposition angle was found when the reference was the forearm (Fig. 4C).

This result is further illustrated in Fig. 5 for the object-centered and the head-centered frames. The positions of the tips of the index finger and thumb from one representative subject have been plotted for the three object sizes and the six object positions. In Fig. 5A, where object-centered coordinates have been used, the finger positions appear clearly distinct for each object position. In Fig. 5B, where head-centered coordinates have been used, the finger positions are superimposed. Note that in both cases the finger positions for objects of different

Fig. 3 Effect of object location on maximal grip amplitude. The curves of maximal grip amplitude versus object position are plotted for each of the three object sizes



sizes placed at the same location tend to be aligned. This shows that the orientation of the opposition axis was little influenced by the size of the objects.

Effect of object position and size on the angle of the wrist

The angle of the wrist at the end of the movement was not affected by the position of the objects [$F(5,25)=0.52$; $P<0.7558$]. Wrist angle was affected by the size of the object [$F(2,10)=10.97$; $P<0.003$]. The angle was larger (i.e., corresponding to a wrist flexion) for larger objects.

Spatial paths

The mean spatial paths of the displacements of the three markers during movements at the six object locations are displayed for one typical subject in the upper part of Fig. 6. Note that the markers positions in the X and Y dimensions only are represented. The pattern of the spatial paths, and particularly those for the two fingertips, is closely similar to earlier descriptions (Paulignan et al. 1991). For this reason, they were not submitted to further analysis.

The variability of the displacements of the markers over repeated trials is illustrated by the horizontal and vertical bars on each spatial path, which represent the amplitude of 1 standard deviation with respect to the mean in the X and Y dimensions, respectively. The time course of variability, expressed as the square root of SD X^2+SD Y^2+SD Z^2, is illustrated in the lower part of Fig. 6 for each of the three markers. It is clear that variability was not evenly distributed across movement time, being larger during the early part of the movement (during the acceleration phase) and sharply decreasing as the hand approached the object. During this late phase, as exemplified by the graph in Fig. 6, the variability of the spatial paths of the fingers became less marked than that of the wrist. A statistical comparison in all four subjects of the last recorded point on the three curves of variability revealed a significant effect when the marker (wrist, index finger or thumb) is the factor [$F(2,6)=31.67$; $P<0.0006$]. The post-hoc analysis showed that the point for the wrist was significantly different from those for the fingers.

