ANALYSIS OF HAND-OBJECT ALIGNMENT DURING REACHING-TO-GRASP MOVEMENT

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Abstract: In this study the hand orientation during prehensile movements is investigated. We developed the robot-assisted experimental set-up for 3D measurement of reaching-to-grasp trajectories in versatile conditions that include various objects in different poses. The hypothesis of hand-object alignment during approaching phase of grasping was tested and validated.

Introduction

The complex apparatus of the human hand is used both to grasp objects of different shapes and sizes through the coupled action of multiple digits and to perform the skilled, individual finger movements needed for a variety of creative and practical endeavors, such as handwriting, painting, and playing a musical instrument [1]. Although primates have developed the ability to use individual movements of single digits in special situations, most behavioral use of the hand, even in humans, entails simultaneous motion of multiple digits for one purpose: grasping.

Grasping is a highly dexterous and sophisticated process which makes the human being unique among mammals. Key components include the ability to perceive the qualities of an object and, having decided that it is appropriate to a task, to reach for it, grasp and lift it, manipulate or use it to act on some other object, and finally place it back [2]. Prehension, or reaching-to-grasp movement, requires the solution of several complex problems. Once a target object has been localized, the brain must translate the position, orientation, size, and shape of the object into a set of muscle commands that will bring the hand in contact with it while employing the appropriate hand configuration, aperture, speed and manipulative forces [2]. Grasping is a complex movement which involves rotations of numerous joints. While the pose of object in space may be described by six degrees of freedom (three positional coordinates and three angles of rotation), the hand and arm allow over 30 degrees of freedom [2,3].

The objective of our research is the assessment and evaluation of reaching-to-grasp movements in healthy subjects. We designed and developed the comprehensive experimental set-up for 3D measurement of grasping trajectories [4]. So far, the grasping configuration of the hand was described by the aperture, the term defining the distance between the tips of thumb and index finger [5,6]. The drawback of such representation is that the most of grasping techniques which include all five fingers are observed only through the behavior of the thumb and index finger while the influence of other fingers is ignored. We introduced a new method for evaluating hand preshaping which makes use of all five fingers [4]. The positions of markers attached to the finger-tips were recorded and the adjacent finger-tips were interconnected, thus obtaining a planar pentagon whose various characteristics were investigated. Various parameters of pentagon such as surface area, angle between the pentagon and hand normal vectors, and the angle between the pentagon and object normal vectors were analyzed in order to evaluate the fingers preshaping (fingers opening and alignment to the hand and object) [4].

In this study we investigated the hand orientation during reaching-to-grasp movement. We tested the hypothesis concerning the hand-target alignment in preparation for the grasping act, expressed by Tomovic [7,8]. The hypothesis stated that the normal line to the palmar surface of the preshaped hand will be aligned with the normal line emanating from the center of the grasping zone before the actual enclosure process starts. We measured the prehensile movements during grasping three different objects and analyzed trajectories of angles between hand and object normal.

Materials and Methods

Six right-handed healthy subjects (males, aged 27y ± 2.36) participated in the study. The volunteers did not suffer from any neurological or muscular disorders. Informed consent was obtained from the subjects.

Hand movements were recorded by a 3D tracking system OPTOTRAK/3010 (Northern Digital, Waterloo, Canada). Fourteen infrared-emitting markers, sampled at a frequency of 100Hz, were used. Five markers were attached on the tips of all fingers and three on the dorsum of the right hand (one at the center of the capitate bone and two at the distal end of the metacarpal bone of the 2nd and 4th finger), Fig.1d). Three markers were attached to the object used and three to the table where the subject was seated.

