MANIPULATION STRATEGY OF A DEXTEROUS HAND

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Abstract: In this study hand kinematics was investigated. We used a motion tracking device to display a real object within virtual environment. A subject was asked to bring the real object to a desired pose which was displayed on the screen. The movements of the forearm, dorsum and of the hand fingers were observed. Due to hand redundancy a specific object pose can be reached by different hand postures. However, a good repeatability of hand movements was observed both for single and for the group of twelve healthy subjects tested. The motion was carried out in the way the joint limitations were avoided. When the wrist flexion-extension and forearm pronation-supination were close to their limitations, the movement was initiated by fingers, while in other cases forearm movement preceded that of the hand dorsum and fingers.

Introduction

The reproduction of human hand dexterity has been an interesting challenge in the field of robotics over the past two decades. The common goal of the studies was the development of multi-fingered, articulated hands, which would replace an array of cumbersome and cost ineffective special-purpose grippers used in industry, and proposal of complex rehabilitation methods. The work was motivated by an idea, that fine manipulation can only be accomplished by relatively fast and small motion of the fingers.

A grasping task is composed of three phases: pre-grasp phase, static grasp phase and manipulation phase. In reaching-to-grasp studies effect of object extrinsic (position and orientation) and intrinsic (shape, size, weight) properties on wrist, hand opening and grasp pre-shaping was investigated. On the other hand, psychologists attempted to explain how the brain develops and optimizes the reaching paths. Pre-grasp phase consist of more simple transport phase and more complex prehension phase. Hand preshaping has been mostly described by indices taking into account thumb and index finger. New indices were proposed in [1].

The work done in the area of static grasp, i.e. form and force closure of 2D and 3D objects is vast. Effect of finger motion over the object surface, including finger gaiting, rolling contact and sliding was considered and mathematically described. There are some reports on automatic, model or knowledge based grasp planning, taking into account grasp quality measures, but the gap between theoretical promise and practical delivery remains [2]. This holds for the dexterous finger motion too.

In manipulation phase Doeringer and Hogan [3] tried to explain how the human finger motion is guided by the central nervous system. The task is in their opinion broken into shorter sequential postures. The same idea was used in [4] to propose manipulation strategy for an anthropometric hand. The model was based on distinct topologies and analytical solutions of the inverse kinematics for each successive movement. Several other papers treated manipulation of objects by robot grippers, however, as surveyed by Bicchi in [5], the research of multi-fingered hands has been mainly focused on kinematic analysis of enveloping grasps. A statistical model for such grasp was proposed by Buchholz and Armstrong in [6]. The grip posture was estimated by an algorithm that determines contact between two ellipsoids, which are used to approximate the geometry of the cutaneous surface of the hand segments. Another model for power-grip posture was proposed by Lee and Zhang [7]. The optimization goal of this model is based on a premise that hand prehensile configuration should best conform to the shape of the object in a power grip. It is achieved when distances from the finger joints to the object surface are minimal. These models are focused only on the enveloping grasps. In contrast, when finely manipulating objects, we mostly use our fingertips and distal phalanges, what makes the movement far more dexterous.

The aim of our work was to propose a method for dexterity assessment of fingertip grasps, employing an optical motion tracking device and virtual environment. We tried to explain some aspects of fingertip grasp dexterity for three different hand gestures. We were interested in temporal activities of forearm pronation-supination, wrist flexion-extension and abduction-adduction, and fingers activity, measured by a change of object pose.

Materials and Methods

Twelve volunteers, 11 males, 1 female, with no deficiencies in functionality of their right hand, participated in this study. A subject was installed in an armchair. Its height and inclination had been adjusted in the way the right arm could rest comfortably in a custom designed brace, firmly attached to a desk (Figure 1). The angle between forearm and the desk was

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adjusted to approximately 40°. Wrist was able to move freely, forearm pronation-supination was limited to some degree by the straps, while elbow flexion was kept fixed at approximately 55°.

