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Estimation of hand preshaping during human grasping

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Abstract

A new method for evaluating hand preshaping during reaching-to-grasp movement is proposed. The method makes use of all five fingers in estimation of prehension. The investigation was performed on six healthy subjects grasping three different objects at various positions and orientations. The objects were presented to the subjects by means of a robot, which also induced perturbations in both object position and orientation. Positions of markers attached to the finger-tips and dorsum of the hand were recorded by means of a 3D optical tracking system. In the data analysis, the adjacent fingertips were interconnected, thus obtaining a planar pentagon whose various characteristics were investigated and discussed. New parameters for the evaluation of finger preshaping, such as pentagon surface area, angle between the pentagon and hand normal vectors, and the angle between the pentagon and object normal vectors were introduced. The proposed pentagon approach is expected to be useful in future work when examining grasping abilities of subjects with neuromuscular disorders.

Keywords: Reaching-to-grasp movements; Hand opening; Finger preshaping; Finger pentagon; Rehabilitation

1. Introduction

The analysis of lower limb movements has been well established in kinesiological research and in the rehabilitation environment for a long time [1]. While human walking can be assessed by analyzing the repeating nature of hip, knee, and ankle joint angles and by measuring the ground reaction forces, it is impossible to apply the same methods to upper limb kinematics and dynamics which are determined by the task and characterized by much more complex movements which are normally not cyclical. Therefore, the introduction of the assessment of arm and hand movements in clinical practice is of utmost importance for improved evaluation of various therapeutical procedures.

In the past 25 years, reaching and grasping studies have often been carried out by cognitive psychologists who attempted to explain how the brain develops and optimizes the reaching paths [2,3]. Jeannerod [4] suggested that the reaching-to-grasp movement consists of two independent components controlled by different visuo-motor channels: a relatively simple transport phase and a more complex prehension phase. More recent studies [5,6] show that hand preshaping appears to be coordinated with hand transport. As stated by Haggard and Wing [6], the pattern of coordination depends both on cognitive factors, such as subject's degree of certainty about the accuracy of hand transport, and lower-level factors responsible for maintaining synergy between preshaping and transport components.

In the field of biomechanics, most upper-limb studies have been oriented towards arm movement, exploring joint angles of shoulder, elbow, and wrist [7,8] with the intention of developing prosthetic limbs and complex rehabilitation therapies such as robotic assistance in neuro and motor rehabilitation [9]. Recent studies dealing with fingers [10,11] are mostly oriented towards measurement and analysis of finger forces or torques, which occur during gripping in finger joints and between fingers and an object.

In this study, we are less interested in arm movement during the approaching phase and grip forces during the contact phase, but more in preshaping of the fingers into an appropriate grip. From the rehabilitation point of view, the approaching phase of the hand represents an important aspect of grasping. It is known that spastic (e.g. stroke or incomplete spinal

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cord injury) patients have more difficulties opening the hand than closing it. Schettino et al. [12] studied the evolution of hand preshaping in Parkinson patients. Their results indicate that these patients are capable of specifying the movement direction, while their hand prehension exhibits substantial deviations.

So far, hand preshaping has usually been described by terms such as hand aperture [6] and hand orientation [13,14]. The term 'hand aperture' describes hand opening during the approaching phase of grasping and is defined as the distance between the thumb and the index finger. The advantage of such a description is its simplicity. Despite the fact that the thumb and index finger probably have an important role in grasping, it should not be forgotten that most of the grasping modes require the cooperation of all five digits and not only the thumb and the index finger. Therefore, such a definition of hand aperture unjustifiably ignores the influence of other fingers. Hand orientation is described by the opposition axis (the line connecting the tips of the thumb and the index finger at the end of movement) and hand azimuth (the projection of the hand longitudinal axis to the horizontal plane). In this case, the opposition axis and the hand azimuth describe the orientation of the palm, while the information about finger orientation towards the palm is missing.

The purpose of this study was to develop a new concept for estimating hand preshaping, which will include all fingers, with the aim of evaluating grasping in the rehabilitation process and in planning grasping modes of multifingered robotic hands.

2. Methods

2.1. Subjects

Six young-adult healthy subjects (average age 27 ± 2.36 year) with no prior history of neurological disorders and neuromuscular injuries have participated in the study. All volunteers were right-handed males who after being informed about the experimental aim of the study gave their consent.

