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# Measurement and Analysis of Human Hand Kinematics

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***Abstract*—**Measurements and quantitative analysis of kinematic parameters of human hand movements have an important role in different areas such as hand function rehabilitation, modeling of multi-digits robotic hands, and the development of machine-man interfaces. In this paper the assessment and evaluation of the reach-to-grasp movement by using computerized and robot-assisted method is described. Experiment involved the measurements of hand positions of seven healthy subjects during grasping three objects of different shapes and sizes. Results showed that three dominant phases of reach-to-grasp movements could be clearly identified.

***Keywords*—**Human hand, kinematics, reach-to-grasp movement.

## I. 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.

The research of human hand and grasping is becoming an interesting scientific area in many laboratories for biomedical engineering, biomechanics and robotics. The study of grasping plays an important role in rehabilitation of upper arm and hand function [2], [3], development of multi-fingered robotic hands [4], [5] and design of man-machine interface [6], [7]. Key components of grasping 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 [8]. Therefore, the study of grasping can be divided into three areas of research: reach-to-grasp movement toward the object to be grasped [9]-[11], exerting digit force on the object [12], [13] and dexterity of the fingers while manipulating the object [14], [15].

Prehension, or reach-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 [8]. 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 [8], [16]. When interpreting grasping movements, one has to select the variables to study and motivate one's choice. Jeannerod [17] suggested that prehensile movements involve two independent visuo-motor channels. The first channel uses information about the position of the target in egocentric space in order to move the hand toward the target. Haggard and Wing used the term hand transport to refer to the operation of this channel [18]. The second channel uses information about the object itself (e.g. its size, weight, compliance, etc.) to preshape a grasping configuration of the hand that is appropriate to picking up the object. Haggard and Wing used the term hand aperture to refer to this second channel, because the opening of the hand during the course of movement is a suitable behavioral measure of its operation [18]. Jeannerod further suggested that the hand transport and hand aperture channels are independent, in the sense that they deal with different kinds of information, and the information used by one channel is not available to the other. This "classical approach" has allowed tremendous development in the research of grasping during past 20 years. A recent study by Karl and Whishaw explains different evolutionary origins for the reaching movement and the grasping the object, controlled by those dual visuomotor channels positioned in primate parietofrontal cortex [19].

The focus of this paper is the assessment and evaluation of the reach-to-grasp movement by using computerized and robot-assisted measurements of hand and fingers kinematics in healthy population [20], [21]. Generally, kinematics studies the motions without taking into consideration the forces causing those motions. Kinematic research of the human hand includes measurements of hand and fingers positions during movements, calculation of velocities and accelerations, orientations, angular velocities and angular accelerations. In this paper, we will use the optical motion-capturing system to measure the positions of the wrist and fingertips during reach-to-grasp movement toward objects of different shapes and sizes. From the measured data, we will calculate the distance between the objects and the hand during the whole grasping movement, and wrist tangential velocities and accelerations. The measure of hand aperture (or fingers opening) will be calculated by the method proposed in our paper [20]. By analyzing the measured and calculated data, we will propose the quantitative description of reach-to-grasp movement and the division of the movement into three dominant phases [21].

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## II. Methods

### A. Experimental Setup

Seven right - handed healthy subjects (males, aged 23 to 30 years) participated in the experiment. The volunteers did not suffer from any neurological or muscular disorders and the informed consent was obtained from all subjects prior participation in the experiment.

Hand movements were recorded by a 3D optical motion - tracking system OPTOTRAK/3010 (Northern Digital, Waterloo, Canada). It uses a set of six infrared cameras which could trace the positions of active infrared-emitting markers with very high precision. The sampling frequency of the system is 100 Hz. We used fourteen markers: five of them 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), as shown in Fig. 1. Three markers were attached to the object used and three to the table where the subject was seated.

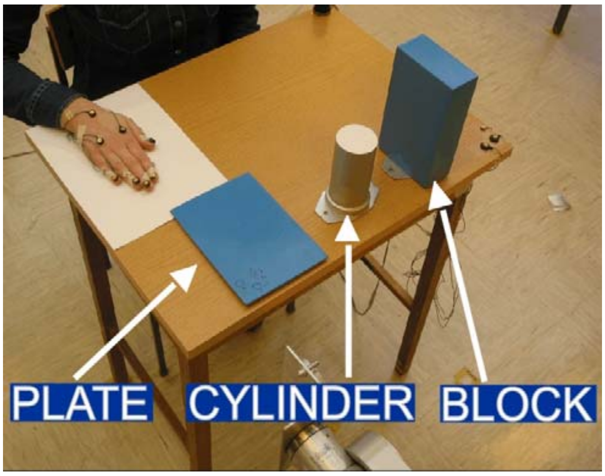


Fig. 1 Objects used in the experiment and subject's hand with Optotrak markers attached to the skin

The subject was asked to grasp three different objects. The objects were chosen in a manner to be similar to the daily - used objects such as book, glass or paper magazine. The objects 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.