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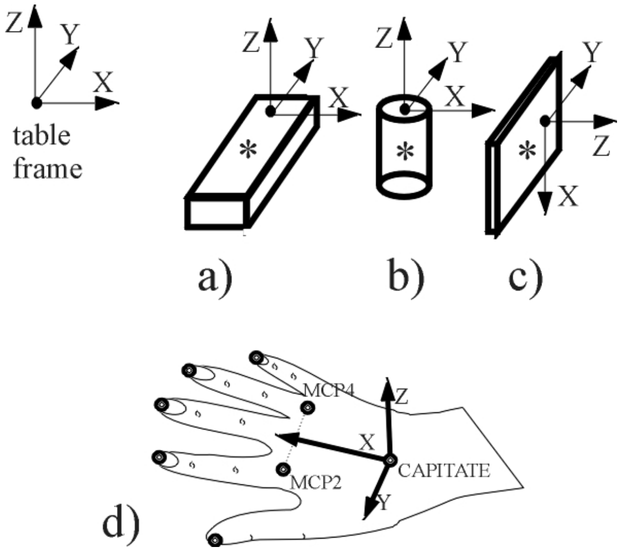

Figure 1. Objects used in the experiment: a) block, b) cylinder, c) plate, (* indicates the object's center of gravity); d) Markers location on the hand and hand reference frame

The subject was asked to grasp three different objects. The objects, made out of glass-reinforced polyester with polyurethane foam, were: *a block* (width=12cm, height=6cm, length=20cm), *a cylinder* (diameter=6cm, height=12cm) and *a thin plate* (thickness=5mm, width=14cm, length=20cm), Fig.1a), b), c). The objects were presented to the subject by means of a robot. A positionally-controlled anthropomorphic 6DOF robot manipulator *Stäubli RX90* was used for precisely moving the objects into selected positions and orientations.

The robot was particularly convenient for generating very fast perturbation in the object's position and orientation. The objects were attached to the robot end-effector by permanent magnets.

The subjects sat comfortably in front of a table (width=64cm, length=50cm and height=78cm), with the right hand placed at the right corner of the table as shown in Fig. 2. All subjects were instructed to reach, grasp and detach the magnet-attached object from the robot end effector, and place it at the center of the table. They were asked to make fast, accurate and natural arm and hand movements while not moving the trunk during the task.

The origin of the table frame was positioned at the back edge of the table so that the **y** axis coincided with the longitudinal axis of the table (Fig. 2). The frames attached to the objects are shown in Fig.1a), b), c). The three objects were placed in different positions or orientations, as explained in Table 1. The block and plate changed the orientation maintaining the same position, while the opposite was true for the cylinder. Five trials of each grasping condition were performed. In case of object perturbation, the robot rapidly moved the objects from initial to final position (or orientation) as shown in Table 2.

The hand coordinate frame was defined using markers attached to the dorsum of the hand, Fig. 1d). The origin of the frame was defined by the marker which was positioned at the center of the capitate bone. The **x** axis pointed from the origin to the middle point between the MCP2 and MCP4 markers. The **z** axis was perpendicular to the plane defined by the three dorsum markers making the **y** axis a cross-product of the axes **z** and **x**.

