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Research report

Hand orientation for grasping depends on the direction of the reaching movement

Agnès Roby-Brami[a,b,*], Nezha Bennis[a], Mounir Mokhtari[a,c], Pierre Baraduc[a]

[a] INSERM U 483, 9 quai St. Bernard, 75005 Paris, France
[b] Service de rééducation neurologique, Hôpital Raymond Poincaré, 92380, Garches, France
[c] Institut National des Télécommunications, 9 rue Charles Fourier, 91011, Evry, France

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Abstract

The 3D orientation of the hand for grasping was studied while subjects reached for objects placed at several locations on a horizontal board, with movements starting from three initial hand positions. The hand movements were recorded with electromagnetic sensors giving 3D position and orientation information. The study focused on the azimuth, which is the projection of the hand orientation in a horizontal plane. The hand azimuth for grasping was linearly correlated with the direction of the reaching movement and not with the object direction in head- or shoulder-centered coordinates. This relationship was valid regardless of the initial hand position. A control experiment with constant movement direction showed a weaker, probably postural, effect of object direction in shoulder-centered coordinates. We suggest that hand orientation for grasping is mainly controlled in relation to the reaching movement direction.

Theme: Motor systems and sensory motor integration

Topic: Posture and movement: reach and grasp

Keywords: Hand orientation; Prehension; Reaching to grasp movements; Humans

1. Introduction

The orientation adopted by a grasping hand is known to depend on the shape [10,15] and orientation of the object [4–6,14]. In addition, two recent studies have demonstrated that the orientation of the grip opposition axis also depends on the location of the object, independently of its shape and orientation [8,16]. However, the interpretation of this observation remains unclear despite its importance for understanding the coordination between reaching and grasping [17]. Paulignan et al. [16] have proposed that the orientation of the grip opposition axis is related to the direction of the object with reference to the head. However, several studies of pointing [9,19] and grasping movements [3] have shown that the final configuration of the upper limb is affected by its initial posture.

The present study was performed to assess the relationships between the hand orientation for grasping and the spatial parameters of reaching movements: in particular the initial hand position and the location of the target object. To this end, we concentrated on the horizontal projection of natural 3D movements and analyzed the hand orientation in the horizontal plane (hand azimuth) during grasping an axially symmetrical vertical object. Variations in the azimuth of the hand for grasping which is not constrained by the shape of the object were then studied as a function of the initial position of the hand and of the object in a relatively wide but central workspace. The present work extends and generalizes previous findings by demonstrating that changes in hand orientation are predominantly linked to the direction of the movement from the initial to the final hand positions.

*Corresponding author. INSERM U483, 9 quai St. Bernard, 75005 Paris, France. Tel.: +33-1442-72624; fax: +33-1442-73438.
E-mail address: aroby@snv.jussieu.fr (A. Roby-Brami)

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2. Materials and methods

2.1. Subjects

Six right-handed healthy subjects, three men and three women, aged 26–47 yr (mean 35.5 yr) volunteered for this study, which was approved by a regional ethics committee.

2.2. 3D movement recording

The 3D motion analysis was performed with Fastrack™ Polhemus sensors. This system uses an electromagnetic field generated by a transmitter to determine the position and orientation (Euler angles) of two remote sensors (sampling rate 30 Hz). The static accuracy of these sensors is 0.08 cm RMS for the marker positions and 0.15° RMS for the marker orientations. Calibration measurements showed that the system was accurate within 0.7 m of the transmitter. The sensors were attached distally to the dorsum of the hand (middle part of the third metacarpal bone) and proximally at shoulder level on the ipsilateral acromion. This study concentrates on the azimuth of the hand, which is the projection of its longitudinal axis in the horizontal plane (angle about the vertical Z reference axis, Fig. 1).

2.3. Task and experimental set-up

The task was to grasp a cardboard cone (10 g weight, 5 cm diameter and 17 cm tall) using the most natural hand configuration. Fig. 1A shows the experimental set-up. The subject sat in front of a horizontal wooden board with three initial hand positions (P1–P3) and seven object locations. The origin of the reference frame was fixed in the middle of the board back edge. The board was placed about 15 cm from the subject's abdomen so what his/her right shoulder was located 30 cm behind the reference frame ($Y=-30$ cm). The subject was instructed to look forward so that the head was situated in the midline of the board (at $X=0$). The right hand was placed comfortably in one of the three initial positions, palm down, its longitudinal axis along the Y reference direction. The seven object locations were comprised within a 20×20 cm work space in front of the subject (between $Y=12$ cm and $Y=32$ cm from the reference frame). Subjects were told to reach and grasp the cone when asked to do so, and to place it on the board in front of the abdomen at a constant final location (situated at $X=0$, $Y=0$). No emphasis was placed on the reaction or execution time. The subjects performed five movements in each of 21 conditions (3 initial hand positions×7 object locations).