2.2. 3D movement recording

A 3D tracking system OPTOTRAK/3010 (Northern Digital, Waterloo, Canada) was used to precisely record the hand movements during the experiment (Fig. 1). Fourteen infrared-emitting markers were used and measured at a sampling frequency of 100 Hz. Eight markers were attached to the right hand: five on the tips of all fingers and three on the dorsum of the hand (one at the centre of the capitate bone and two at the distal end of the metacarpal bone of the second and fourth fingers). Out of the remaining six markers three were attached to the observed object and three to the table providing us with information about the table and object coordinate systems.

2.3. Instrumentation and experimental set-up

The aim of the experiment was to study various grasping strategies used in interaction with objects of various intrinsic (primarily shape) and extrinsic characteristics (position and orientation). Their sizes and shapes were chosen in such a way that objects used in the experiment corresponded to the objects widely used in daily life (e.g. glass, book, video-cassette, paper file, etc.).

The task presented to the human subject was to grasp three different objects by performing the most natural hand movement. The objects were: *a block* (width = 12 cm, height = 6 cm, length = 20 cm), *a cylinder* (diameter = 6 cm, height = 12 cm), and *a thin plate* (thickness = 5 mm, width = 14 cm, length = 20 cm). The objects were made out of glass-reinforced polyester with a polyurethane foam core, ensuring low object weight.

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 (Fig. 1). We found multiple advantages to using robots in grasping experiments. Firstly, it needs to be emphasized that the experiment could be smoothly controlled by the robot. Once the subject started with the movement, there was no direct interaction between the subject and the experimenter making the measurement process almost completely automated. Secondly, it should be mentioned that the robot movements are highly precise, ensuring exactly the same initial positions of objects in every consecutive experiment. Our intention was also to study the influence of sudden object initial position (or orientation) changes inflicted on grasping movement. The use of the robot was found to be very convenient since, it was possible to move or reorient the object with high velocity and precision.

The object–robot interface was designed as a tray-like structure attached to the robot end-effector. A permanent

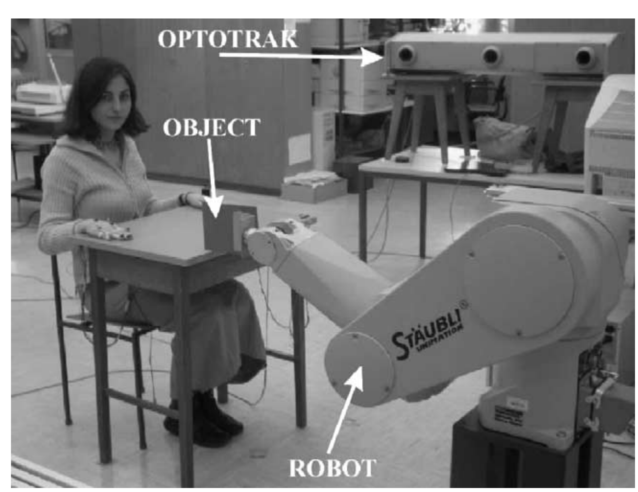

Fig. 1. The object presented to the subject by a robot. Movement was recorded with the OPTOTRAK system.

magnet was mounted on the tray, while a thin iron surface was attached to the bottom of each object. The force of the magnet was chosen in such a way that the magnet was strong enough to carry the object during fast changes of orientation (light weight material was used for objects construction) and yet weak enough to allow easy object lifting from the magnet by the subject.

The subjects were seated comfortably in front of a flat table (width = 64 cm, length = 50 cm, height = 78 cm), as shown in Fig. 2A. It can also be seen that the right hand was placed at the right corner of the table with the palm facing the table and the third finger touching a marked line. With the left hand, a push-button at the left corner of the table was pressed in order to initiate the experiment when the subject was ready. All subjects were instructed to reach, grasp and detach the magnet-attached object, and finally place it at the center of the table. They were asked not to move their trunk during the task and to make fast and accurate arm and hand movements.