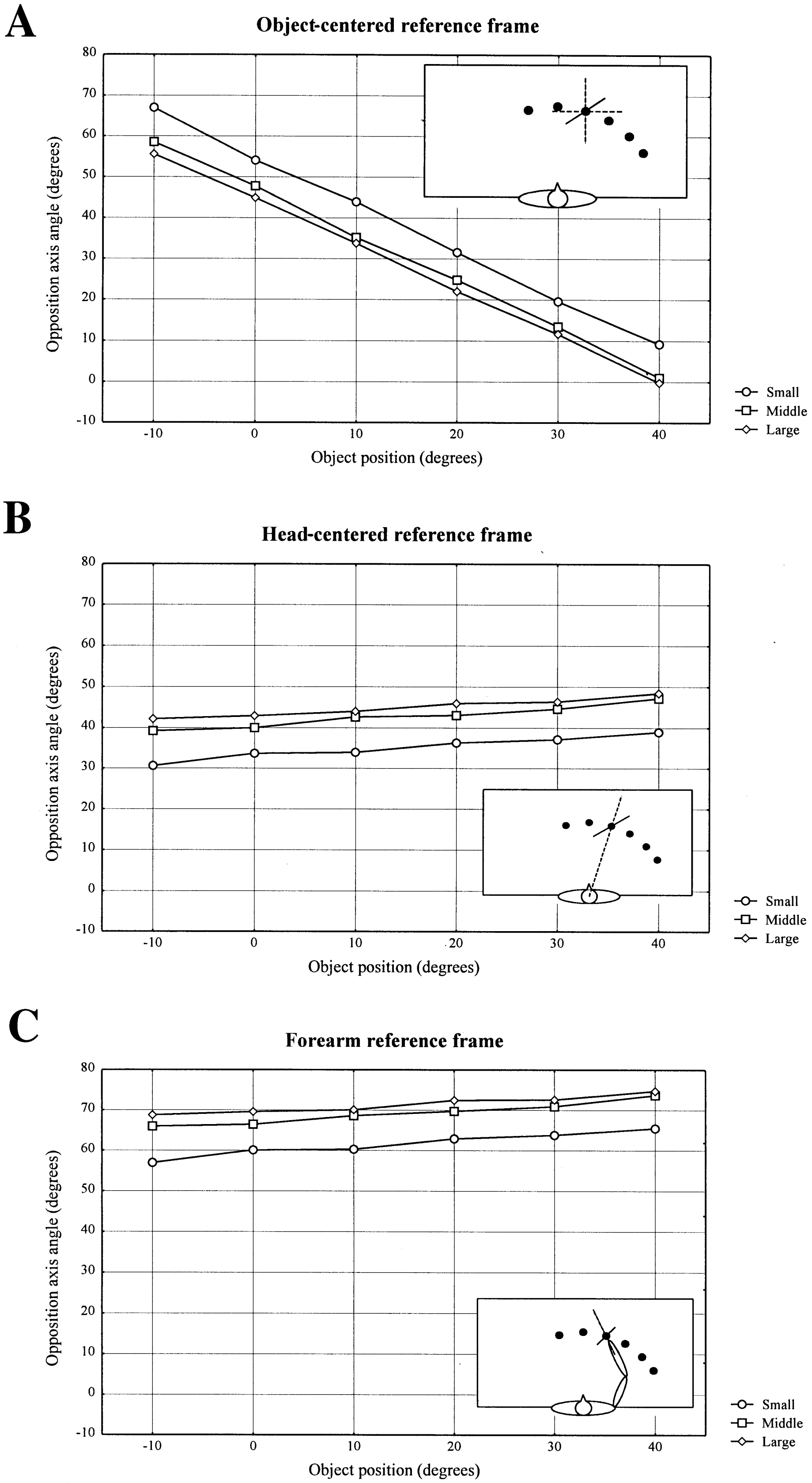
Discussion

Effects of object position on prehension movements

The present results add to our understanding of prehension movements. In contrast to previous studies which were limited to movements of different amplitudes in the sagittal plane (or in a limited zone of the workspace near the sagittal plane), here we explored movements directed at objects widely distributed in the workspace. It should be noted, however, that, due to our design of placing the objects concentrically relative to the subject's vertical axis, objects at different locations were also at different distances from the resting hand position. For this reason, the effects of changing movement direction and amplitude on the pattern of prehension were partly confounded.

Object position in the workspace first affected the duration and the kinematics of the reaching phase of prehension (the transportation component). Movement duration, duration of the acceleration phase (time to peak velocity) and amplitude of peak velocity were significantly influenced. These results are largely explained by changes related to the distance of the objects: as shown in Fig. 2A and B, the effect of distance on movement duration and duration of acceleration accounts for all object positions. Peak velocity, however, did not correlate with amplitude of movements directed at objects placed at different distances, as is usually observed when move-

Fig. 4A–C Effect of object location on orientation of the opposition axis. The final orientation of the opposition axis is plotted versus object position within three different reference frames: an object-centered (**A**), a head-centered (**B**) and a forearm-centered reference frame (**C**)



