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Assessment of reach-to-grasp trajectories toward stationary objects

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ABSTRACT

Background: Patients with pronounced spasticity reveal difficulties in hand opening during the approaching grasping phase. The general description and assessment procedures of reach-to-grasp movement for rehabilitation purposes is still not established. There is a necessity to develop a universal methodology to describe the approaching phase in grasping which would allow clinical evaluation of movement pathologies.
Methods: In the paper, the evaluation of approaching trajectories assessed during grasping by healthy subjects is described. The experiment, undertaken by 7 healthy volunteers, consisted of grasping three different stationary objects positioned in various poses by a robot. 3D recordings of the hand and fingertip trajectories were performed. The kinematic trajectories of the hand and finger markers were analysed in order to evaluate the reach-to-grasp movement.
Findings: The results of the kinematic analysis suggest that the reach-to-grasp movement of a healthy subject can be divided into 3 dominant phases (*hand acceleration, hand deceleration,* and *final closure of the fingers*).
Interpretation: The presented evaluation method can provide relevant information on the modalities the hand preshapes and approaches toward the object in order to obtain a stable grasp. The potential use of the approach for rehabilitation purposes is discussed.

1. Introduction

Grasping is a highly dexterous and sophisticated process which makes human beings unique among mammals. Due to its complexity, research into grasping still lags behind that of human gait. While kineziological laboratories are widely spread in the rehabilitation and sport environments, laboratories for upper extremity evaluation are still in a rudimentary phase of development. In such a laboratory one would be in a position to study the approaching phase, grasping forces, and the dexterity or coordination of the fingers. The ability to reach, grasp, transport, and release objects is essential for performing activities of daily living, such as eating and grooming (Butler et al., 2010). The approaching phase of grasping and hand preshaping are of great importance in disabled persons, such as patients with a certain degree of spasticity like children with cerebral palsy (Coluccini et al., 2007; Ronnqvist and Rosblad, 2007), or people afflicted by Parkinson's disease (Ansuini et al., 2010). Standardized protocols for three-dimensional upper limb motion analysis, however, still do not exist (Jaspers et al., 2009). With more universal methodology describing reach-to-grasp movements, similar to gait analysis, it would be possible to make clinical evaluations of reaching movements.

The stride phases (stance phase and swing phase, further divided into subphases, (Perry, 1992)) are well established in gait analysis, while the division of the grasping movement into phases is a rather demanding task. Human walking is a cyclical process and the gait phases can be clearly distinguished. In contrast, the grasping movement is highly complex, and depends on many factors such as the target shape, position, orientation, perturbation, hand-object distance, and presence of obstacles (MacKenzie and Iberall, 1994). Behavioural studies showed that intrinsic and extrinsic object properties influence both the selection of the type of grip and the grasp kinematic implementation (Gentilucci, 2002; Goodale et al., 1994; Jakobson and Goodale, 1991). Tomovic et al. (1995) stressed that in the case of reaching movements an infinite number of options are available in the selection of the approach trajectories to the target. The selection depends on the approach direction, the grasping mode, and the shape of the target (Tomovic et al., 1995). Reaching trajectories have been the scope of scientific interest for more than the past two decades. An early study by Morasso (1983) investigated arm trajectories based on hand velocity profiles. Nowadays, the limitations of recording techniques are overcome by modern motion-tracking systems which allow detailed insight into spatial trajectories, not only of the arm, but also of the hand and fingers.

Jeannerod (1981) proposed a new approach, suggesting that the grasping movement consists of two independent components: the transport component (i.e. the movement of the hand toward the object) and the grip component (i.e. preshaping of the fingers). This

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"traditional approach" allowed noticeable development in the research of grasping over the past 20 years (Smeets and Brenner, 1999).

Since Jeannerod's original article, a number of reports have suggested that the channel controlling hand aperture has access to information about the progress of hand transport (Haggard and Wing, 1991, 1995; Paulignan et al., 1991). The studies suggest that hand aperture appears to be coordinated with hand transport. Smeets and Brenner (1999) proposed an alternative description of grasping which consists of determining suitable positions on the object – based on its shape, texture, etc. – and moving the thumb and fingers more or less independently to the determined positions.