For each object we selected different initial positions or orientations. The block object changed only its orientation thus maintaining constant position. It was initially placed in front of the right hand, in the right corner of the table (Fig. 2A) with its longitudinal axis parallel to the subject's sagittal plane, at a distance of 24 cm. The horizontal distance between the tip of the third finger and the block's center of gravity (COG) was 30 cm. The initial orientation of the object was horizontal as seen from Fig. 2A. The coordinate frames were attached to the object and the table. Therefore, for the horizontally oriented block, the object coordinate frame axes corresponded to the table coordinate frame axes. The second orientation was vertical, obtained from the horizontal position rotating the object by 90° counter-clockwise, along the *y*-axis of the object, while not changing the position of the block's COG. The perturbations consisted of rapid changes in block orientation from horizontal to vertical in counter-clockwise direction and back to horizontal in clockwise direction. Therefore, the block was placed in a total of four different configurations: HO (horizontal), VE (vertical), PERT1 (from horizontal to vertical), and PERT2 (from vertical to horizontal).

The cylinder changed its position while maintaining constant orientation. During the perturbation, it was abruptly moved from position 1 to 3 (Fig. 2B). For all three positions the COG remained on a plane, which is parallel to the subject's frontal plane, along the line, which is 45° inclined towards the *x*-axis of the table frame. In each position, the *z*-axis, emanating from the top surface of the object, corresponds to the vertical axis of the table frame. The different cylinder configurations were labeled as: DL (down-left), UR (up-right), and PERT (perturbation of the cylinder).

The plate went through two orientations while maintaining the same position. In the first case, it was placed in front of the right hand of the subject, parallel with the sagittal plane of the subject, as shown in Fig. 3C. In this vertical orientation of the plate, the *z*-axis of the object reference frame, emanating from the right surface of the plate, corresponded to the *x*-axis of the table coordinate frame. During the perturbation the plate was rotated by 30° counter-clockwise, starting from the initial vertical position seen in Fig. 3C. The different configurations of the plate were labeled as: VE (vertical) and PERT (perturbation).