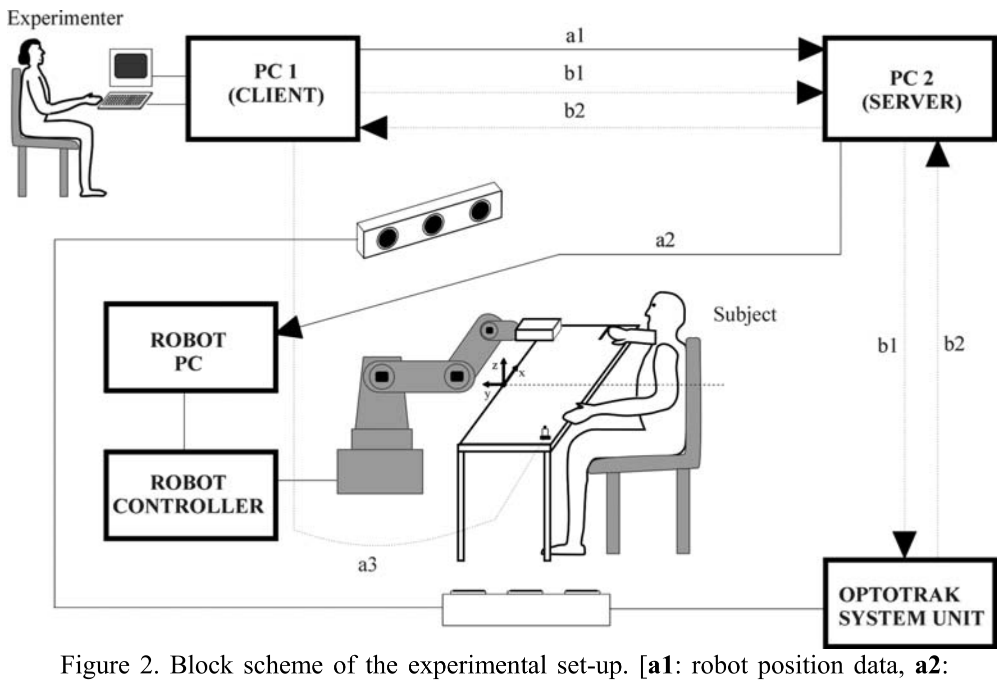

Figure 2. Block scheme of the experimental set-up. [**a1**: robot position data, **a2**: "move robot" command, **a3**: pushbutton signal, **b1**: "start OPTOTRAK acquisition" command, **b2**: OPTOTRAK data]

Table 1: Object position and orientation

Test No.	Object	Test Notation	Position of the COG [cm]			Orientation toward the table frame		
			x_{COG}	y_{COG}	z_{COG}	$\mathbf{x_o}$	$\mathbf{y_o}$	$\mathbf{z_o}$
1	block	HO (horizontal)	24	0	9	$\mathbf{x_t}$	$\mathbf{y_t}$	$\mathbf{z_t}$
2	block	VE (vertical)	24	0	9	$\mathbf{z_t}$	$\mathbf{y_t}$	$\mathbf{-x_t}$
3	cylind.	DL (down-left)	-10	0	10	$\mathbf{x_t}$	$\mathbf{y_t}$	$\mathbf{z_t}$
4	cylind.	UR (up-right)	10	0	30	$\mathbf{x_t}$	$\mathbf{y_t}$	$\mathbf{z_t}$
5	plate	VE (vertical)	24	10	9	$\mathbf{-z_t}$	$\mathbf{y_t}$	$\mathbf{x_t}$

Table 2: Object perturbation

Test No.	Object	Test Notation		Position of the COG [cm]			Orientation toward the table frame		
				x_{COG}	y_{COG}	z_{COG}	$\mathbf{x_o}$	$\mathbf{y_o}$	$\mathbf{z_o}$
6	block	PERT	in.or.	24	0	9	$\mathbf{x_t}$	$\mathbf{y_t}$	$\mathbf{z_t}$
		1	fi.or.	24	0	9	$\mathbf{z_t}$	$\mathbf{y_t}$	$\mathbf{-x_t}$
7	block	PERT	in.or.	24	0	9	$\mathbf{z_t}$	$\mathbf{y_t}$	$\mathbf{-x_t}$
		2	fi.or.	24	0	9	$\mathbf{x_t}$	$\mathbf{y_t}$	$\mathbf{z_t}$
8	cylind.	PERT	in.po.	-10	0	10	$\mathbf{x_t}$	$\mathbf{y_t}$	$\mathbf{z_t}$
			fi.po.	-5	0	15	$\mathbf{x_t}$	$\mathbf{y_t}$	$\mathbf{z_t}$
9	plate	PERT	in.or.	24	10	9	$\mathbf{-z_t}$	$\mathbf{y_t}$	$\mathbf{x_t}$
			fi.or.	24	10	9	rotated by 30°	$\mathbf{y_t}$	rotated by 30°

$\mathbf{x_o, y_o, z_o}$: object frame axes; $\mathbf{x_t, y_t, z_t}$: table frame axes
in.or, fi.or: initial and final orientation; in.po, fi.po: initial and final position
(COG signifies object center of gravity)