This paper describes an attempt to divide the reach-to-grasp movement into characteristic phases by simultaneously observing two aspects of the movement (hand transport and fingers preshaping). We identified three dominant phases of reach-to-grasp movement. Some recent studies (Sangole and Levin, 2008a, b) already reported on the identification of several grasping phases during hand shape modulation. However, the main focus of their study was the description of the palmar cavity during hand preshaping, and to that end, Sangole and Levin introduced a new valuable biomechanical parameter called the kinematic transverse palmar arch, which quantitatively describes the ability to shape the palmar cavity to accommodate the object in a secure hand-object interface. However, in the case of reach-to-grasp phase identification, they only based their method on the observation of temporal trajectories of the wrist tangential velocity. In our approach, the transport component is described by several kinematic parameters such as hand-object relative distance, tangential velocities, and accelerations, while hand opening is described by the surface area of a pentagon defined by interconnecting the fingertips (Supuk et al., 2005). Our approach thus provides a more detailed description of reach-to-grasp movement phases. The ultimate goal of our research is the evaluation of hand movements in rehabilitation environments.

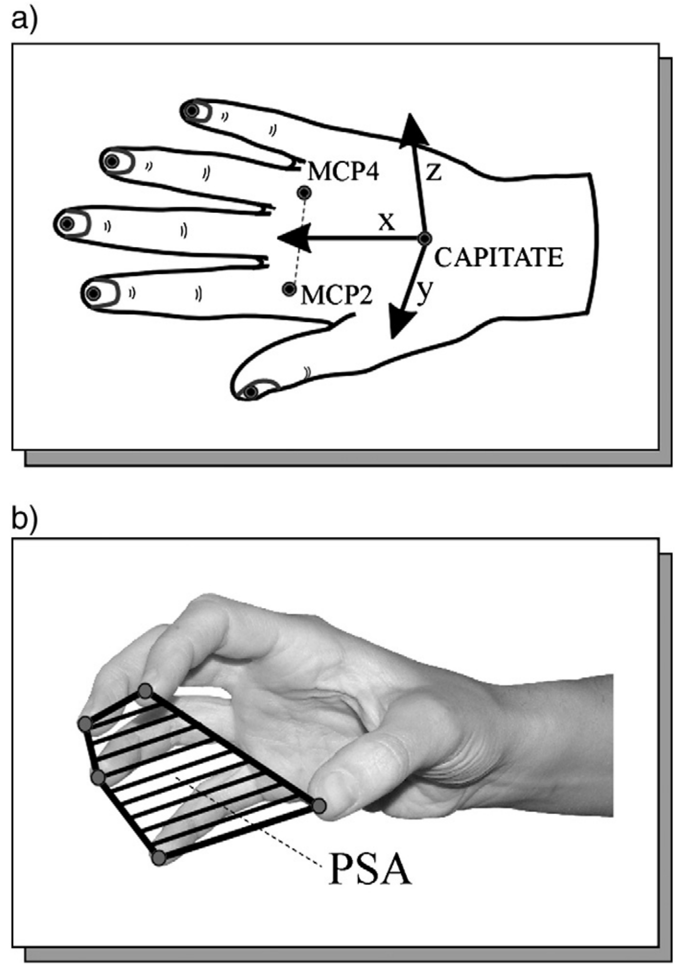

Fig. 1. a) Markers location on the hand and hand reference frame. b) Pentagon obtained by interconnecting the markers of adjacent fingertips and pentagon surface area (PSA) representing hand opening.

2. Methods

2.1. Participants

Seven right-handed, healthy male individuals (mean age 27 (SD 2.31) years), with no neurological or muscular disorders, participated in the study. Prior to the investigation, all subjects were informed of the test procedures and gave their consent to participate.

2.2. Experimental setup

Hand and finger movements were recorded by a contactless optical measuring system, OPTOTRAK/3010 (Northern Digital, Waterloo, Canada). Fourteen infrared-emitting markers, sampled at a frequency of 100 Hz, were used. Five markers were attached on the tips of the fingers and three markers were positioned on the dorsum of the right hand; one at the centre of the capitate bone (denoted capitate marker) and two at the distal end of the metacarpophalangeal (MCP) bone of the 2nd and 4th finger (denoted MCP2 and MCP4 markers) (Fig. 1a). Three markers were also attached to the object, and three were attached to the table where the subject was seated. The hand coordinate frame was defined by the markers attached to the dorsum of the hand as shown in Fig. 1a. The origin of the frame was defined by the marker which was positioned at the centre of the capitate bone. The x axis pointed from the origin to the midpoint between the MCP2 and MCP4 markers. The z axis was perpendicular to the plane defined by the three dorsum markers, while the y axis was defined as the cross-product of the axes z and x to define the right-handed coordinate system. We have decided to use the MCP4 marker for the hand-frame definition, instead of the marker attached to the metacarpophalangeal joint of the little finger, to provide a rigid base for the coordinate system definition. The fifth metacarpophalangeal joint is prone to relative movement with respect to the remaining markers or the dorsum due to palm arching during hand closure. The origin of the table coordinate frame was positioned at the backside edge of the table, with the **y** axis coinciding with the longitudinal axis of the table (Fig. 2b). The coordinate frames attached to the objects used in the experiments are shown in Fig. 2a.