The hand coordinate frame was defined using markers attached to the dorsum of the hand, Fig. 2 (d). 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**. The frames attached to the objects are shown in Fig. 2. 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. 3.

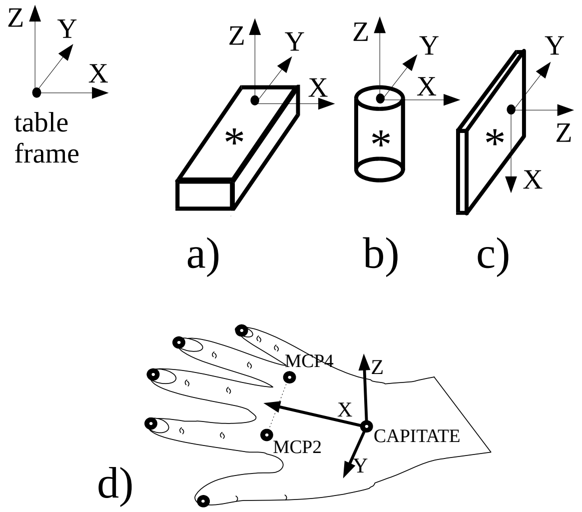


Fig. 2 Coordinate frames attached to the objects and the hand (* indicates the object's center of gravity)

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 objects were attached to the robot end-effector by permanent magnets, Fig. 3. The three objects were placed in five different positions or orientations, denoted as Test 1 to Test 5 in Table I. The block changed the orientation maintaining the same position, while the opposite was true for the cylinder. Plate was placed into one predefined position. Five trials of each grasping condition were performed, thus having in total 175 reach-to-grasp movements recorded and analyzed.

The experiment protocol was as follows: 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. 1. 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.

TABLE I
Object Distance from Hand at Movement On-Set, Position, and Orientation

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

$\mathbf{x_o, y_o, z_o}$: object frame axes; $\mathbf{x_t, y_t, z_t}$: table frame axes (see Fig. 3)

(* Hand - object spatial distance is determined as the spatial distance between capitate marker on the hand in initial position and capitate marker recorded at the end of the movement (** COG signifies object center of gravity shown in Fig. 2)

Each experiment trial started at the moment when the subject pressed the pushbutton with his left hand, and the object is transferred by a robot into a randomly selected initial position, while the OPTOTRAK starts to collect the data, Fig. 3. After three seconds, the subject is informed by an audio signal to start grasping. 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. Upon grasping the object by a subject and placing it to the table, OPTOTRAK stops collecting the data.

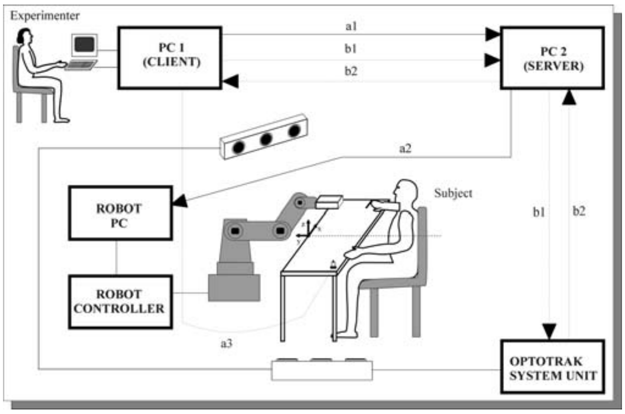


Fig. 3 Block scheme of the experimental set – up [**a1**: robot position data, **a2**: "move robot" command, **a3**: pushbutton signal, **b1**: "start OPTOTRAK acquisition" command, **b2**: OPTOTRAK data]

### *B. Data Processing*

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 time instant when the inter-finger distances stopped decreasing [11]. All recorded data were digitally processed by MATLAB software package (The Mathworks Inc.). Firstly, all recorded trajectories were low – pass filtered by a second order, 10 Hz dual pass Butterworth filter, and then normalized with respect to the movement duration. From the obtained trajectories, we calculated kinematic parameters which we used for quantitative analysis of reaching movement, as follows:

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

$$V_T = \sqrt{V_X^2 + V_Y^2 + V_Z^2} \tag{1}$$

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

In order to observe hand opening during the reaching movement, we defined fingers pentagon as a planar shape interconnecting the markers of adjacent fingertips [20]. The time-depending trajectories of the pentagon surface area, denoted as PSA, describe the level of hand opening. Since the value of this parameter clearly depends on hand size, in order to average it across subjects, the PSA trajectories prior to averaging were normalized according to initial PSA value (palm facing the table, at the onset of the movement). The peak value of PSA represents maximal hand opening. We introduced the pentagon concept as an alternative approach to the hand aperture defined as the distance between thumb and index finger tips [18]. 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 thumb and index finger. Therefore, such a definition of hand aperture provides insufficient information about fingers preshaping [20]. The numerical differentiation of PSA trajectories was performed to obtain the rate of hand opening, denoted as dPSA/dt.