Movement distances and directions for each trial were calculated for the initial hand and object positions. The movement direction was the angle between the frontal X axis and the vector joining the initial hand position to the target (Fig. 1A). The object direction was also expressed in shoulder-centered coordinates [20] and in head-centered coordinates [16]. Fig. 1A shows, for the purpose of comparison, object location 5 expressed as movement direction (angle α1), and as object direction in shoulder-centered (angle α2) and head-centered coordinates (angle α3). The initial shoulder position was given by the sensor on the acromion; the center of the head was assumed to be at $X=0$ and $Y=10$ cm in front of the shoulder sensor.

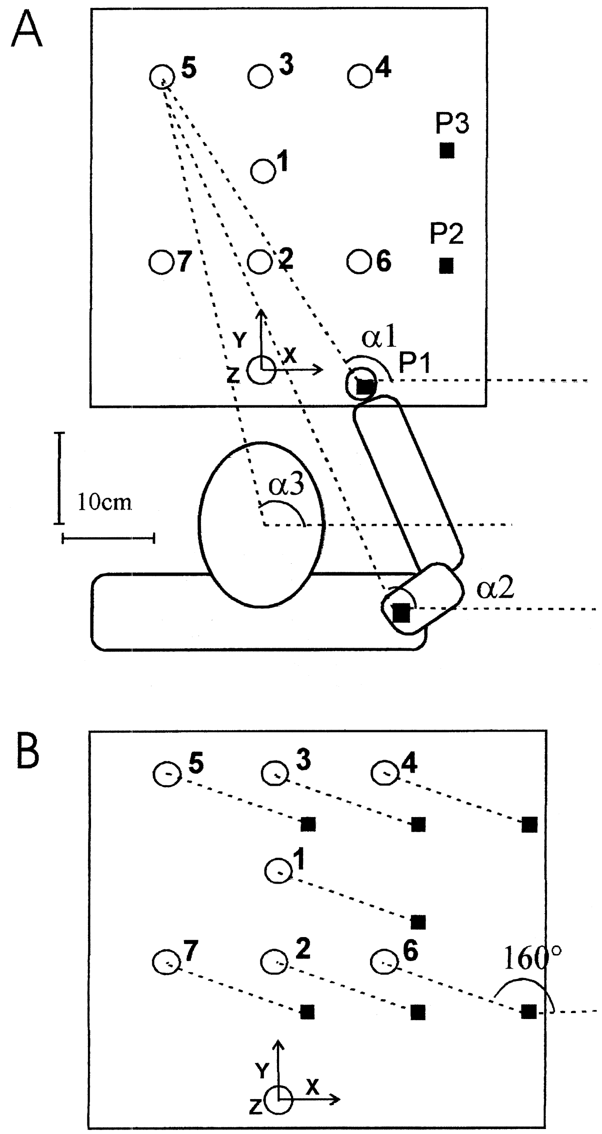

Fig. 1. (**A**) The experimental set-up. Horizontal board showing the object positions numbered 1–seven and the initial hand positions numbered P1–P3. The position of the reference axes XYZ is indicated. The direction of the object number 5 is indicated in coordinates centered on the initial hand position (movement direction, α1 angle), the shoulder (α2 angle) and the head (α3 angle). (**B**) Control experimental set-up. Same board. The objects were placed at the same locations; the initial hand positions were such that the distance (15 cm) and direction (160°) to the object were constant.

In a control experiment, the subjects had to reach and grasp objects placed in the same seven locations from seven different initial hand positions. These positions were chosen so that the direction of the movements was constant (160°), and in the midrange of the movement directions ($\alpha 1$) calculated from all the trials in the first experiment. The movement distance was 15 cm (Fig. 1B).

2.4. Data analysis

The hand sensor tangential velocity was computed by differentiation of the position signal. The position and orientation of the hand sensor were measured at the onset of movement (determined as the first sample above the velocity threshold of 0.01 ms^{-1}) and at the time of grasping (determined as the time of the minimum velocity, corresponding to the turning point of the hand trajectory).

The mean of five movements repeated in each condition was analyzed statistically with ANOVA, which included the azimuth of the hand as a dependent parameter and the factors 'object location' and 'initial position'. Regression analysis and analysis of covariance (ANCOVA) were used to study the hand azimuth angle as a function of movement distance, movement direction or object direction in body-centered coordinates. ANCOVA included the 'initial position' factor and movement distance, movement direction or object direction factors as a covariate. The level of significance threshold was $P=0.05$.