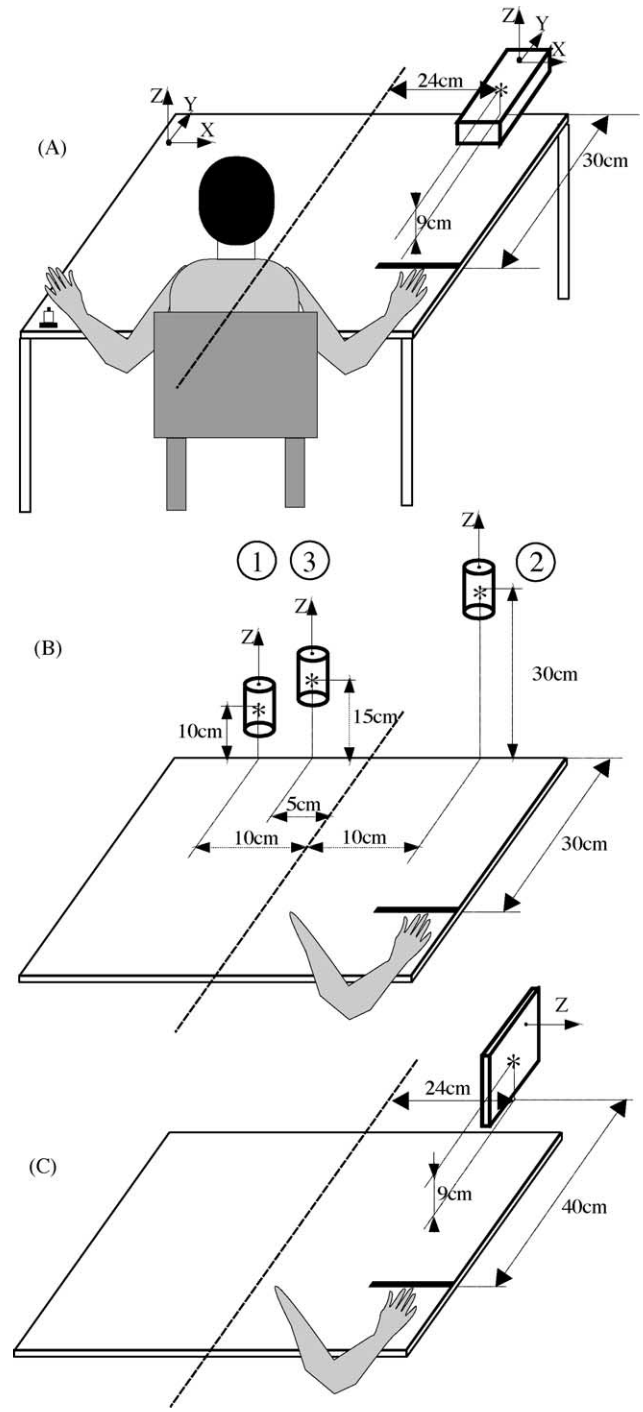

Fig. 2. Experimental set-up: positions and orientations of the block (A), cylinder (B), and plate (C) (* signifies the object COG).

Although the subjects were instructed to grasp the objects in the most comfortable manner, and no precise instructions about the grasp type were given, all the subjects used the

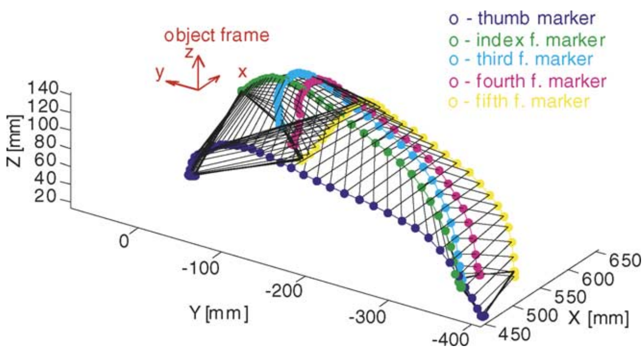

Fig. 3. Trajectory of the fingers pentagon during the reaching-to-grasp movement.

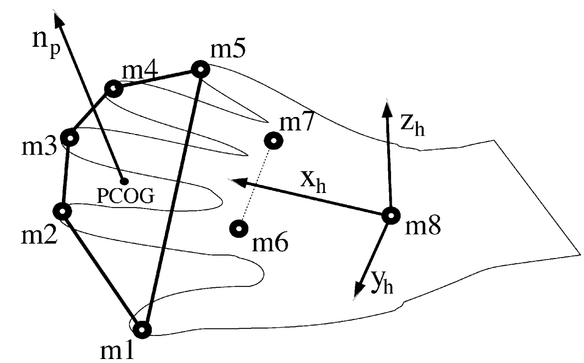

Fig. 4. Position of eight markers on the tips of the fingers and dorsum of the hand. The pentagon connecting the finger markers is characterized by its center of gravity (PCOG) and normal n_p. ($x_h y_h z_h$) represents hand coordinate system.

same grasping approach: the block and the cylinder were grasped by a power, volar grasp involving fingers and the palmar surface. The grip used for grasping the plate was a pinch grasp involving all fingers and barely the palm. We could also deduce that the block was grasped from the top, the cylinder from the side and the plate from the front side, nearest to the subject.

2.4. Experimental procedure

The experimental procedure was always started with a command issued by the experimenter instructing the robot to move the object into the “home” position. The subject, when ready, pressed a push-button on the table and the robot transferred the object into a randomly selected initial position. When the object reached the initial position, OPTOTRAK started with data acquisition. Three seconds later, an audio signal informed the subject to commence with grasping. In the case when there was a perturbation, robot moved the object into a new position (for cylinder) or orientation (for block and plate), 0.3 s 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. OPTOTRAK stopped the data acquisition after 6 s and the subject returned the object back to the robot tray. The experimenter moved the robot back into the “home” position and the procedure continued until five trials of object grasping in all previously described positions and orientations were recorded. As each grasping attempt was repeated five times, there were all together $5 \times (4_{block} + 3_{cylinder} + 2_{plate}) = 45$ recordings for every subject.

2.5. Data processing

The reaching-to-grasp movement started with lifting of the palm from the table and finished with a stable object grasp. The purpose of detaching the object from the tray at the robot end-effector and placing it on the table was primarily to obtain a movement as natural as possible and was out of the scope of our interest.

The movement onset was determined as the first change of the capitate marker position since we have always observed that this marker starts moving before the others do. The end of the movement was determined with the moment when the vertical and horizontal positions of all finger markers stabilized for a while, prior to a new change caused by lifting the object and placing it on to the table. The endpoint of the movement was further determined by observing the point where the interfinger distance stopped decreasing [15]. The time normalization of all the assessed data was performed. The marker trajectories were plotted against the percentage of the movement duration.