The assessment of reach-to-grasp movement was performed for three different objects: *block* (width = 12 cm, height = 6 cm, length = 20 cm), *cylinder* (diameter = 6 cm, height = 12 cm) and *thin plate* (thickness = 5 mm, width = 14 cm, length = 20 cm) (Fig. 2a). Their sizes and shapes were chosen in such a way that objects used in the experiment corresponded to the objects used widely in daily living (e.g. glass, book, paper file or magazine). The objects were made of glass-reinforced polyester with polyurethane foam. A position-controlled anthropomorphic robot manipulator *Stäubli RX90* (Stäubli GmbH, Bayreuth, Germany) with six degrees of freedom was used to precisely place the objects into predefined positions and orientations in front of the subject. The objects were attached to the robot end effector using permanent magnets to allow for easy detachment and attachment during the experiments.

During the assessment, the subjects were seated comfortably in front of a rectangular table (width = 64 cm, length = 50 cm and height = 78 cm), with their right hand placed at the right corner of the table as shown in Fig. 2b. All subjects were instructed to reach, grasp,

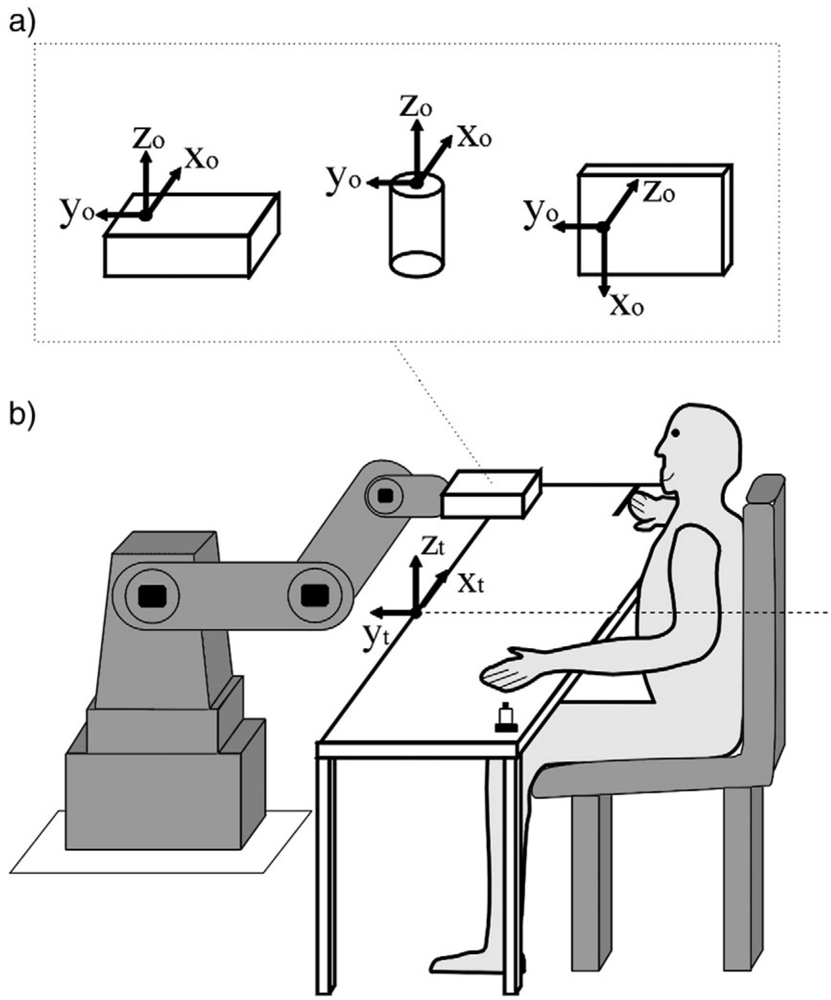

Fig. 2. a) Objects used in the experiment (block, cylinder and plate). b) Scheme of the experimental set-up.

and detach the object from the robot end effector, and place it at the centre of the table. They were asked to make fast, accurate and natural arm and hand movements while restricting any movement to the trunk.

The three objects were placed in different positions or orientations, as explained in Table 1 (Tests 1 to 5). The block has changed its orientation whilst maintaining the same position, while the position was changed for the cylinder. Five trials were performed for each grasping condition, and therefore $5*7_{subjects}*(2_{block}+2_{cylinder}+1_{plate})=175$ reach-to-grasp trials were recorded in total.