3. Results

Fig. 2A shows the trajectory of the hand during prehension movements towards an object placed on location 5 (open circle) from the three initial positions in a representative subject. The filled symbols represent the reaching movement; the open ones represent the return movement of the hand to place the cone to its final location (cross). Both reaching and return movements are characterized by a smooth bell-shaped velocity peak (Fig. 2B) [11]. The turning point of the trajectory in all trials corresponded to the time of the minimum velocity. Direct visual examination showed that all subjects grasped the cone by using all the finger pulps (multi-pulpar grip configuration). The diagram in Fig. 2C explains the geometrical relationships between the object, the hand position and orientation, and the finger configuration at the time of grasping. The finger configuration can be approximately assessed by the distance between hand sensor and object location, and by the angle between the hand axis and the direction of the object (grasp angle: γ)

3.1. Kinematics of the hand

The amplitude of the velocity peak during reaching was used to characterize hand kinematics. The peak velocity of the hand varied with the object location ($F(6,105)=18.6$, $P=0.0001$) and the initial hand position (ANOVA: $F(2,105)=7.3$, $P=0.001$); it was 0.60 ± 0.03 ms^{-1} (mean±S.E.M.) for P1; 0.64 ± 0.02 ms^{-1} for P2 and 0.69 ± 0.03 ms^{-1} for P3. An analysis of covariance showed that these differences were due to a linear relationship between object distance and the hand peak velocity (ANCOVA: $F(1,120)=240.4$, $P=0.0001$) regardless of the initial hand position ($F(2,120)=0.83$, $P=0.44$). The peak velocity of the hand did not vary significantly with either the direction of the reaching movement or the object direction in head- or shoulder-centered coordinates.

3.2. Initial posture

The subjects all adopted reproducible initial hand positions. Despite the instruction to keep the initial hand orientation along the Y axis, the initial azimuth of the hand varied slightly but significantly with the initial resting hand position (ANOVA: $F(2,105)=17.7$, $P=0.0001$). It was: $102.3°\pm1.3$ (mean±S.E.M.) for P1; $94.9°\pm1.2$ for P2; and $91.6°\pm1.2$ for P3. The initial hand azimuth did not vary with object location ($F(6,105)=0.14$ ns).

The shoulder initial position was $X=12.6$ cm±0.4, $Y=-30.4$ cm±0.5 and $Z=32.2$ cm±0.6.

3.3. Variation of the hand azimuth for grasping

Fig. 3A shows a projection of the position and orientation of the hand in the horizontal plane at the initial position (thin arrows with diamonds) and at the time of grasping (thick arrows). The tail of each arrow represents the position of the hand, and the orientation of the arrow represents the hand azimuth. The azimuth of the hand at the time of grasping varied with both the object location (ANOVA: $F(6,105)=41.4$, $P=0.0001$) and the initial position of the hand ($F(2,105)=66.7$, $P=0.0001$). The mean and sem in the group of subjects are presented in Table 1. Post hoc analysis showed that the individual differences between initial hand positions were significant ($P<0.0001$). The one by one differences between object locations were significant ($P<0.01$ to $P<0.0001$) excepted between the object locations 1, 5 and 6.

3.4. The relationship between hand azimuth and movement direction

We determined the relationships that link the hand azimuth for grasping to the object location and to the initial hand posture. Since hand azimuth altered with both variables, we concentrated first on the effect of movement direction (angle $\alpha 1$ between the initial hand position and the object on Fig. 1A). There was a highly significant linear relationship between the movement direction and hand azimuth. Fig. 4 illustrates this relationship for initial hand position P1 in the six subjects. The effect of the