Finally, the trajectories of all reach-to-grasp kinematic parameters previously described were averaged over 7 subjects and 5 repetitions of each experiment trial.

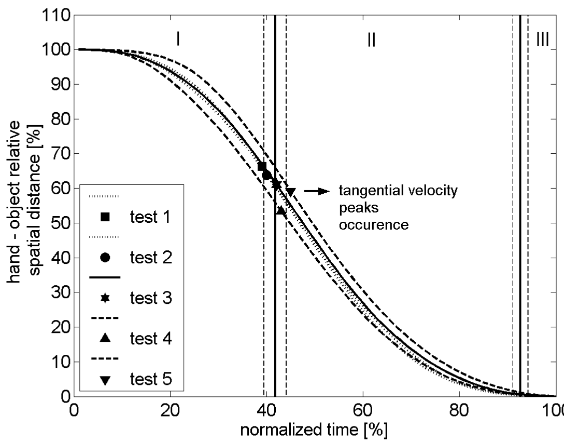


Fig. 4 Hand – object relative spatial distance for all five tests (see Table I). Reach – to – grasp movement phases are separated b vertical solid lines and denoted as I, II, and III. Dashed vertical lines represent +/- SD of phase duration

## III. Results

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

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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 type of the object and its position.

Fig. 5 presents the tangential velocity trajectories of the capitate marker. The curves are bell shaped, reaching a maximum value at 41.8% (with standard deviation, SD of 2.3%) of the duration of the movement. This value is obtained by averaging the peak times for all five tests.

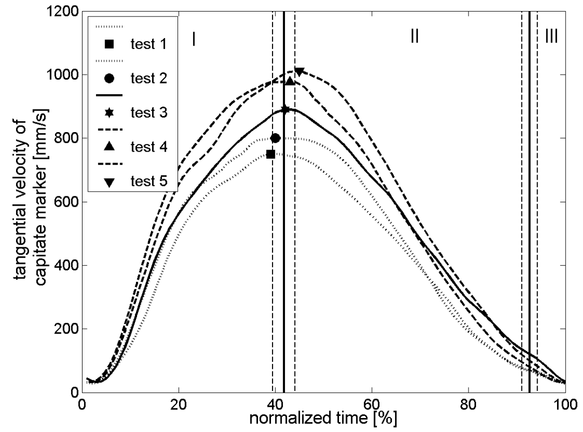


Fig. 5 Tangential velocity of capitate marker; Markers denote peak values

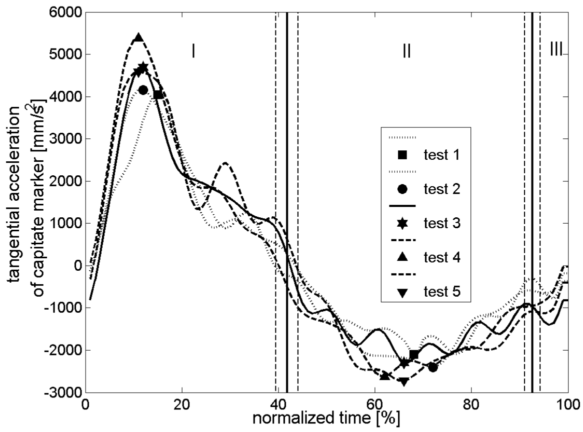


Fig. 6 Tangential acceleration of capitate marker; Markers denote peak values

Fig. 6 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. 6. The times of velocity peak occurrence are also marked in Fig. 4.

Figs. 7 and 8 show the trajectories of PSA and its time derivative which represents the rate of hand opening, respectively. PSA increases during the first part of the approaching movement and then decreases during the second part, Fig. 7. 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. 8.