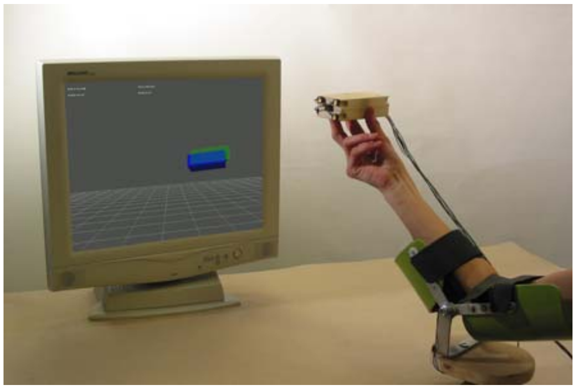

Figure 1: Exercise in the virtual environment

Three infra red markers were placed on the brace to acquire the reference frame. Other markers were placed on anatomical landmarks, found by palpation. One marker was attached to the elbow (olecranon), two on the forearm (ulnar and radial styloid process), one on the wrist (centre of capitate bone) and two on the dorsal side of the hand (end of 2nd and 4th metacarpals). Six markers were placed on the prismatic object (115 x 45 x 35 mm) to guarantee that at least three markers were visible in every reachable pose. 3D positions were recorded by an optical tracking device (Optotrak, Northern Digital Inc.) and sent via local area network to the client computer for visualization.

The visualization was made within Maverik, a virtual reality system, which enables rapid production of complex virtual environments as well as providing many functions that are valuable to anyone developing applications with 3D graphics or using 3D peripherals.

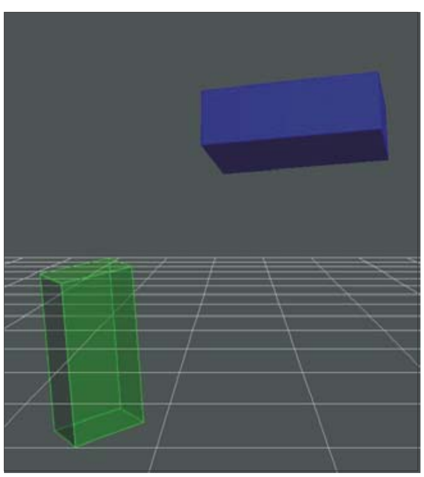

Figure 2: Reference and mobile object

The object from a real world is displayed within virtual environment with opaque colour (Figure 2). In further text we will refer to this object as a mobile object. At the same time a semi-transparent object, with bright coloured vertices, is shown on the screen. The goal of the task is accomplished when mobile object resides within reference object. The criteria estimating the goal fulfilment are the distance between centres of gravity and the difference between orientations of both virtual objects A new reference object posture generation is triggered when both, position and rotation deviations are reduced below arbitrarily chosen values. At that time the mobile object colour changes. Its pose is perfectly aligned with the reference one, the screen freezes for two seconds and afterwards a new reference pose is displayed. The chosen position error limit corresponds to a 2 mm shift within real world, while the rotational error limit was set to 8°.

Each subject was given 15 minutes prior the recordings to get accustomed with the environment. All subjects felt a sufficient degree of immersion. We tried to additionally improve the display of the virtual objects by adding texture gradient and linear perspective. After the trial period the subjects did not have any difficulties imagining the real position and orientation of the object. A subject was able to see the virtual as well as the real object nevertheless he/she was asked to concentrate onto the virtual object. The scale of virtual environment was equalized with the scale from the real world.

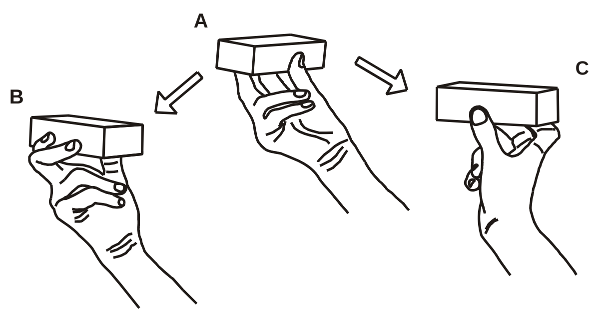

Figure 3: A. Initial posture. Reference postures: B. Screw posture. C. Unscrew posture.