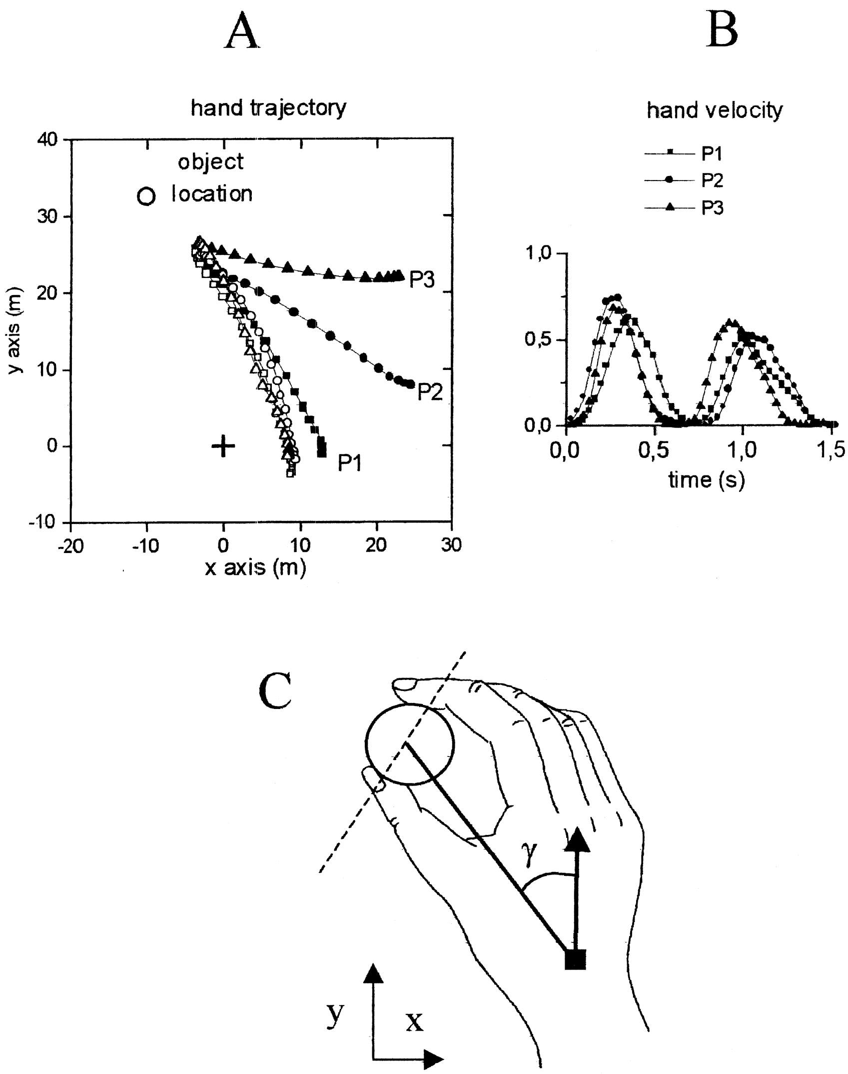

Fig. 2. Trajectory of the hand in a representative subject. (**A**) Hand trajectories of movements from initial hand positions P1–P3 toward an object placed on location 5 (open circle). The filled symbols represent the reaching movement and the open symbols the return movement. (**B**) Tangential velocity profiles for the same reaching and return movements. (**C**) Diagram of the geometrical relationships between object, hand position and orientation and the finger configuration at the time of grasping. Filled square: hand sensor; open circle: object location; arrow: hand azimuth; γ: grasp angle between the hand axis and the direction of the object.

movement direction was highly significant (ANCOVA $F(1,30)=790$, $P=0.0001$), and it was not affected by the differences between subjects ($F(5,30)=0.1$ ns). The linear relationships were significant for each individual subject ($r^2=0.936$ to 0.983). The slopes of the regression lines were quite similar (0.53–0.69, mean 0.60±0.022) while the intercept was more variable (15.5–39.6° mean 26.7±3.58°).

The relationship between the movement direction and the hand azimuth remained the same when the initial position of the hand was changed (Fig. 5A). ANCOVA showed that the linear relationship between movement direction and hand azimuth for grasping ($F(1,90)=360$, $P=0.0001$), did not depend on the initial hand position ($F(2,90)=0.77$ ns) nor on subject ($F(5,90)=0.98$ ns). So, variations in hand azimuth with either the initial hand position or the object location can be explained by a unique linear relationship linking hand azimuth to movement direction.

The individual relationships between movement direction and hand azimuth were significant for five subjects for P2 ($r^2=0.831$ to 0.987) and in four subjects for P3 ($r^2=0.692$ to 0.89). In all the cases where the regression was not significant, examination of the graphs showed that the result for object location 6 deviated from the linear trend of the others. Because of the geometry of the set-up (Fig. 1), the movement direction from P3 to the object location number 6 was maximal. We therefore assumed that in some subjects it was beyond the limit of the relationship, and we verified that all the linear relationships became significant when position number 6 was removed from the calculations. The mean (±S.E.M.) slope and intercept of the