The hand coordinate frame was defined using markers positioned at the dorsum of the hand, as shown in Fig. 4. The frame origin was defined by the m8 marker, which was positioned at the center of the capitate bone. The x_h-axis points from the origin to the middle point between m6 and m7 markers positioned on metacarpophalangeal joints of second and fourth finger. The z_h-axis is perpendicular to the plane defined by the three dorsum markers making the y_h-axis a cross-product of the axes z_h and x_h.

We defined the *fingers pentagon* as a planar shape interconnecting the markers of adjacent fingertips. Since all finger markers never lie in the same plane, we selected three markers defining the pentagon plane, while the markers of the remaining two fingers were perpendicularly projected onto the plane. Taking into account the leading role of the thumb and index finger in grasping, we defined this plane with these two markers while the third marker was chosen between the third and fourth finger. It was assumed that the fourth finger plays a minor role in grasp formation. Therefore, a selection was made between two plane definitions: thumb–index finger–third finger (‘123 digits’) and thumb–index finger–fourth finger (‘124 digits’) plane. Table 1 states the distances between real and projected marker positions for the remaining fingers. It can be deduced that the average distances (i.e. errors) have considerably lower values for the ‘124 digit’ plane. Therefore,

Table 1
Selection of the markers defining the pentagon plane according to the mean distances between the real and projected positions of markers of the remaining two fingers for '123 digits' and '124 digits' plane

Object	Mean distance (±S.D.) (mm)			
	123 digits plane		124 digits plane	
	4th digit	5th digit	3rd digit	5th digit
Block (HO)	6.1 (±2.6)	15.8 (±9.2)	3.1 (±1.2)	8.6 (±4.2)
Block (VE)	7.6 (±2.9)	18.0 (±6.9)	3.5 (±1.6)	9.1 (±2.7)
Block (PERT1)	7.5 (±3.8)	19.8 (±9.5)	3.6 (±1.9)	9.2 (±1.7)
Block (PERT2)	6.6 (±1.8)	15.8 (±8.4)	3.0 (±1.1)	8.6 (±4.3)
Cyl (DL)	10.5 (±2.4)	28.0 (±3.0)	5.6 (±1.2)	12.3 (±2.7)
Cyl (UR)	12.6 (±1.5)	32.4 (±2.7)	6.8 (±0.9)	14.0 (±2.5)
Cyl (PERT)	11.3 (±2.7)	29.8 (±7.6)	6.3 (±1.9)	13.0 (±4.9)
Plate (VE)	9.1 (±1.9)	24.8 (±4.1)	4.6 (±0.8)	10.8 (±3.6)
Plate (PERT)	9.3 (±2.5)	25.6 (±7.7)	4.8 (±1.2)	11.3 (±4.8)
Mean (±S.D.)	8.9 (±2.2)	23.3 (±6.2)	4.6 (±1.4)	10.7 (±2.0)

Distances are averaged for six subjects, over five repetitions and for the whole duration of the movement.

the plane defined by the thumb, index, and fourth finger was chosen as the pentagon plane.

An example of the pentagon spatial visualization is shown in Fig. 3. The figure presents a trajectory of the pentagon toward the block in horizontal position, as assessed for one of the tested subjects.

Three pentagon characteristics were analyzed. The *first* parameter was pentagon surface area denoted as PSA, which describes hand opening. The peak value of PSA hence represents maximal hand opening. The *second* parameter was defined to be the angle between the pentagon normal emanating from the pentagon center of gravity and the hand normal defined by the z_h-axis of the hand coordinate frame. Here, it must be noticed that the direction of the pentagon normal is the same as the direction of a normal defined by a triangle connecting the tips of the thumb, index, and fourth finger. The pentagon, pentagon normal n_p, and hand normal z_h are presented in Fig. 4. The angle between the pentagon and hand normals describes the fingers preshaping with regard to the dorsum of the hand. As the *third* parameter we have introduced the angle between the pentagon and object normals, which indicates the fingers preshaping with regard to the object. 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. 2A and C, 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. 2B) since the normal to the lateral surface is never unique. The spatial angle between both normals was then calculated as:

$$\angle(\vec{n}_p, \vec{z}) = \arccos \frac{\vec{n}_p \vec{z}}{|\vec{n}_p||\vec{z}|}$$

where $\vec{n}_p$ is the pentagon and $\vec{z}$ is the hand or object normal.