The object normal was defined as the **z** unit vector of the object frame, emanating from the top surface of the block (in HO orientation) and from the right side of the plate (as seen in Fig. 1a) and 1c) respectively). In the case of the cylinder we have taken the normal to be the **z** unit vector from the circular surface (as seen in Fig. 1b) since the normal to the lateral surface is never unique. The spatial angle between both normals was then calculated as:

$$\angle\ (\vec{z}_o, \vec{z}_h) = \arccos \frac{\vec{z}_o \vec{z}_h}{|\vec{z}_o||\vec{z}_h|} \qquad (1)$$

where $\vec{z}_o$ and $\vec{z}_h$ are object and hand normal, respectively.

The block scheme of the experimental set-up is presented in Fig. 2. After the subject presses the pushbutton, the object is transferred into a randomly selected initial position and the OPTOTRAK starts to collect the data. After three seconds, the subject is informed by an audio signal to start grasping. In the case of perturbation, the robot moved the object into a new pose 0.3s after the issued audio signal. This movement occurred so rapidly that the object reached the new position (or orientation) before the subject's hand could come in contact with the object. Upon grasping the object the subject detached it from the magnet and placed it at the center of the table. As each grasping attempt was repeated five times, there were all together $5*(4_{block}+3_{cylinder}+2_{plate}) = 45$ recordings for every subject.

All the subjects applied the same grasping technique. The block and the cylinder were grasped using a power, volar grasp involving all fingers and the palmar surface. The block was grasped from the top and the cylinder from the lateral side. The plate was grasped from the front side by a pinch grasp involving all fingers but barely the palm.

The reaching-to-grasp movement started with the palm being lifted from the table and ended with a stable grasp of the object. The start of the movement was determined by the first vertical change of the capitate marker position since it was observed that this marker starts moving before others. The end of the movement was determined as the instant when the inter-finger distances stopped decreasing [9].

Results

Figure 3 shows trajectories of the angles between the hand and object normal, averaged over six participants and five repetitions +/- std. Fig. 3a) presents the angle trajectories during approaching to the block. When grasping the block in HO orientation it can be noticed that the angle maintains almost the constant value of 20°. The situation is similar for the block in VE position where the angle slightly varies between 95° and 100°.

For the perturbated block (PERT 1), during the first 20% of time, the angular trajectory coincides to the trajectory for the block in HO orientation, which is expected since the perturbation PERT1 is consisted of block rotation from horizontal to vertical orientation. At the onset of the perturbation (20% of time) angle starts to increase to the final value which concurs to the angle for the block in VE orientation. This coincidence occurs at the end of the perturbation (80% of time). The opposite can be applied to the angular trajectory for the block perturbated from the vertical to horizontal orientation (PERT2). The trajectory decreases as the block changes its orientation.

To grasp the cylinder and the plate, the hand had to rotate from the initial position by 90°. In case of the cylinder, the hand-cylinder angle changes from app. 20° to app. 70° (Fig.3b). Different positions and perturbation of cylinder position do not influence the shape of the trajectory since the change of position implies the unchanged orientation.

In case of the plate (Fig.3c) when the hand rotates toward the object, the angle decreases from the initial value of 80° toward the final value of 40°.

Discussion and Conclusions

As the block was grasped from the top side, expected angles were as follows: 0° for block in HO orientation, 90° for block (VE), rising from 0° to 90° for block (PERT1), decreasing from 90° to 0° for block (PERT2). In case of cylinder, which was grasped from the side, expected angle should rise from 0° to 90°. In case of plate, it is difficult, rather say impossible, to speak about object-hand alignment since the subjects grasped the object from the front, thin side, using the pinch grasp which does not include the palm.

Let us focus on the angle between hand and block in horizontal position, which has the value of app. 20°, Fig 3a). At the first moment, value of 20° confuses since the expected value was 0°, but we should have on mind the anatomic characteristics of the hand. While the hand lies on the table, palm facing the table, dorsum of the hand is not ideally parallel to the table (the area above the capitate is thicker than the area above MCP bones), and therefore, the hand normal is not ideally aligned with the **z** axes of table and block frame. Instead, this angle has the value of app. 20°. In the light of this fact, it is clearly that hand and object normals are aligned, during the whole movement. The same result was obtained for the block in vertical position where the average angle has the value of 95°, Fig. 3a). Furthermore, results for disturbed movements (PERT1, PERT2) verified expected values.