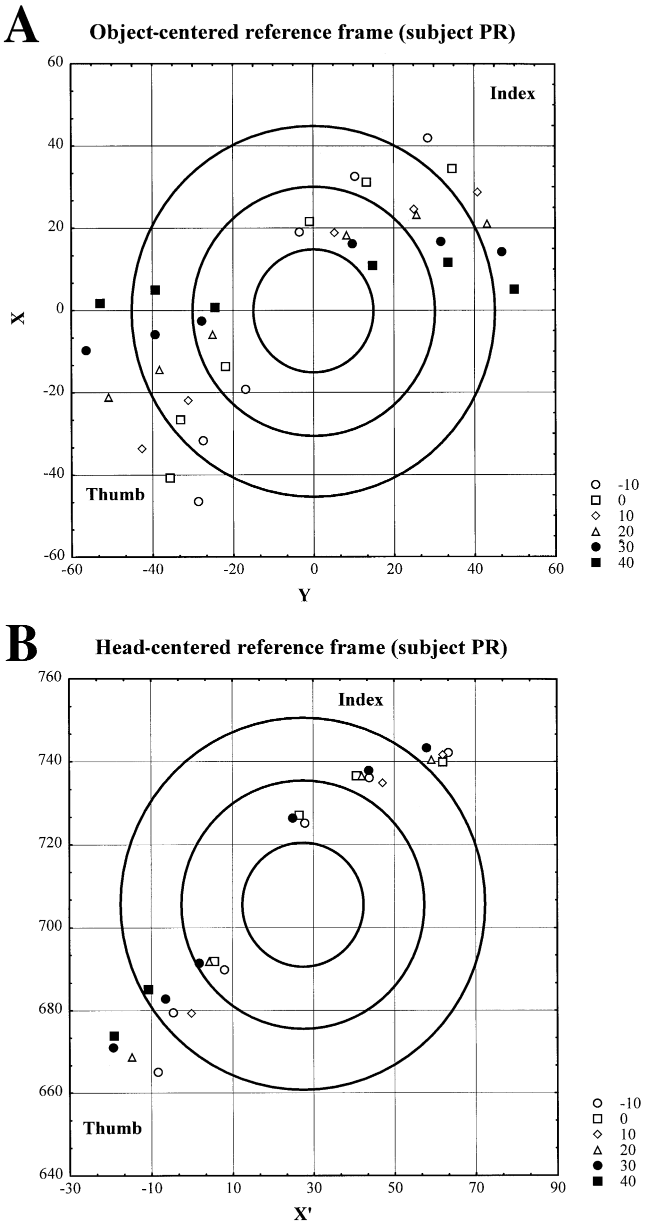


Fig. 5A, B Effect of object position and size on final finger position. The final position of the fingers is calculated in each reference frame (**A** object-centered, **B** head-centered). Note in the object-centered frame that finger position changes with object location and size. In the head-centered frame finger positions for different object locations are superimposed. The three *circles* represent objects of different sizes

ment amplitude varies along one direction (e.g., Jeannerod 1984).

Similar effects were also found for the grasping component. The time to maximum grip aperture and the amplitude of maximum grip aperture were affected by object position. Finger grip size, for example, tended to be larger for an object of the same size when it was placed on the right side (and thus at a shorter distance from the hand resting position) than when it was placed on the left side of the display. This result is in apparent contradiction to earlier results showing that grip size tends to increase with object distance in the sagittal plane (Jakobson and Goodale 1991; Chieffi and Gentilucci 1993). The possibility cannot be excluded that increasing object distance in each direction would yield an increase in maximum grip aperture as described by these authors.

What our results reveal is thus a relative isotropy of the workspace with respect to the organization of prehension movements. This result is rather surprising, at least as regards the transport component. Movements in different directions involve different combinations of joint rotations. A movement directed at the leftmost object involves shoulder adduction and elbow extension, whereas a movement directed at the rightmost object involves shoulder abduction and moderate elbow extension. In spite of these large differences in limb configuration, the same temporal frame scaled to distance is used for executing the movements.