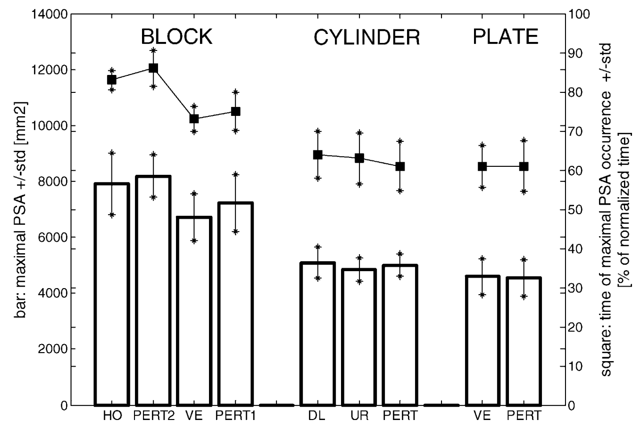

Fig. 5. Maximal pentagon surface area (±S.D.) (columns) and time of occurrence (black squares), for all objects and their positions and orientations.

3. Results

3.1. Pentagon surface area

PSA is first increasing and afterwards decreasing during the approaching phase of grasping. The curve is bell shaped and characterized by a single peak whose value and time-of-occurrence vary, depending on the characteristics of the object to be grasped. Fig. 5 shows the maximal PSA values and corresponding times of occurrence together with appertaining standard deviations, averaged over six subjects and five repetitions of the grasping movement. It can be observed that maximal PSA depends on the object shape and the area of the object surface towards which the hand approaches. PSA has the highest values for the largest object, i.e. block. The lowest values of maximal PSA occur for the thin plate. Different orientations of the block obviously also influence the maximal PSA. The value for the block in HO orientation is noticeably higher then for the block in VE orientation. Also, the perturbation of the block during grasping influences the hand opening. Maximal PSA is higher for PERT2 orientation of the block with regard to its HO orientation and similarly for PERT1 with regard to VE orientation. In the case of the cylinder, the maximal PSA values remain constant, regardless of the position and perturbation of the object. The perturbation also had no effect on maximal PSA in case of a thin plate. According to Fig. 5, the time of occurrence of maximal PSA is clearly related to the value of maximal PSA: the higher the value of the maximal PSA, the later its occurrence.

3.2. The angle between the pentagon and the hand normal

Fig. 6 shows the trajectories of the angles between the pentagon and hand normals. All curves start to ascend almost linearly at the beginning, which indicates that fingers preshape with regard to the hand already at the onset of hand movement. After reaching the peak, curves decrease to their final values, which depend on the object shape. It can be

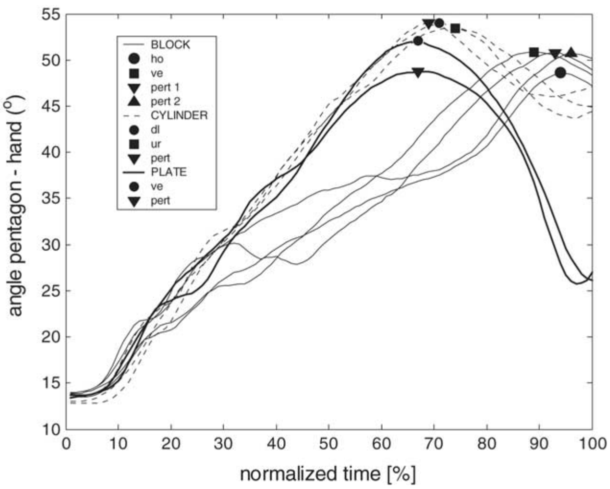

Fig. 6. Average angle trajectories between the pentagon and hand normal vectors for all objects.

observed that, regardless of the object type or its extrinsic characteristics, maximal angles always have the value of approximately 50°. Comparing the time of maximal PSA in Fig. 5 and the time of maximal angle occurrence in Fig. 6 it can be observed that they are closely related.