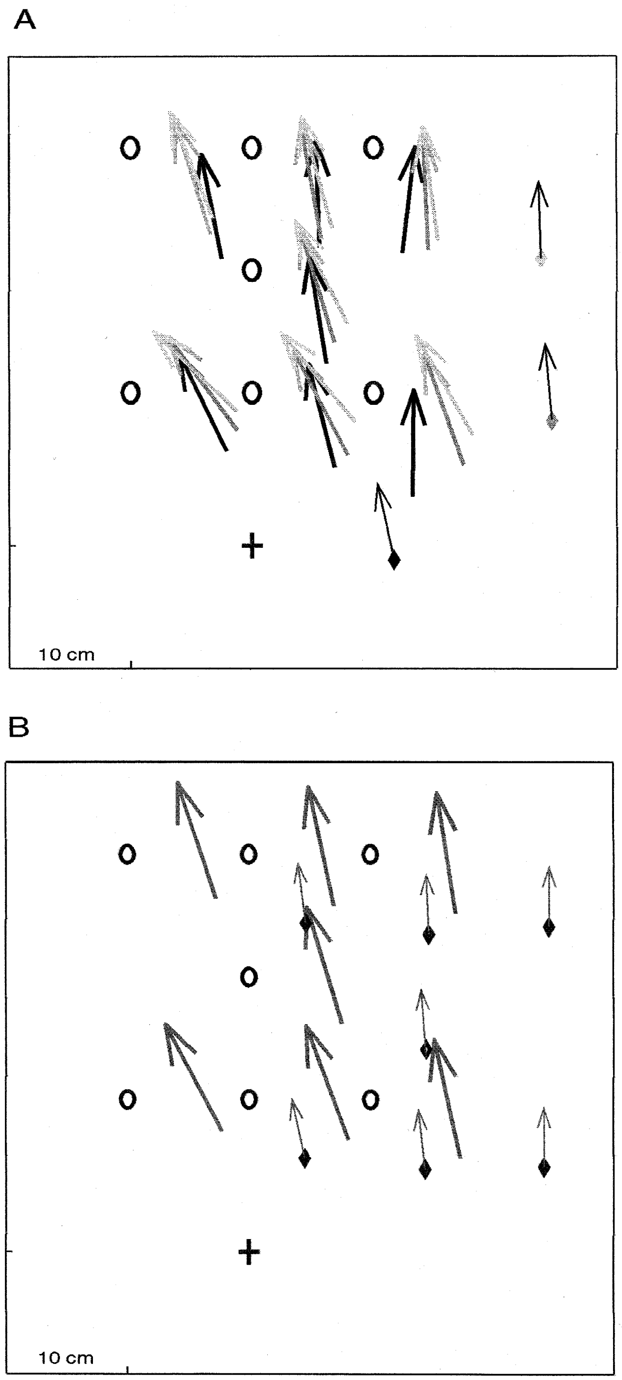

Fig. 3. Position and orientation of the hand at the time of grasping. (**A**) Projection in the horizontal plane. The tail of each arrow represents the position of the hand and its orientation represents the hand azimuth. The position of the object is indicated by circles. The thin arrows originating from diamonds correspond to the hand initial posture, and the thick arrows to the hand posture at the time of grasping. The grayscale color distinguishes grasping from initial position P1 (black), P2 (dark gray), P3 (light gray). Each value is the mean in six subjects. (**B**) Same representation for the control experiment.

regression lines were 0.58±0.016 and 20±2.8° and did not depend on the initial hand position (ANOVA $F(2,15)=0.5$ and $F(2,15)=3.3$ respectively, ns).

Table 1
Hand azimuth (in degrees) for grasping during reaching movements toward seven object locations (OL1–OL7) and starting from three hand initial positions P1–P3[a]

	P1	P2	P3	Control exp.
OL1	98.74±3.13	107.1±2.25	117.29±3.81	107.2±1.9
OL2	105.2±2.87	117.89±3.28	130.12±3.61	110.49±2
OL3	92.68±2.43	99.87±2.03	105.33±3.63	102.26±2.2
OL4	81.95±2.23	92.52±1.87	97.61±3.55	98.86±3.1
OL6	86.79±3.16	109.74±3.9	120.28±4.64	102.59±3.2
OL5	102.2±2.14	107.5±2.21	111.74±3.39	108.65±2.7
OL7	115.98±3.11	126.73±2.94	136.45±3.59	118.17±1.9

[a] The results are compared to those of a control experiment with reaching movements toward the same object locations with constant movement direction. Each value is the mean (±S.E.M.) of six subjects.

3.5. The relationship between hand azimuth and the object direction

The hand azimuth for grasping was also studied as a function of object direction expressed in shoulder-centered (angle $\alpha 2$ at the shoulder, Fig. 1A) or head-centered coordinates (angle $\alpha 3$ at the estimated center of the head). The hand azimuth for grasping was significantly linked to the object direction in shoulder-centered coordinates (Fig. 5B, ANCOVA $F(1,90)=135.2$, $P=0.0001$) without any initial hand position effect (ANCOVA $F(1,90)=2.2$ ns). The azimuth angle was also significantly linked to the object direction in head-centered coordinates (Fig. 5C, ANCOVA $F(1,90)=54.2$, $P=0.0001$) but this relationship varied significantly with the initial hand position (AN-

