Division of reach-to-grasp trajectories into phases

TAMARA SUPUK[1], TADEJ BAJD[2], VLASTA ZANCHI[1]
[1]Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture - FESB, University of Split
Rudjera Boskovica bb, CROATIA
[2]Faculty of Electrical Engineering, University of Ljubljana,
Trzaska 25, SLOVENIA

Abstract: - In this paper the evaluation of approaching trajectories assessed during grasping performed by healthy subjects is described. The investigation including grasping of three different objects in various poses and 3D recording of the fingertips trajectories was undertaken in 6 healthy volunteers. The aim of the research was the division of the reach-to-grasp movement into characteristic phases. The potential use of the approach for rehabilitation purposes is discussed.

Key-Words: - reach-to-grasp movements, fingertip spatial trajectory, grasping movement phases, rehabilitation

1 Introduction

Grasping is highly dexterous and sophisticated process which makes the human being unique among mammals. Due to its complexity, the research of grasping still lags behind that of the human gait. While gait laboratories are widely spread in the biomechanical, clinical, and rehabilitation environment, the “arm&hand” laboratories are still in a very rudimentary phase of development. In such laboratory one would be in position to study the approaching phase, grasping forces, and the dexterity or coordination of the fingers. The approaching phase of grasping and hand opening are of utmost importance in disabled persons such as patients with pronounced spasticity. The ultimate goal of our research is the evaluation of hand movements in rehabilitation environments.

The stride phases (stance phase and swing phase, further divided into subphases, [1]) are well established in gait analysis while the division of the grasping movement into phases is rather demanding task. While human walking is a cyclical process and the gait phases can be clearly distinguished, the grasping movement is highly complex and depends on many factors such as target shape, position, orientation, perturbation, hand-object distance and presence of obstacles. Tomovic et al. [2] stressed that in the case of the reaching movements an infinite number of options is available in the selection of approach trajectories to the target. They depend on the approach direction, the grasping mode and the shape of the target [2]. The approach, introduced by Jeannerod [3], suggests that the grasping movement consists of two components: the transport component (the movement of the wrist toward the object) and the preshaping of the fingers (grip component). The aim of this paper is to investigate whether some characteristic phases of grasping movement can be recognized. We analyzed the direct approaching trajectories toward objects of different extrinsic and intrinsic characteristic properties with the aim to identify specific phases common to all grasping movements and independent of any object characteristic or grasping mode used. The Cartesian projections of the spatial trajectories of the capitate marker (representing the movement of the wrist i.e. the transport component of the grasping movement) and its velocity, acceleration and jerk trajectories, together with the hand aperture and aperture velocity, were closely analyzed.

2 Methods

Six right-handed healthy subjects (males, aged 23 to 30 years) 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 centre of the capitate bone and two at the distal end of the metacarpal bone of the 2nd and 4th finger), Fig 1. Three markers were attached to the object used and three to the table where the subject was seated. 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 1.

TABLE 1
OBJECT POSITION AND ORIENTATION

Test	Object	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	24	0	9	$\mathbf{x_t}$	$\mathbf{y_t}$	$\mathbf{z_t}$
2	block	24	0	9	$\mathbf{z_t}$	$\mathbf{y_t}$	$\mathbf{-x_t}$
3	cylind.	-10	0	10	$\mathbf{x_t}$	$\mathbf{y_t}$	$\mathbf{z_t}$
4	cylind.	10	0	30	$\mathbf{x_t}$	$\mathbf{y_t}$	$\mathbf{z_t}$
5	plate	24	10	9	$\mathbf{-z_t}$	$\mathbf{y_t}$	$\mathbf{x_t}$