Table 1
Object distance from hand at movement on-set, position and orientation.

Test	Object	Hand-object distance[a] [mm]	Position of the object COG[b] [mm]			Orientation toward the table frame		
			x_{COG}	y_{COG}	z_{COG}	x_o	y_o	z_o
1	block	370	240	0	90	x_t	y_t	z_t
2	block	384	240	0	90	z_t	y_t	$-x_t$
3	plate	410	240	100	90	$-z_t$	y_t	x_t
4	cylind.	483	-100	0	100	x_t	y_t	z_t
5	cylind.	513	100	0	300	x_t	y_t	z_t

x_o, y_o, z_o: object frame axes; x_t, y_t, z_t: table frame axes (see Fig. 1).
[a] Hand-object spatial distance is determined as the Euqlidian distance between the capitate marker on the hand in its initial position and the capitate marker recorded at the end of the movement.
[b] COG signifies the object's centre of gravity.

2.3. Experimental procedure

At the beginning of the experimental procedure, the selected object is in its “home” position. After the subject initiates the procedure by pressing the pushbutton, the object is moved by the robot into a randomly selected initial position. Simultaneously the OPTOTRAK starts to collect the marker location data. After 3 s, the subject is informed by an audio signal to start the task. After grasping the object, the subject detaches the object and places it at the marked position on the table surface. For the start of the next trial the robot is moved back to the “home” position.

All the subjects applied the same grasping technique. The block and the cylinder were grasped using a 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 and thumb without using the palm.

2.4. Data processing

The reach-to-grasp movement starts with the palm being lifted from the table and ends with a stable grasp of the object. The start of the movement was determined from the measured outputs by analysing the vertical component of the capitate marker position. The results show that this marker starts moving before the others. The end of the movement was determined from the time instance at which the inter-finger distances stopped decreasing, indicating that the object is fully grasped (Paulignan et al., 1997). All recordings were analysed through MATLAB (The Mathworks Inc.), where they were firstly smoothed by using a second order, 10 Hz dual-pass Butterworth filter, and normalised with respect to the movement duration. An inter/intra-subject variability analysis of spatial trajectories of all markers was carried out. Variability, denoted as V, was calculated as follows (Paulignan et al., 1997):

$$V = \sqrt{(SDx)^2 + (SDy)^2 + (SDz)^2} \tag{1}$$

Where SD x, SD y, and SD z are standard deviations of the x, y, and z marker positions in mm. The variability results, presented in the Results section, show small variability across subjects, therefore, for clarity, we present the average kinematic data in the charts. The trajectories of all reach-to-grasp parameters presented in this paper were averaged over 7 subjects and 5 repetitions of each trial.

The parameters which describe the reaching component of the hand (determined from the spatial trajectories of the capitate marker) were hand-object distance, tangential velocity, and tangential acceleration. Hand-object distance, which indicates the relative distance between the hand and object during the reaching movement, was determined as the Euqlidian distance between the capitate marker (as measured during the reaching movement) and the location of the same marker at the end of the movement when the object was fully grasped. The tangential velocity was obtained as follows:

$$\mathrm{V_T} = \sqrt{\mathrm{V_X^2} + \mathrm{V_Y^2} + \mathrm{V_Z^2}} \tag{2}$$

where the velocity components 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 the capitate marker. Tangential acceleration was calculated by numerical differentiation of the tangential velocity.

In order to observe hand opening during the reaching movement, we defined a pentagon interconnecting the markers of adjacent fingertips (Supuk et al., 2005) (Fig. 1b). The temporal trajectories of the pentagon surface area, denoted as PSA, describe the level of hand opening. Since the value of this parameter clearly depends on the hand size, the PSA trajectories were normalised to the subject's hand size (obtained as the initial PSA value in resting position) prior to averaging. The peak value of PSA represents the maximal hand opening. We introduced the pentagon concept as an alternative approach to the hand aperture defined as the distance between the tips of the thumb and index finger (Haggard and Wing, 1998). Despite the important role of the thumb and index finger, the majority of grasping modes require the coordinated movement of all five digits and not only the thumb and index finger. Therefore, such a definition of hand aperture provides insufficient information about finger preshaping (Supuk et al., 2005). The numerical differentiation of PSA trajectories was performed to obtain the rate of hand opening, denoted as dPSA/dt.