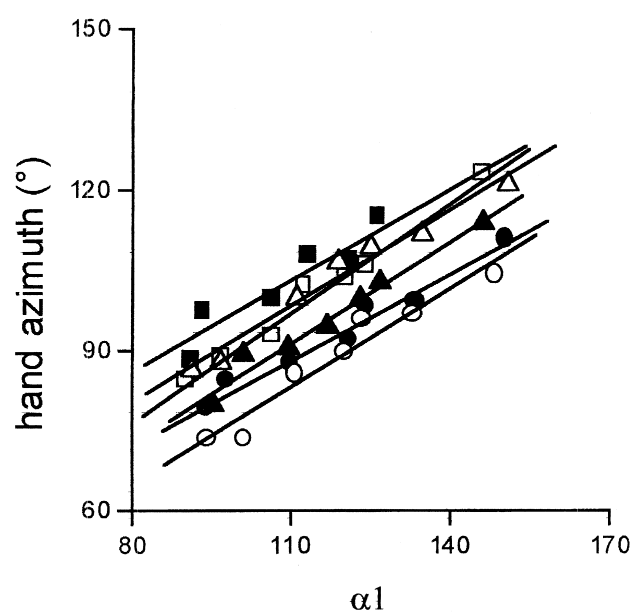

Fig. 4. Hand azimuth at the time of grasping as a function of movement direction. Reaches from the initial hand position P1. Each point is the mean of five trials in a subject for a given object position; different symbols represent different subjects; the individual regression lines are indicated.

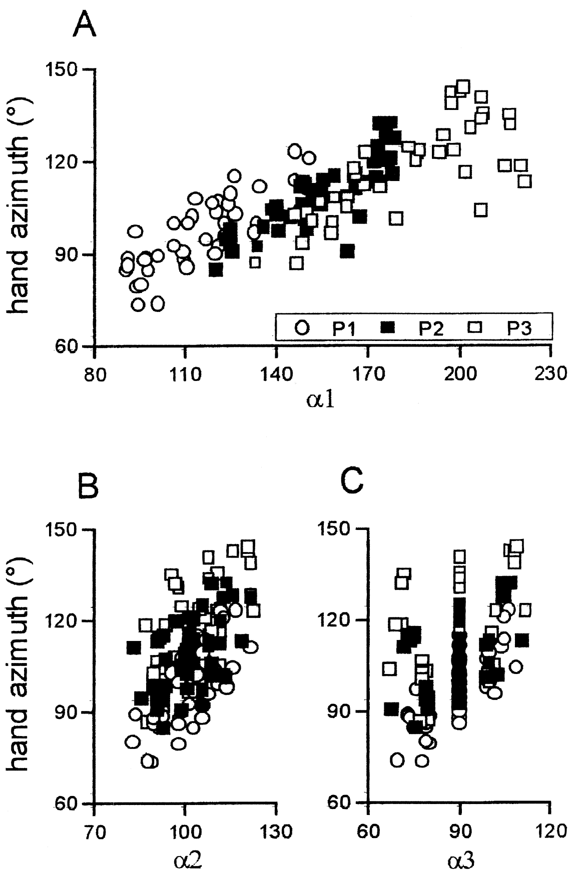

Fig. 5. Hand azimuth at the time of grasping; comparison of different initial hand positions. (**A**) Hand azimuth as a function of movement direction α1. Reaches from three initial hand positions in six subjects: P1 (open circles), P2 (black squares), and P3 (open squares). Each point represents the mean of five trials in a subject for a given object position and hand initial position. (**B**) Hand azimuth as a function of object direction in shoulder centered coordinates α2. (**C**) Hand azimuth as a function of object direction in head centered coordinates α3.