3.3. The angle between the pentagon and the object normal

Fig. 7 shows trajectories of the angles between the pentagon and object normals, for all objects and their positions and orientations. Fig. 7a presents the angle trajectories during approaching to the block. When grasping the block in HO orientation it can be noticed that the angle slightly increases from the initial value of approximately 0° towards 30°. The situation is similar for the block in VE position where the angle increases from approximately 90° towards 100°. This minor angular change leads to the assumption that the subject tends to preshape the fingers in such a manner that the pentagon normal is aligned with the normal emanating from the object grasping surface during the whole course of the approaching movement. The angular trajectories for perturbed objects (PERT1, PERT2) confirm the latter observation since, after the object reaches the final orientation (at approximately 80% of time), the angles attain similar values to those found for static objects (positions HO and VE in Fig. 7a). In PERT1 case, the angle trajectory starts to slightly increase even before the onset of the perturbance. However, the difference between angles for PERT1 and HO cases is within the limits defined by standard deviation for static block in HO 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 pentagon-cylinder angle similarly changes from approximately 0° to 100° (Fig. 7b), which means that the pentagon normal almost perpendicularly aligns with the object normal emanating from the top surface of the cylinder. The shape of the curve remains the same, regardless of the object position or perturbation.

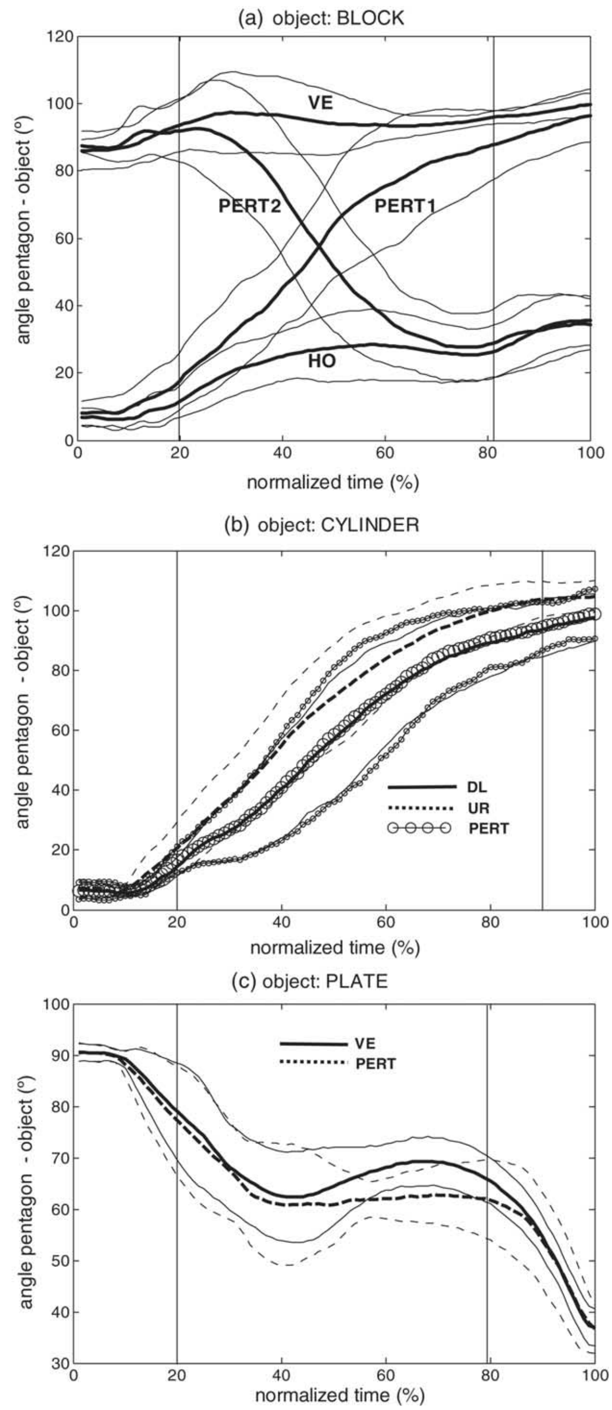

Fig. 7. Average angle trajectories between pentagon and object normal (±S.D.) for (a) block, (b) cylinder, and (c) plate. Vertical lines represent start and end-point of object perturbance.