2. Results

Fig. 3 presents the inter-subjects variabilities (top row) and intra-subject variabilities (bottom row) of the spatial trajectories of the capitate marker (used for the calculation of the transport parameters of the reaching movement: hand–object distance, tangential velocity and acceleration), and of the spatial trajectories of markers attached to the tips of the thumb and index finger (dominant fingers in the calculation of PSA values). In the top row of Fig. 3 it can be observed that the inter-subjects variability has low values. Maximal variability, V = 25.6 mm, is obtained for the index finger marker while grasping the block (test 1), while all other variabilities have lower values. In the bottom row of Fig. 3 the intra-subject variabilities for the three subjects are shown; only those variabilities with the highest values are presented. It can be noticed that the intra-subject variabilities have lower values with respect to the inter-subjects variabilities, as expected. Maximal intra-subject variability (V = 12.1 mm) is obtained for the capitate marker while grasping the block (test 1). All other intra-subject variabilities have lower values. From the variability analysis presented above, it can be concluded that the tested healthy subjects display similar motor patterns, and it is therefore reasonable to average the trajectories of reach-to-grasp parameters over subjects and repetitions of experiments.

Fig. 4 presents the hand-object relative spatial distance during the reaching movement. Since the objects were placed in different positions and distances from the hand in its initial position, the trajectories obtained were normalised according to the initial hand-object distance, and presented as a percentage of the total hand-object distance. Matching the shapes of the trajectories indicates that when the hand approaches the object, the relative distance between the hand and object decreases in a similar manner, regardless the object position.

Fig. 5 presents the kinematic trajectories of the capitate marker. Tangential velocity trajectories are shown in Fig. 5a. The curves are bell shaped, as it was already observed (Morasso, 1983), reaching a maximum value at 41.8% (SD 2.3%) of the duration of the movement. This value is obtained by averaging the peak times for all five tests. Fig. 5b presents corresponding tangential acceleration curves. The maximum acceleration of the hand is reached at 12.2% (SD 1.64%) of the total time, while the minimum value is reached at 66.8% (SD 3.6%) (Fig. 5b). The times of velocity peaks are also marked in Fig. 4 with different point shapes for each test.

Fig. 6a and b show the trajectories of PSA and its time derivative which represents the rate of hand opening. PSA increases during the first part of the approaching movement and then decreases during the second part (Fig. 6a). The curve is characterised by a single peak which depends on the size and shape of the object to be grasped. The PSA velocity trajectories are characterised by a minimum value which occurs at 92.6% (SD 1.6%) of the total time (Fig. 6b).

Focusing on the trajectories shown in Figs. 4, 5, and 6, we made an attempt to distinguish the dominant phases of grasping movement which could be applicable to the majority of reaching movements toward stationary objects, regardless the object position, distance, orientation or shape. It can be concluded that the distinguishing feature in the reach-to-grasp movement is the peak of the velocity profile (Fig. 5a) which divides the reaching movement into a hand acceleration phase (positive values of tangential acceleration) and hand deceleration phase (negative values of acceleration) (Fig. 5b). Although the peak of the tangential velocity occurs for all five tests in a short time interval (at 41.8% (SD 2.3%) of the total movement time) (Fig. 5a) some interesting information can be extracted from the recordings. Generally, the longer the distance to be travelled by the hand, the later the peak velocity occurred, as already observed by Paulignan et al. (1997). The mean peak velocity first occurred for the block, whose centre of gravity was the closest to the hand. The velocity peak times for the plate and the cylinder whose centre of gravity was furthest from the hand, occurred at later times respectively. Secondly, we observed that the amplitude of the peak velocity depends also on the hand-object distance, in a similar way to the time of its occurrence. It is interesting to observe the location of the hand at the moment of reaching peak velocity. In Fig. 4 the times of the velocity peaks are marked on hand-object spatial distance trajectories. It can be seen that at the moments of peak velocities, the hand is 60.6% (SD 5.1%) distant from the object. In other words, at the peak velocity, the hand travelled 39.4% (SD 5.1%) of the total hand-object distance.

The PSA trajectories are discussed in detail by Supuk et al. (2005). Here we can shortly report that the maximal hand opening represented by PSA value depends not only on object size, but also