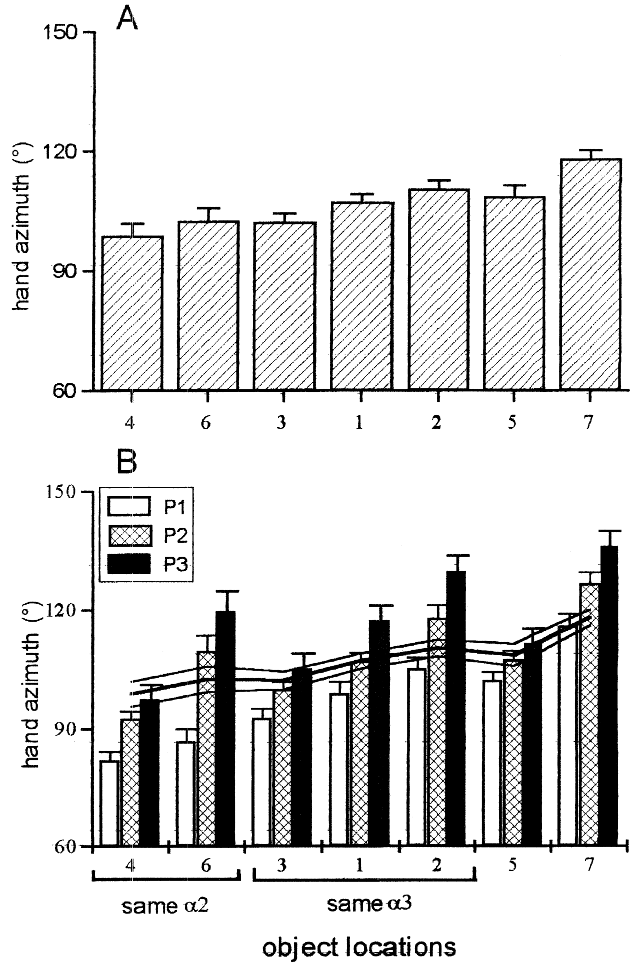

Fig. 6. Hand azimuth at the time of grasping to objects put at different locations. (**A**) Hand azimuth for grasping obtained in the control experiment with the same movement direction. Each bar is the mean of six subjects; the sem is indicated. The object locations are ordered as a function of object direction in shoulder-centered coordinates. (**B**) Comparison of the hand azimuth for grasping in the two experiments. The values of (**A**) are represented by three lines (the thick line is the mean±S.E.M.) superimposed on the results obtained with different initial hand positions P1–P3 (white, stippled and black bars).

COVA $F(2,90)=4.9$, $P=0.01$). Graphical observation suggests that the hand azimuth for grasping is primarily linked to movement direction and not to object direction with respect to either head or shoulder (Fig. 5A, B, C).

This was further investigated by comparing the hand azimuth for grasping objects situated in the same head- or shoulder-centered directions. The object locations 4 and 6 were situated in similar directions by reference to the shoulder (α2 respectively 91.6°±1.8 and 92.9°±2.3, non-significantly different). However, the hand azimuth for grasping these objects was different, and also varied with the initial position of the hand as shown by the post-hoc analysis of the ANOVA presented above (Table 1, Figs. 3A and 6B). Similarly, the object locations 1–3 were situated in the same forward direction by reference to the head (α3=90°), but the hand azimuth for grasping these objects was different and also varied with the hand initial position. This demonstrates that the variation of hand azimuth for grasping objects placed in different locations is directly linked to movement direction and not to the direction of the objects with reference to head or shoulder.

3.6. Hand azimuth and finger configuration

The present experimental set-up did not include a direct measure of finger posture or aperture during grasping. The assessment of finger configuration can be approached in two ways: the distance between the hand and the object (grasp length); and the angle between the hand axis and the direction of the object (grasp angle γ, Fig. 2C). ANOVA showed that neither grasp length (9.4 cm±0.1, mean±S.E.M.) nor grasp angle (30.7°±0.8) depended on object location or initial hand position ($F(6,105)=1.5$ ns; $F(2,105)=1.1$ ns and $F(6,105)=1.7$ ns; $F(2,105)=2$ ns respectively).

3.7. Hand azimuth for reaching with same movement direction

In order to confirm the fact that hand azimuth varies with the direction of the movement we designed a control experiment where movements were performed along the same direction (in cartesian space) in different areas of the workspace. To that purpose, six subjects performed prehension movements towards the same seven object locations, but starting from different initial hand positions so that the direction (160°) and the extent (15 cm) of the movement were the same (Fig. 1B). The working hypothesis was that the hand azimuth for grasping would be the same for the different object locations. Figs. 3B and 6A represents the hand position and orientation for grasping obtained in the control experiment. There were significant variations of the hand azimuth for grasping (ANOVA: $F(6,35)=5.8$, $P=0.0003$) but their amplitude were much smaller than those linked to movement direction (compare Fig. 3A and B and Fig. 6A and B). The effect of the workspace area independently of movement direction seems to be related to a shoulder-centered variable as suggested by the order of the targets on the x axis of Fig. 6A. An ANCOVA confirmed that the variations of hand azimuth for grasping obtained in the control experiment were correlated to the object direction in shoulder-centered coordinates ($\alpha 2$) (ANCOVA ($F(1,40)=10.1$, $P=0.002$). The same trend was also observed for hand posture before reaching movements (thin arrows originating from diamonds on Fig. 3B). Despite the instruction to orient the hand along the Y axis before movement, the initial hand azimuth varied significantly with the direction of the hand with respect to the shoulder ($F(1,40)=11$, $P=0.02$).

Fig. 6B summarizes the results of the two experiments and compares the effect of movement direction on the hand azimuth for grasping (white, stippled and black bars) and the effect of workspace area, independently of movement direction (thick line). Within the workspace considered here, both movement direction and, to a lesser extent, object direction with respect to the shoulder independently influenced the hand azimuth for grasping.

4. Discussion

The present study explores variation in hand posture for grasping as a function of the initial relative positions of hand and object. It concentrates on variations of hand orientation in the horizontal plane (azimuth) which is not constrained when grasping a vertical, axially symmetrical object. Therefore, the present experimental design gets round the influence of object shape and utilization on the hand orientation for grasping.

Grasping the conic object required a multipulpar grip, which is functionally related to a precision grip rather than a palmar grasp [10,15]. It was then possible to define an opposition axis between the positions of the fingertips involved in gripping. The opposition axis was not directly measured in this experiment. We assumed that its orientation in the horizontal plane was linked to hand azimuth because the grasp angle and length, which were used as estimates of finger configuration, did not vary consistently with the experimental parameters.