TABLE 2
OBJECT PERTURBATION

Test	Object		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	i.o.	24	0	9	$\mathbf{x_t}$	$\mathbf{y_t}$	$\mathbf{z_t}$
		f.o.	24	0	9	$\mathbf{z_t}$	$\mathbf{y_t}$	$\mathbf{-x_t}$
7	block	i.o.	24	0	9	$\mathbf{z_t}$	$\mathbf{y_t}$	$\mathbf{-x_t}$
		f.o.	24	0	9	$\mathbf{x_t}$	$\mathbf{y_t}$	$\mathbf{z_t}$
8	cylind.	i.p.	-10	0	10	$\mathbf{x_t}$	$\mathbf{y_t}$	$\mathbf{z_t}$
		f.p.	-5	0	15	$\mathbf{x_t}$	$\mathbf{y_t}$	$\mathbf{z_t}$
9	plate	i.o.	24	10	9	$\mathbf{-z_t}$	$\mathbf{y_t}$	$\mathbf{x_t}$
		f.o.	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
i.o, f.o: initial and final orientation; i.p, f.p: initial and final position
(COG signifies object center of gravity)

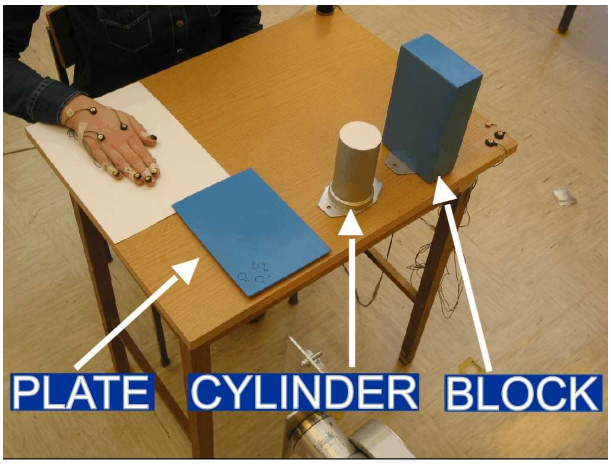

Fig 1. *Objects used in the experiment and subject's hand with Optotrak markers*

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.

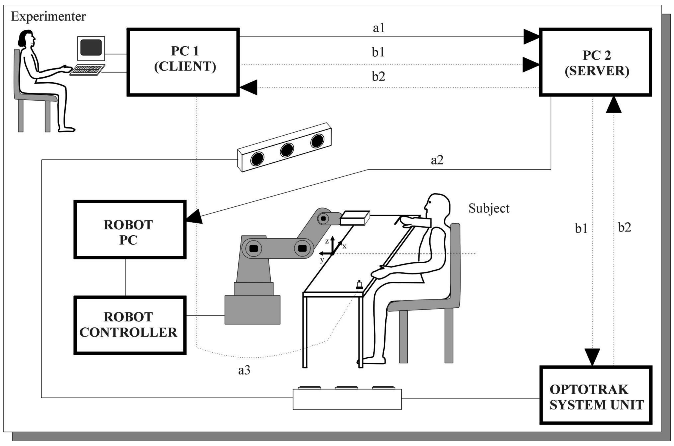

Fig 2. *Block scheme of the experimental set-up. After the subject presses the pushbutton, the object is transferred into a randomly selected initial position and the OPTOTRAK starts to collect the data. After three seconds, the subject is informed by an audio signal to start grasping. In the case of perturbation, the robot moved the object into a new pose 0.3s after the issued audio signal.*
*[**a1**: robot position data, **a2**: "move robot" command, **a3**: pushbutton signal, **b1**: "start OPTOTRAK acquisition" command, **b2**: OPTOTRAK data]*

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 3. 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 3d. 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**.

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.

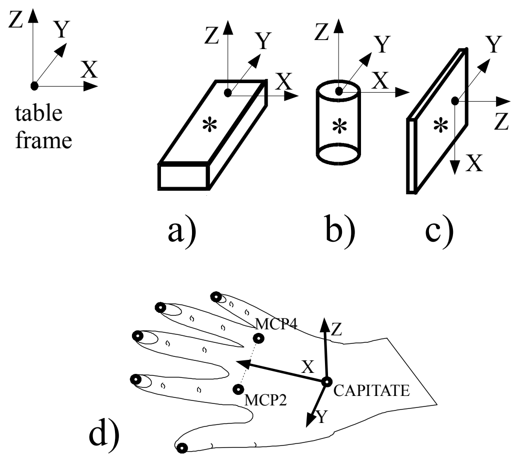

Fig 3. *Coordinate frames attached to the objects and the hand (* indicates the object's center of gravity)*