Determinants of the opposition axis

Another point to be discussed concerns the introduction of the opposition axis as a parameter for the description of prehension. Although this concept has already been used by several authors (Napier 1955; Iberall et al. 1986), only a few systematic studies of the orientation of the opposition axis are available in the literature (Carey et al. 1996; Gentilucci et al. 1996). The present experiment contributes important new results on how the points where the fingertips come in contact with the object surface are selected. The first result is that the spatial paths of the two fingertips over repeated movements directed at the same object tend to converge on the points of contact, as indicated by the sharp decrease in variability during the final part of the trajectory. This strongly suggests that the final finger position (and therefore the orientation of the opposition axis) is the controlled variable of prehension. The second result is that this position is determined not with respect to external (visual) coordinates, but with respect to body-centered coordinates. When measured in the object-centered frame of reference, the difference in orientation of the opposition axes between extreme object positions was 70°. By contrast, when this measure was made with respect to a body-centered reference, the orientation of the opposition axis tended to be invariant. As shown by Fig. 4B and C, the difference in angle between opposition axes on the leftmost and rightmost objects was only 10°. Because wrist angle did not vary for different object locations, the above result implies that the forearm and hand were displaced as a whole, irrespective of object location. This was achieved by combined rotations at the shoulder joint (for matching the object location in azimuth) and the elbow joint (for matching the object distance from the body).

Thus, the position of the fingertips on a cylindrical object results from the selection of an invariant final posture of the arm, not an invariant visual landmark on the object.