The present study has shown that the hand azimuth for grasping, and consequently the orientation of the opposition axis, varies with the direction of the reaching movement in the horizontal plane i.e. to the vector joining the initial hand position to the target. The linear relationship between hand azimuth and movement direction was constant, regardless of the initial hand position, and strikingly similar for all subjects. This relationship was not constrained by biomechanical limitations because all objects could be reached easily; but in the case of an extreme movement direction (from P3 to object location 6) there was a limit.

The fact that the hand azimuth for grasping was related to movement direction implies that it varied with both the location of the object and the initial hand position.

The variation of hand azimuth with the object location is consistent with previous observations that the orientation of the opposition axis varies with the object location [8,16]. Paulignan et al. [16] concluded that the opposition axis is invariant in head-centered coordinates (i.e. that there is a constant angle between the direction of the target and the opposition axis). The discrepancy between their results and ours is probably due to the radial disposition of their objects. Increasing the variety of object locations revealed differences in hand azimuth when reaching to objects located in the same head-centered direction (compare object locations 1–3 on Figs. 3A, 6B). Similarly, a relationship with the target direction in shoulder-centered coordinates [20] could not explain the differences in hand azimuth for grasping objects located in the same shoulder-centered direction (compare object locations 4 and 6 on Figs. 3A, 6B). In addition, allowing several initial hand positions revealed differences in hand azimuth that could not be interpreted in relation to the direction of the object in head- or shoulder-centered coordinates. We conclude that hand azimuth or opposition axis orientation for grasping depends primarily on movement direction and that the previously observed relationship between opposition axis and target direction [16] depended on a geometrical relationship between target direction and movement direction.

The variation of the hand azimuth for grasping with the initial hand position has not been previously reported. Other studies have reported variations in upper-limb posture for pointing when the initial hand position is changed [9,19]. However, our observations of grasping movements showed greater angular variations with the initial hand position (10–30°) compared to those reported for pointing movements (3–4° [9]). Desmurget et al.

studied grasping movements in which the 3D orientation of the hand was fully constrained by the orientation of the object. The upper-limb posture for grasping was stereotyped in a particular subject for a given location and orientation of the object [4–6], but it varied systematically when the initial hand position changed [3]. Our results are similar to this later study because both experiments showed a variation in the first unconstrained degree of freedom when the initial hand position changed. In both cases, the angular variation could well be explained by a relationship with movement direction.

Some of the results obtained in matching tasks could also be explained by the under-emphasized importance of the matching hand position. When subjects have to match the orientation of a visible 3D object with an object held by hand at some distance, the bias of the systematic errors coincides neither with anatomical axes nor with earth-fixed axes [2,21]. We suggest that the bias could be linked to the direction between the matching hand and the matched object akin the movement direction in the present study.

One question to be answered is whether the hand azimuth for grasping is primarily controlled by the central nervous system, or whether the observed regularities result from the control of several selected degrees of freedom. In particular, it has been proposed that reaching is controlled in a shoulder-centered frame of reference as a function of the upper arm azimuth, elevation and elbow extension [20]. The present results and particularly the relationship between hand azimuth for grasping and movement direction cannot be easily explained by a selective control of upper arm azimuth and elbow extension. This should be further confirmed by a computation of the upper-limb inter-joint angles, particularly shoulder horizontal abduction and elbow extension [1]. By opposition, the effect of the workspace area observed in the control experiment, when movement direction is constant, could well depend on some intrinsic shoulder angle as proposed by Soechting and Flanders [20].

We suggest that the hand azimuth for grasping is a combination of two factors. The first and predominant one depends on movement direction. The other one, related to the target direction with reference to the shoulder, is more likely related to the choice of a comfortable posture [18] rather than to movement control per se since it was also observed on the initial hand azimuth before movement. Exploration of a wider workspace would be necessary to examine the combined effect of the posture of the limb and movement direction. Indeed, when the object has to be grasped near the border of the limb workspace, more constraints are exerted on the upper-limb posture and hand orientation [12]. We expect that when grasping objects near the border of the workspace or when starting from extreme postures, the influence of object direction with respect to the shoulder will be greater (and conversely that of movement direction smaller) than for grasping objects located, as in the present study, in the central part of the workspace.

In conclusion, the results show that the hand orientation (azimuth) is primarily determined by the movement direction (vector joining the initial hand position to the target). This rule may be responsible for the correlation between the hand orientation, target location and initial hand position observed in this and in other studies. This implies that hand orientation during reaching to grasp an object is produced in an external rather than in a body-centered (i.e. head- or shoulder-centered) frame of reference. Our observations are consistent with the hypothesis that goal directed movement involves the transition between an initial and a reference equilibrium upper limb configuration [7].

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