The reach-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 [4]. The rectangular components of the velocity V_x, V_y, and V_z were calculated by numerical differentiation of X, Y and Z table-frame projections of the spatial trajectories of all hand markers. We have observed horizontal, vertical and tangential velocities. Horizontal velocity V_H was calculated as:

$$V_H = \sqrt{V_X^2 + V_Y^2} \quad (1)$$

where V_X and V_Y are the X and Y components of velocity. Vertical velocity V_z was equated to the Z component of velocity. Tangential velocity V_T was calculated as:

$$V_T = \sqrt{V_X^2 + V_Y^2 + V_Z^2} \quad (2)$$

Accelerations a_H, a_Z and a_T were calculated by numerical differentiation of horizontal, vertical and tangential velocity. All calculated velocities, accelerations and jerks were filtered by discrete Fourier transformation and higher harmonics were eliminated. The cut-off frequency was set to the seventh harmonic. Time normalization of all the assessed data was performed.

3 Results

Fig 4 shows X, Y and Z trajectories of the capitate marker.

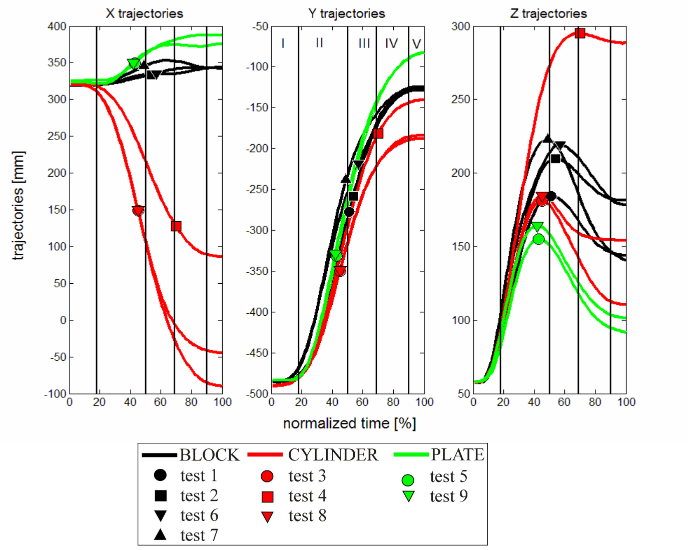

Fig 4. *The X, Y, and Z trajectories of the capitate marker for all three objects in different positions or orientations. The resultant trajectories were averaged over six participants and five repetitions of the grasping movement. Markers indicate maximal vertical positions Z. Grasping movement phases are separated by the vertical lines and denoted as I, II, III, IV, and V.*

The X trajectory represents the movement in the medio-lateral plane, and has, therefore, negligible values for the block and the plate tasks where the respective objects were positioned in front of the hand. The Y trajectory represents the approaching of the hand towards the object, while the Z trajectory represents hand lifting. The Y projection is predominantly linear during the reach-to-grasp movement (20%-70% of movement duration) while the vertical projections display a characteristic curvature which can be best interpolated by the parabolic segments [2]. Fig 5. shows the tangential velocity trajectories of the capitate marker. The curves are bell shaped, as it was already observed [6], reaching the maximum value at 40% (±5%) of the duration of the movement. Fig 6. shows the trajectories of hand opening represented by the surface area of the pentagon obtained by interconnecting the tips of the neighboring fingers, and denoted as PSA [7]. Focusing on the trajectories in Figures 4, 5, and 6, together with the trajectories of tangential acceleration, jerk (time derivative of acceleration), the horizontal and vertical components of velocity and acceleration of the capitate marker, as well as the rate of change of the PSA (which are not presented in this paper), we can distinguish several phases of the grasping movement, which are common