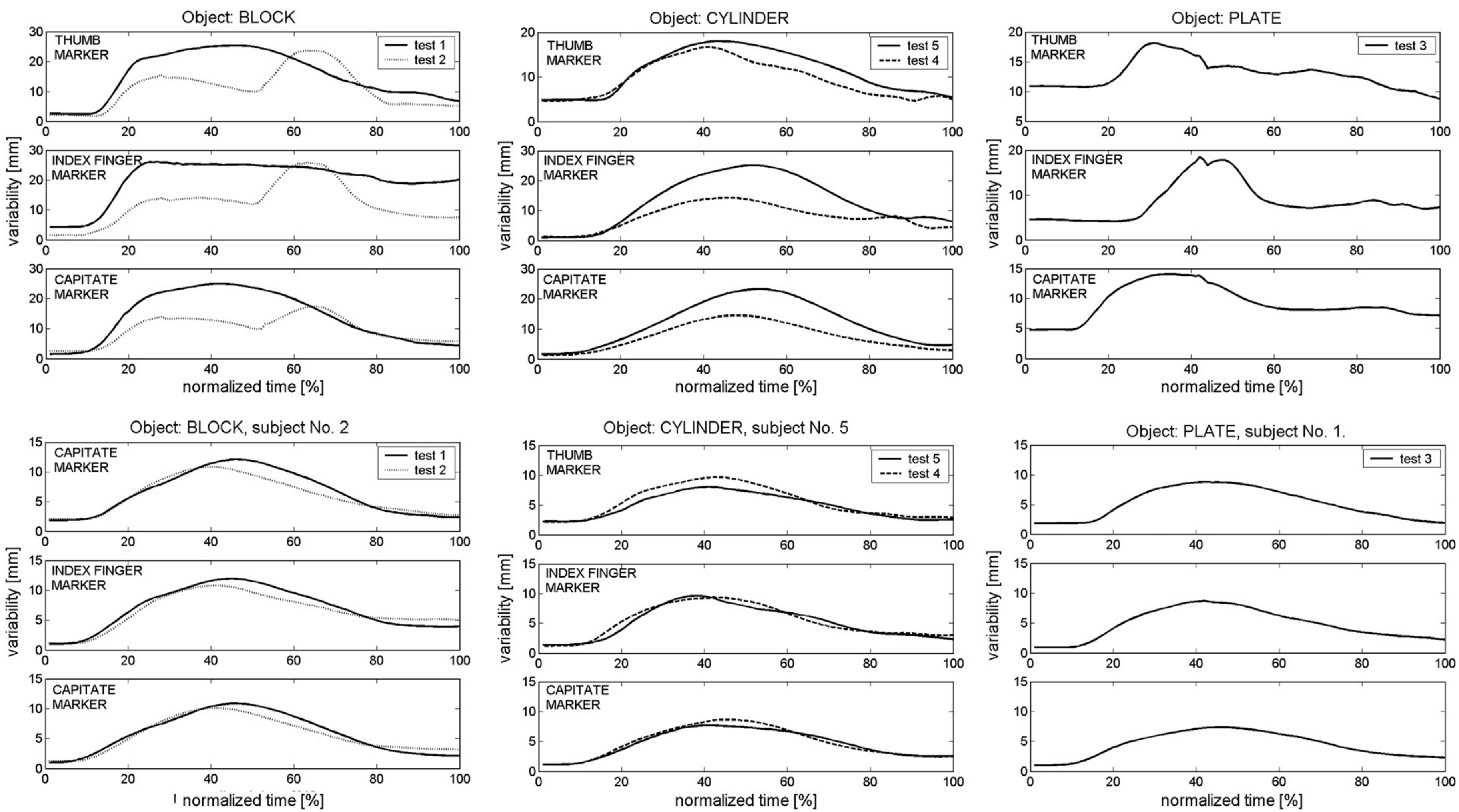

Fig. 3. Inter-subjects variabilities (top row) and intra-subject variabilities (bottom row) of spatial trajectories of thumb, index finger and capitate marker for all reach-to-grasp tests.

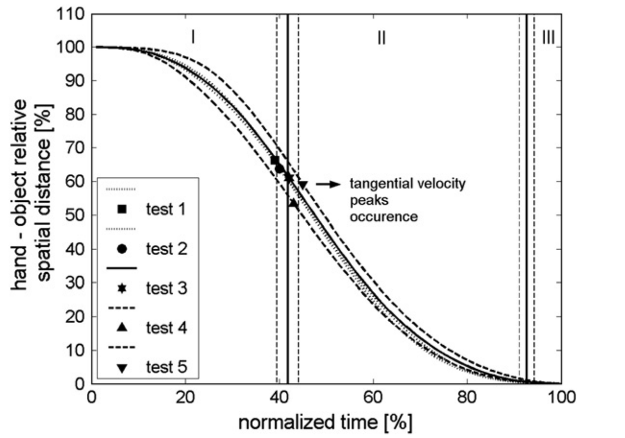

Fig. 4. Hand-object relative spatial distance for all five tests (see Table 1). Reach-to-grasp movement phases are separated by vertical solid lines and denoted as I, II, and III. Dashed lines represent +/−SD of phase duration.

on the shape and the area of the object surface towards which the hand approaches. According to Fig. 6a, the time of occurrence of the maximal PSA is clearly related to the value of the maximal PSA. With a higher maximal value, the time of occurrence of the maximal PSA is further delayed. After reaching the peak of PSA, the fingers are closing and the values of d(PSA)/dt are negative (Fig. 6b). It can be observed that peak values of d(PSA)/dt trajectories occur at 92.6% (SD 1.6%) (Fig. 6b), when the hand-object relative distances stop decreasing (Fig. 4), that is, the hand has reached its final position and the final grasp of the fingers occurs.