In case of the plate (Fig. 7c) when the hand rotates toward the object and when the fingers preshape, the angle decreases from the initial value of 90° toward the final value of 35°. The curves were weakly influenced by the object perturbation.

It is interesting to observe that while the pentagon-cylinder angle trajectory continuously increases as fingers gradually preshape with regard to the object (Fig. 7b) the pentagon-plate angle trajectory on the other hand becomes saddle shaped, with the interval of constant angular values (between approximately 35 to 85% of time). The reason could be the fact that the initial hand-plate distance is lower than the distance between the hand and the cylinder (for all positions). Thus, while in case of the cylinder the hand gradually rotates during the whole duration of the movement, the subject has to act more quickly in case of the plate. He quickly rotates the hand in the first 35% of time (causing the decrease of pentagon-plate angle) and then continues to transport it towards the object at the same orientation and closes the fingers for grasp only in the closest vicinity of the object (85–100% of time).

4. Discussion and conclusion

In this paper, a method for quantitative estimation of human prehension during reaching-to-grasp movement was proposed. The approach makes use of a planar pentagon, which is obtained by interconnecting the tips of adjacent fingers. Several pentagon characteristics were analyzed and proposed as parameters for quantitative evaluation of hand preshaping.

The pentagon surface area describes hand opening during the approaching phase. Jeannerod [4] has identified that hand aperture correlates with the object size and that the maximum aperture occurs in the second half of the movement, at 60–80% of the approaching phase [16]. Our study confirms his statement. The maximal PSA (Fig. 5), representing maximal hand opening, has the highest values for the largest objects, although this relation is not linear (maximal PSA values for a thin plate are only slightly lower than those for a cylinder). The orientation of the object influences the fingers preshaping in the case when changing orientation of an object causes a change in the size of object surface to which the hand approaches. When changing the block orientation from horizontal to vertical, different maximal PSA values were obtained, while different orientations of the plate did not influence maximal PSA values. Position changes and perturbations of the cylinder, during which the size of the object surface to which the hand approaches remains the same, did not influence the hand opening at all. On the other hand, an orientation perturbation of the block causes a larger hand opening than when grasping a static block. In conclusion we can say that the object orientation, position or perturbation influence the PSA only in the case they change the size of object surface to which the hand approaches.

MacKenzie and Iberall [3] stressed the hypothesis that preshaping the hand seems to be fundamentally different than enclosing the hand around the object. Our findings about pentagon-hand angle support their hypothesis. Maximal angles always have constant values (Fig. 6) and immediately follow the maximal hand opening represented by peak PSA. This leads to the conclusion that at the onset of hand closure, fingers always tend to preshape with regard to the hand in an equivalent way, regardless of the target characteristics. At the end of the hand enclosure, in the closest vicinity of the object, fingers preshape with respect to the object, which leads to different final pentagon-hand angles for different objects.

According to another hypothesis stated by MacKenzie and Iberall [3,17], in order to obtain a stable grasp, fingers tend to be placed on the object surface in such a way that the line connecting the thumb and index finger is perpendicular to the surface on both sides. With having in mind the new aspect of prehension description presented in this study, the hypothesis can be generalized with regard to all five fingers. According to the angles between the pentagon and block normals, all fingers tend to preshape in such a manner that the pentagon plane is more or less parallel to the block surface (Fig. 7a). When grasping the cylindrical object, subjects tend to preshape fingers in such a way as to obtain the perpendicular alignment between the pentagon normal and the normal emanating from the top surface of the cylinder (Fig. 7b).

Several aspects of hand prehension described by the pentagon concept were exposed in this work. The pentagon concept provides plenty of information concerning grasping during the reaching-to-grasp movement. In our opinion, the pentagon concept gives a new hitherto unexplored perspective towards the evaluation of grasping, whose various aspects should be further investigated. We can conclude that the pentagon approach involves all five fingers and is therefore more informative than hand aperture used in previous studies [6]. Future directions of research include measurements in patients (post-stroke, incomplete spinal cord injuries, muscle dystrophy) with the intention of evaluating the functional progress in the rehabilitation process and an assessment of the improvements after drug intervention. When transferring the described method into the clinical environment, we plan to use a more simple system based on instrumented gloves.

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