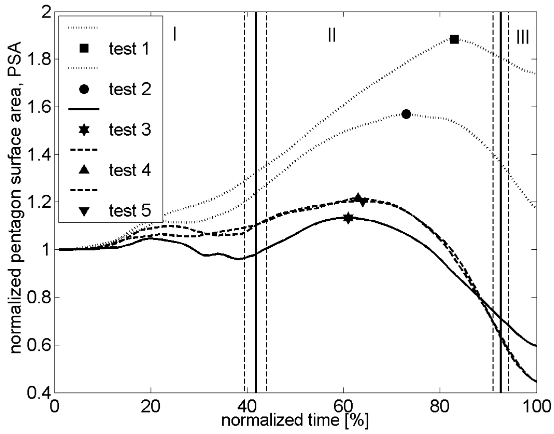


Fig. 7 Hand opening described by PSA trajectories;N Markers denote peak values

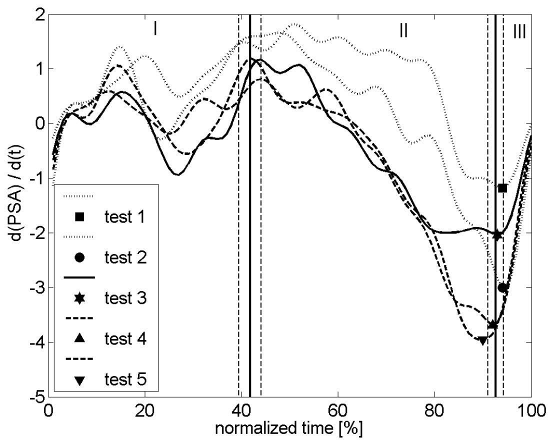


Fig. 8 Velocity of hand opening described by PSA time derivative (d(PSA)/(dt)); Markers denote peak values

Focusing on the trajectories shown in Figs. 4-8 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 turning moment in the reach-to-grasp movement is reaching the peak velocity (Fig. 5) which divides the reaching movement into a hand acceleration phase (positive values of tangential acceleration) and hand deceleration phase (negative values of acceleration), Fig. 5. 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. 5), 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. The mean peak velocity first occurred for the block, whose centre of gravity was the closest to the hand, then for the plate, and finally for the cylinder whose centre of gravity was furthest from the hand. Secondly, the amplitude of the peak velocity also depends 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 in our paper [20]. Here we can shortly report that the maximal hand opening represented by PSA value depends not only on object size, but also on the shape and the area of the object surface towards which the hand approaches. According to Fig. 7, 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. 8. It can be observed that peak values of d(PSA)/dt trajectories occur at 92.6% (SD 1.6%) (Fig. 8), 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.

## IV. Discussion and Conclusion

By close observation of the transport component of reaching movement described by Figs. 4-6, and prehension component described by Figs. 7 and 8, three dominant phases of reaching the stationary objects could 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. 4-8, and marked by I, II, and III. Let us focus on the identified phases in more details.

### *1. Phase 1: Hand Acceleration [0 - 41.8% (SD 2.3%) of Movement Duration]*

During the initial phase of reaching movement the subject is focused on accelerating the hand in order to reach the peak velocity. Maximum acceleration is reached at early stage of the phase, at 12.2% (SD 1.64%) of total time. Prior to acceleration peak, process of fingers opening does not occur since the PSA trajectories retain initial values, Fig. 7. After the acceleration peak, fingers preshaping starts, although that does not necessary imply that fingers are opening and PSA trajectories are increasing – in some cases (test 3) PSA values fall below initial value. At the end of this phase, hand traveled 39.4% (SD 5.1%) of total hand – object distance and reached the peak tangential velocity.

### *2. Phase 2: Hand Deceleration [41.8% (SD 2.3%) – 92.6% (SD 1.6%) of Movement Duration]*

During the second phase subject decelerates the hand and focuses on fingers opening. Fingers are continuously opening until the PSA peak is reached, Fig. 7. Times of PSA peaks vary significantly, since it is already identified that they depend on the values of PSA peaks. This phase is characterized by reaching the deceleration peaks which occur at 66.8% (SD 3.6%), at the half of the total phase duration, Fig. 6.

### *3. Phase 3: Final Closure of the Fingers [92.6% (S 1.6% – 100% of Movement Duration]*

At the end of second phase transportation of the hand toward object finalizes and during the third phase the subject is focused on the final closing of fingers around the object in order to obtain the stable grasp. At the onset of this phase the rate of hand closing is highest (peak values of d(PSA)/dt in Fig. 8), and then decreases toward zero-values.

The goal of this study was to establish the quantitative criteria for the evaluation of the reach-to-grasp movement in healthy persons. We showed that, despite of high complexity of grasping movement and various tasks that human hand is capable to execute, three characteristic phases of the reaching movement performed by healthy humans can be recognized and identified. The next step in our research should 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 the comparison of the reaching movement phases obtained in this paper with the phases assessed in subjects who have difficulties in hand opening, it could be possible to plan the rehabilitation process more effectively.

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