4. Discussion

In summary, taking into consideration the transport component of the reach-to-grasp movement described by Figs. 4 and 5, and the prehension component described by Fig. 6, three dominant phases of reaching the stationary objects can be identified: *hand acceleration phase*, *hand deceleration phase*, and *final closure of the fingers.* Subsequent phases are separated by the vertical lines shown in Figs. 4, 5, and 6, and marked by I, II, and III.

4.1. Phase 1, hand acceleration (0–41.8% (SD 2.3%) of movement duration)

During the initial phase of the reaching movement, the subject is focused on accelerating the hand in order to reach the peak velocity. Maximum acceleration is reached at an early stage of the phase, at 12.2% (SD 1.64%) of total time. Prior to the acceleration peak, the process of fingers opening does not occur since the PSA trajectories retain their initial values (Fig. 6). After the acceleration peak, the fingers start preshaping, although that does not necessary imply that the fingers are opening and PSA trajectories are increasing; in some cases (test 3) the PSA values fall below the initial value. At the end of this phase, the hand has travelled 39.4% (SD 5.1%) of the total hand-object distance and has reached the peak tangential velocity.

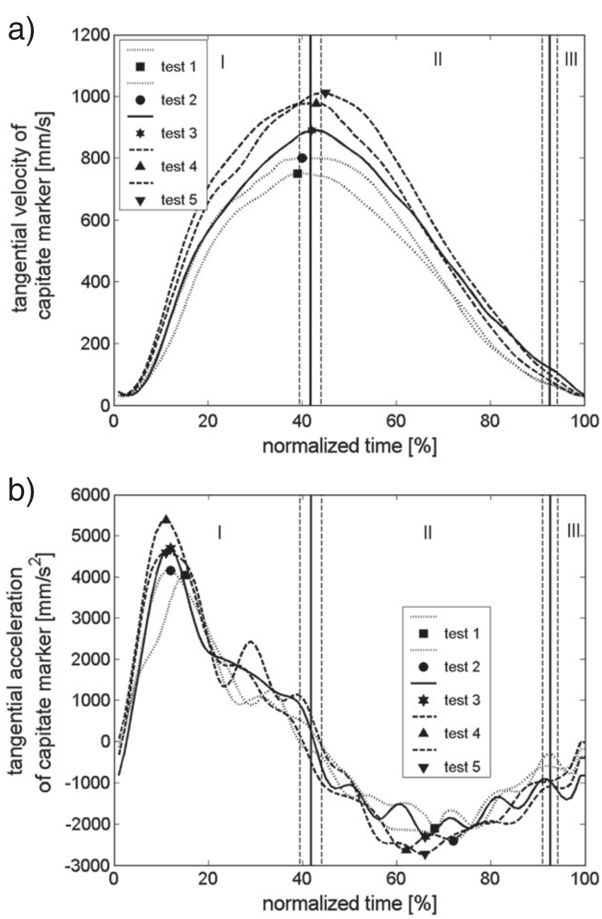

Fig. 5. Tangential a) velocity b) acceleration of capitate marker. Markers denote peak values. Reach-to-grasp movement phases are separated by vertical solid lines and denoted as I, II, and III. Dashed lines represent +/−SD of phase duration.