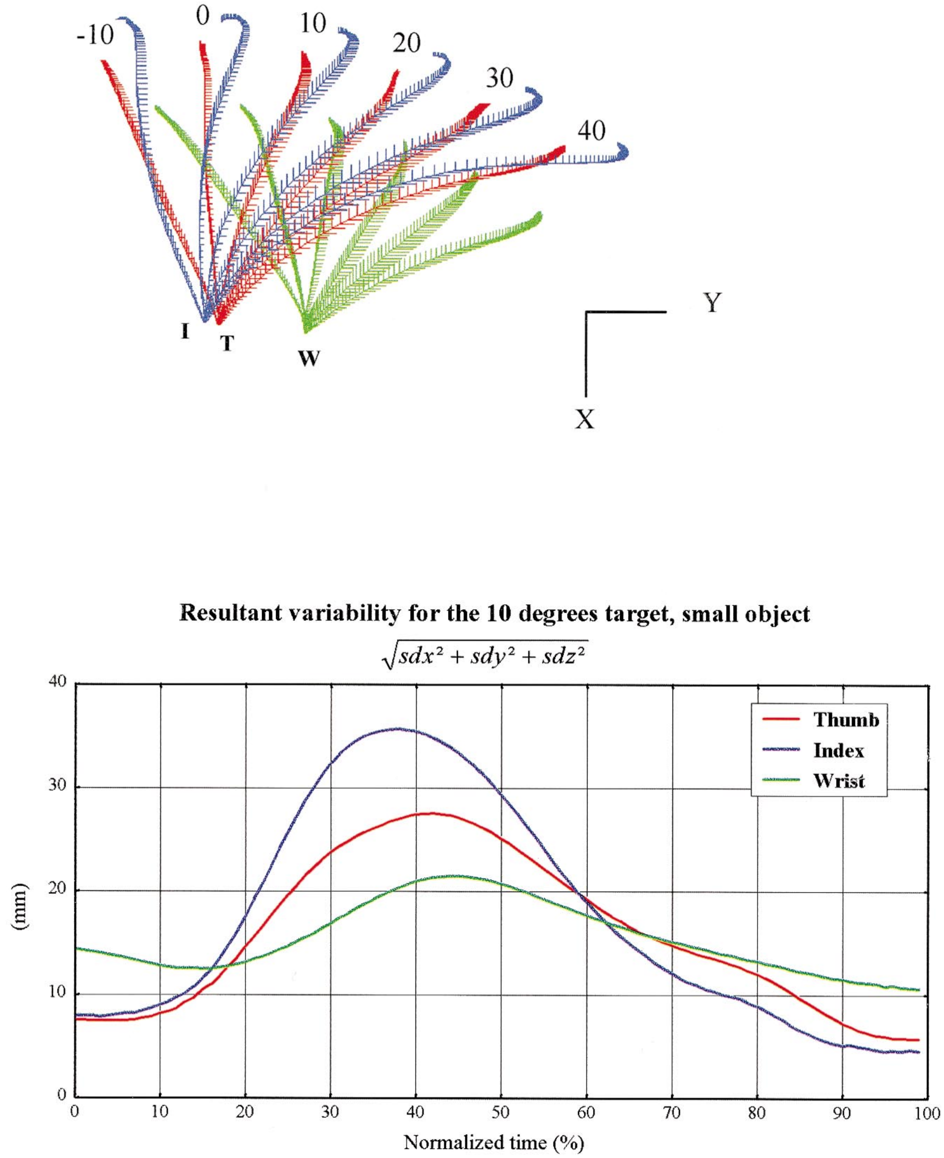


Fig. 6 Spatial path and variability of prehension movements. *Upper figure*: Averaged *XY* spatial paths of ten movements of the wrist (*W*), thumb (*T*) and index finger (*I*) of the same subject (PR). Movements directed to the –10°, 0°, 10°, 20°, 30° and 40° targets have been superimposed. The *horizontal* and *vertical lines* attached to the spatial paths represent the amplitude of 1 standard deviation with respect to the mean spatial path in the *X* and *Y* dimensions, respectively. *Lower figure*: Values of the resultant standard deviation with respect to the mean path of the thumb, index finger and wrist LEDs, as a function of movement time

This finding supports and expands earlier findings by Desmurget et al. (1995, 1996). They recorded the final arm posture when a subject reached to grasp a bar placed at different orientations from the horizontal. On some occasions the orientation of the bar was changed at the onset of the reaching movement. The configuration of the arm was rapidly (i.e., without an increase in total movement time) altered so as to match the new orientation. In doing so, the arm progressively moved to the final posture that was assumed during unperturbed movements directed at a bar with the same orientation. In other words, each orientation of the bar determined a unique final posture of the whole limb (Stelmach et al. 1994). Visual and motor factors thus compete for orienting the opposition axis. Whenever possible, the final arm posture tends to remain invariant and it is only when required by object shape that new degrees of freedom are recruited.

Note that, in normal conditions, there is a possibility for preserving an invariant arm posture in spite of a constraining object shape: it is that the subject rotates his or her body around the object until the orientation of the opposition axis afforded by the object becomes compatible with the optimal arm posture. The fact that the opposition axis is computed with respect to a body reference makes this possibility an economical one in terms of the number of degrees of freedom involved. However, experimental situations like ours, which impose a fixed position of the body with respect to the workspace, exclude this possibility.

Control of arm posture and visuomotor channels

It has been postulated that visuomotor transformations related to reaching (the transport component) and grasping (grip formation), respectively, are controlled independently (the visuomotor channels hypothesis: Jeannerod 1981; Arbib 1981; Jeannerod et al. 1995; Paulignan and Jeannerod 1996). This idea has received strong support from recent anatomical and physiological work showing distinct cortico-cortical pathways for reaching and grasping (Jeannerod et al. 1994). The problem here is to know to what extent it can account for the aspects of prehension described in the present experiment.

Our results tend to show that the position of the fingers on the object is not independent of the proximal component of the prehension movement. In other words, the mechanisms that determine the selection of an appropriate opposition axis are not separate from those that determine the hand position in the workspace. Soechting and Flanders (1993) reported that the errors in matching the orientation of an object with a hand-held rod depended both on the slant of the object and on its location in the workspace. Their conclusion was that the neural transformation from target orientation to hand orientation is influenced by both extrinsic (visual spatial) and intrinsic (arm posture) parameters. It could be that, among extrinsic parameters which determine the pattern of grasping, orientation of the opposition axis has a special status: on the visual side, it pertains both to the object configuration itself and to its situation within the body frame of reference; on the motor side, it involves not only pronation/supination of the wrist and forearm, but also adduction/abduction of the shoulder. In fact, other parameters also affect more than one degree of freedom: increase in object size, as shown here, requires a change in wrist angle in addition to the change in grip size.

The use of a broader range of conditions (for object size and position in the workspace) gives a different view of visuomotor transformation. Whereas many of the previous studies using only one position tended to favour the notion of independent channels for visuomotor transformation, the present study stresses the interdependence of mechanisms for matching object position, orientation and size.

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