In case of cylinder, angle rises from the initial value to the final value of 70°, which can be considered as perpendicularity between hand normal and normal of the top surface of the cylinder. The angle increase, which represents the start of hand rotating *i.e.* the hand alignment process, occurs at app. 30% of time, while

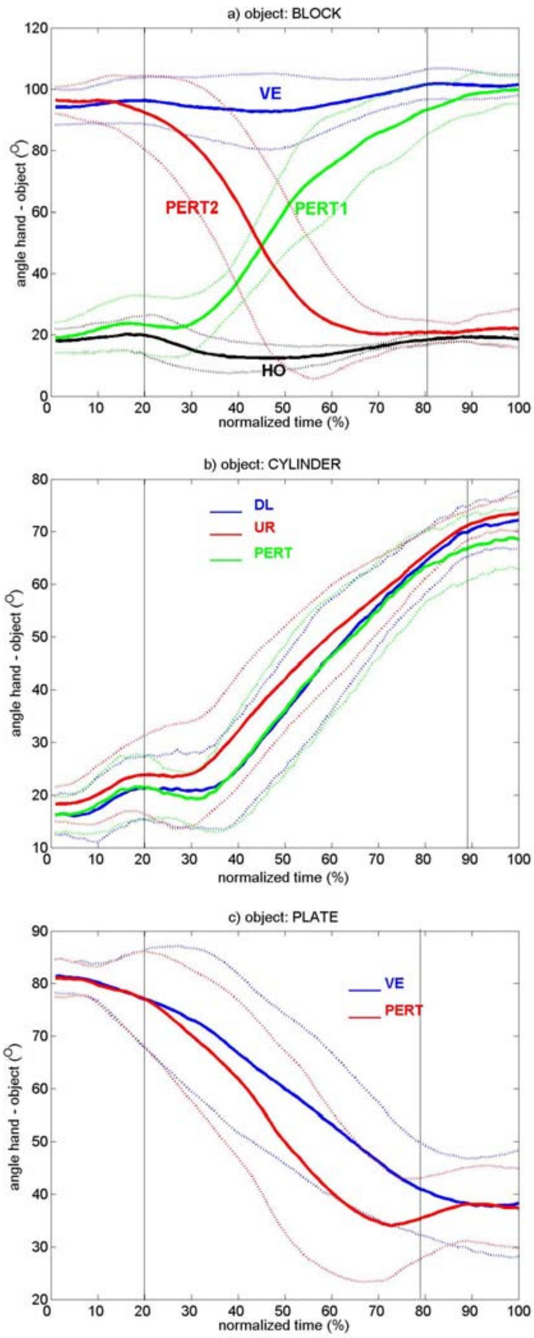

Figure 3: Average angle trajectories between hand and object normal (±std) for a) block, b) cylinder, c) plate. Vertical lines represent start and end-point of object perturbance

the alignment process ends at app. 90% of time, after which the final hand closure occurs.

These facts lead to the conclusion which confirms the Tomovic hypothesis that the preshaped hand will be aligned with the object normal before the actual enclosure process starts. In case of steady objects whose normal is aligned with the hand right from the beginning (block: HO, VE), hand tends to retain the alignment during the whole movement, which results with more-less constant value of the hand-object angle. In case of grasping the objects which require hand

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rotating (cylinder), hand starts to preshape early enough to fully align with the object before the beginning of the enclosure process in the final phase of the grasping movement.

Our research, part of which is presented in this study, is intended to provide a broader insight into the aspects of hand preshaping in grasping tasks, performed by healthy individuals. We expect that the outcomes of the research could provide the guidelines in programming the optimal grasping trajectories in robotic hands.

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