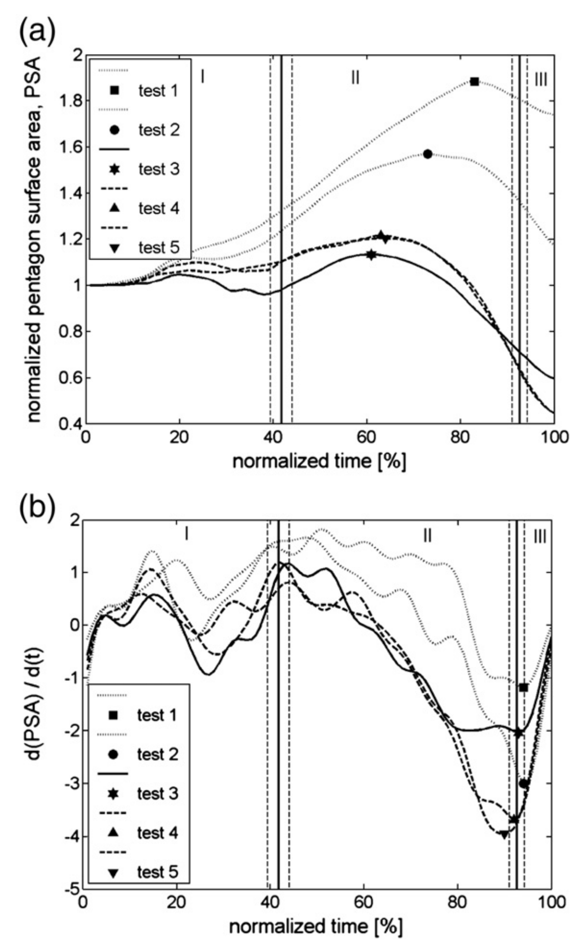

Fig. 6. Hand opening described by a) PSA trajectories, b) PSA time derivative. Markers denote peak values.

4.2. Phase 2, hand deceleration (41.8% (SD 2.3%) – 92.6% (SD 1.6%) of movement duration)

During the second phase, the subject decelerates the hand and the focus is more on the fingers opening. Fingers are continuously opening until the PSA peak is reached (Fig. 6a). Times of PSA peaks vary significantly, since it is already identified that they depend on the value of the PSA peak. This phase is characterised by reaching the deceleration peak which occurs at 66.8% (SD 3.6%), at half of the total phase duration (Fig. 5b).

4.3. Phase 3, final closure of the fingers (92.6% (SD 1.6%) — 100% of movement duration)

At the end of second phase, transportation of the hand toward the object finalises, and during the third phase the subject is focused on the final closing of fingers around the object in order to obtain a stable grasp. At the onset of this phase the rate of hand closing is at its highest (peak values of d(PSA)/dt in Fig. 6b), and then decreases toward zero-values.

5. Conclusion

The complexity of the grasping process, highly dependent on target features, implies the use of different grasping techniques determined by multiple characteristics such as hand and finger trajectories, hand orientation toward the object, finger opening, etc. It is a rather demanding task to identify some of the features that would be common to all grasping movements. Therefore, we have included in our study a number of different objects with various intrinsic and extrinsic properties to investigate whether we can identify some general phases of the reach-to-grasp movements in everyday activities. Based on our experiments we found three characteristic phases which describe the reach-to-grasp movement.

A wide variety of motor disorder conditions, such as cerebral palsy, strokes, and Parkinson's disease (PD) greatly affect the performance of reach-to-grasp movements (Ansuini et al., 2010; Ramos et al., 1997; Rash et al., 1999, Ronnqvist and Rosblad, 2007). Schettino et al. (2004) showed that PD patients are capable of specifying the movement direction, but their hand prehension exhibits substantial deviation. About one-third of cerebral palsy cases have spastic hemiplegia (O'Reilly and Waltenynowicz, 1981). The typical pattern of such spasticity includes ulnar deviation and flexion of the wrist with the thumb adducted and flexed into the palm (Dahlin et al., 1998). Such a deformity makes it difficult to grasp and manipulate different objects. Some recent findings (Sangole and Levin, 2009) provided additional insight into how a stroke impacts on hand configuration during the performance of functional hand tasks in patients with hemiparesis after a stroke. Thus, it is very important to evaluate reaching with quantitative methods for rehabilitation practitioners and researchers, to objectively describe the coordination and functional status of the impaired upper limb (Chang et al., 2005).

The future work should include much larger number of healthy people of different age groups to confirm if the findings presented in this paper are consistent across such population. Future work could also involve measurements of subjects with specific hand impairments, in order to observe the differences in reaching movements between an impaired and healthy group. We believe that by comparing the reaching movement phases described in this paper with the phases assessed in patients, it may be possible to detect which characteristic phase parameters are delayed or missing in a patient's movements. Therefore, the analysis of reach-to-grasp phases could potentially be a helpful tool to determine how the impairment affects the upper-extremity movements and to plan the rehabilitation process more effectively. When transferring the described method for evaluation of the reach-to-grasp movement into a clinical environment, it may be possible to use a simpler and less expensive data recording system based on instrumented glove and video cameras to track the hand position. Another suggested application of the results reported in this paper is in the area of physical rehabilitation assisted by virtual reality (VR) (Bailenson et al., 2008). It could be possible to develop a VR-based motion training system which could provide feedback to the patients during reach-to-grasp movement. This feedback would be established by comparing patient's reach-to-grasp phases with the phases of a healthy population using our proposed method, and thus influence the patient to correct his/her movement pattern.

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