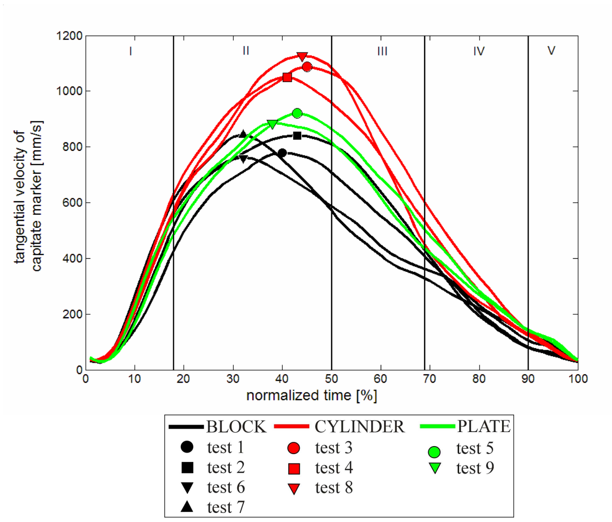

Fig 5. *Tangential velocity of the capitate marker for all three objects in different orientations (positions), averaged over subjects and experiment repetitions. Markers denote peak values. Grasping movement phases are separated by vertical lines.*

for all objects, regardless of their shape, distance, orientation and perturbation.

The first phase is represented by hand lifting from the table, which lasts for approximately 18% (±3%) of time and is characterized by relatively constant X and Y trajectories of the capitate marker (Fig 4). Hand opening does not occur during this phase and the PSA value is also constant (Fig 6). This phase is characterized by rapid vertical and tangential velocity increase (Fig 5), and maximal vertical and tangential acceleration occurring at 11% (±2%) and 12% (±2%) of the total reach-to-grasp movement. The end of the phase is determined by first minimum of the tangential jerk.

During *the second* phase, between approximately 18% (±3%) and 50% (±8%) of reaching to grasp duration, the hand starts to approach horizontally toward the object (change of X and Y values) while lifting is continued. During this phase horizontal, vertical and tangential velocities increase toward the maximal values occurring at 40% (±8%), 22% (±3%), and 40% (±5%) of the grasping movement (Fig 5) and the hand-opening starts (Fig 6). The end of this phase is determined by the hand reaching the maximal vertical position.

During *the third* phase, the hand starts descending toward the object, the velocity is decreased as hand opening increases. Minimal horizontal and tangential accelerations occur at 59% (±8%) and 65% (±9%) respectively. The end of this phase is determined by the maximal hand opening, at approximately 69% (±8.5%) of time (Fig 6). At the coinciding moment (at approximately 67% (±7%)), the hand reaches the minimum of vertical velocity.

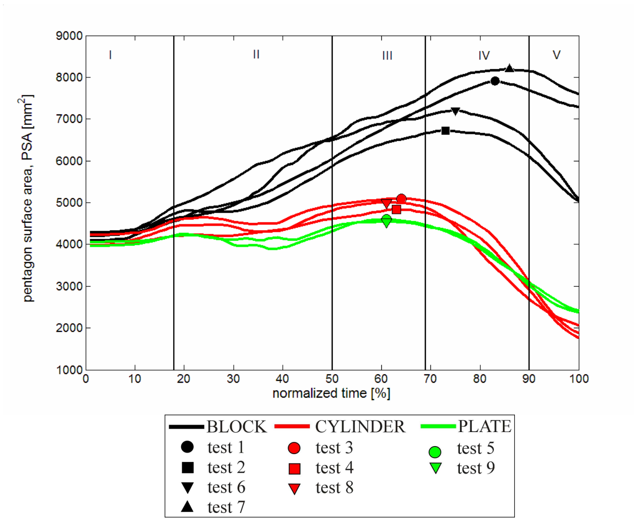

Fig 6. *Hand opening described by PSA, averaged over subjects and experiment repetitions. Grasping movement phases are separated by vertical lines. Markers denote peak values.*

The fourth phase is characterized by rapid hand closure (Fig 6) while the hand is continuing with horizontal approach and descent toward the object, however more slowly than during the third phase.
This phase ends by reaching the maximum absolute value of the aperture change which occurs at 90% (±2.8%) of the reach-to-grasp movement.

By the end of the fourth phase the hand reaches its final position and during the last, *fifth* phase X, Y and Z positions of the capitate marker remain constant. During this phase the hand closes around the object and final grasp occurs.

Although the peak of the tangential velocity occurs for all objects in short time interval (Fig 5), some interesting information can be extracted from the measurements. Generally, the longer the distance to be traveled by the hand, later the peak velocity occurred, as already observed by Paulignan et al [4]. The mean peak velocity first occurred for the block, whose center of gravity was the closest to the hand, then for the plate and finally for the cylinder whose center of gravity was the most distant from the hand. Secondly, the amplitude of the peak velocity also depends on the hand-object distance, in the similar way as the time of occurrence. Thirdly, by observing the curves for each object separately, it can be noticed that the wrist reaches the peak velocity first in the case of the perturbated objects (change of orientation for block and plate). In the case of cylinder, maximal velocity for the perturbated object (test 8) occurs at the same moment as that of the static cylinder (test 3).

4 Discussion and Conclusion

In this paper a method of assessment of reach-to-grasp trajectories and their division into characteristic phases was presented. Two aspects of reach-to-grasp movement were observed, the transport component presented by the trajectory of the wrist marker and the hand opening described by the pentagon square area. Wrist trajectory was analyzed in details: horizontal, vertical and tangential velocities, accelerations and jerks were analyzed, together with the PSA and PSA velocity trajectories. It is shown that, despite of high complexity of grasping movement and various tasks that human hand is capable to execute, some characteristic phases of the movement can be recognized. We showed that the hand does not start to approach horizontally toward the object from the very beginning of the movement. During first 18% (±3%) of reach-to-grasp movement the trajectory is predominantly vertical, while during the *second* phase, hand starts with the horizontal approach. During this phase hand reaches the maximal velocity and lifts toward the highest vertical position, after which, during the *third* phase, descents and decelerates. Meanwhile, the fingers continue to open until the maximal aperture occurs at the end of the *third* phase. In some cases, when the object is positioned in a higher place, as in test 4, the hand reaches maximal vertical position rather late (at 69% of movement duration, Fig 4). Therefore, it should be considered to join the *second* and the *third* phase into a single phase represented by hand lifting and opening until reaching maximal values of vertical position and aperture. The *fourth* and *fifth* phase are characterized by hand closure.

The goal of this study was to establish the criteria for the evaluation of the reach-to-grasp movement in healthy persons. The next step in our research will involve measurements in subjects with specific hand impairments in order to observe the differences in reaching movements between this group and the healthy group. We believe that comparing the reaching movement phases obtained in this paper with the phases assessed in subjects who have difficulties in hand opening, it will be possible to plan the rehabilitation process more effectively.

Acknowledgements:

The first author whishes to thank to Dr. sc. Gregorij Kurillo, Dr. sc. Timotej Kodek and the staff of the Laboratory of Biomedical Engineering and Robotics from the Faculty of Electrical Engineering at the University of Ljubljana for their help during setting-up the experimental environment. This work was partially supported by the Croatian Ministry for Education, Science and Sport and Ministry of Republic of Slovenia for Education, Science and Sport.

References:

[1] J. Perry, *Gait analysis: normal and pathological function*, Thorofare: Slack Inc., 1992.

[2] R. Tomovic, D. Popovic, R. B. Stein, *Nonanalitical methods for motor control*, Singapore: World Scientific Publishing Company, 1995.

[3] M. Jeannerod, Intersegmental coordination during reaching at natural objects, In: J. Long, A. D. Baddeley (eds) *Attention and Performance*, IX. Erlbaum, Hillsdale, NJ, pp.153-169, 1981.

[4] Y. Paulignan, V. G. Frak, I. Toni, M. Jeannerod, Influence of object position and size on human prehension movements, *Exp. Brain Res.*, vol. 114, pp. 226-234, 1997.

[5] A. P. Georgopoulos, J. F. Kalaska, J. T. Massey, Spatial trajectories and reaction times of aimed movements: effects of practice, uncertainty and change in target location *J. Neurophysiology*, vol. 46, pp. 725-743., 1981.

[6] P. Morasso, Three dimensional arm trajectories, *Biol. Cybern*., vol. 48., 1983, pp.187-194.

[7] T. Supuk, T. Kodek, T. Bajd, Estimation of Hand Preshaping During Human Grasping, *Medical Engineering & Physics*, **27(9)**, 2005, pp.790-797