The reference poses were chosen from regular daily activities like replacing a bulb or holding a book. At the beginning of the experiment the initial pose is displayed (Figure 3, A). After reaching the initial pose, which is very close to the pose subjects are asked to start with within the real world, the first reference pose, i.e. screw, is displayed (Figure 3 B). When the mobile object coincides with the reference one, the initial pose is displayed again. A new reference pose (Figure 3 C, unscrew) replaces the initial one when the mobile object is repositioned into its initial position.

The depth of the mobile object, displayed within virtual environment, depends on the real object pose, relative to the reference frame (Figure 4), defined by the three markers attached to the brace. Although the object is held in the same hand posture, its pose changes for different subjects due to different anthropometry. For example, the depth of the mobile object is greater for the subjects with longer extremities. Therefore, we considered online adjustment of the initial and reference poses to different subjects. Hand segment lengths acquired online were used to carry out the adaptation of poses displayed within virtual environment to guarantee their reachability.

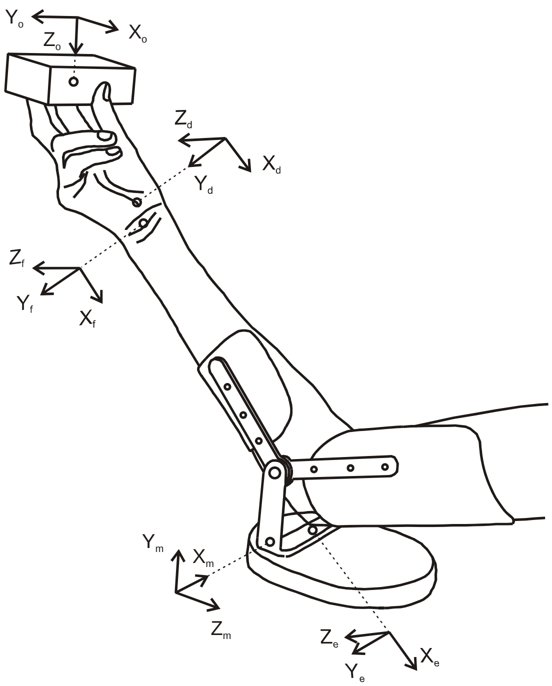

Figure 4: Monitor, elbow, forearm, dorsum and object frame positions are depicted with bold circles.

One subject, who did not take part in further study (i=0), was asked to held his hand comfortably in several postures, which resemble those from every day life. Object poses were recorded for each posture and afterwards displayed to the same person as the initial and reference poses within virtual environment. Because they were recorded exactly for this subject, their reachability was not questionable. The frames (Figure 4) attached to the elbow, forearm, hand dorsum and object were calculated for initial (j=0) and reference poses (j=1,2). The matrices describing transformation of elbow to forearm, forearm to hand dorsum and hand dorsum to object frame, were calculated. The matrices related to initial pose were further decomposed into two parts: rotation and position.

The transformation matrices calculated for reference postures, were decomposed into two parts as well. The first part was equal to the transformation matrices, obtained for initial posture, while the second part accounted for a translation and rotation of hand frames, which occur with hand movements.

During the system initialization subject i (i=1,…,n) assumes the starting hand posture depicted in Figure 4, which is very close to the one that brings the object into the initial pose (Figure 3 A). The transformation matrices of this posture (j=0) are calculated online and then decomposed into position and orientation. A new set of transformation matrices is then estimated by multiplying the matrices which describe the position of the frames during starting posture, by the rotation matrices obtained for the same posture in the subject i=0. The initial pose (j=0) was calculated by postmultipliplication of the elbow frame with these transformation matrices.

The reference poses (j=1,2) are calculated from transformation matrices obtained during initialization, matrices, calculated for subject i=0 and reference poses j=1,2, and the elbow frame, which is kept fixed by the brace for all postures.

The object pose estimation is based on an assumption that all healthy subjects are capable of similar movements of forearm, dorsum and fingers, as long as joint limits are avoided. If subject i (i=1,…,n) wants to reach pose j, he or she will be able to achieve this at least in one way: by applying the same forearm, dorsum and finger movement as observed in subject i=0.

The marker data were recorded on a host computer hard drive and processed off-line. As it can be noticed from Figure 4, the movement of the forearm, dorsum and fingers can be described separately, by the transformation matrices calculated from the frames attached to the arm. Because the humans, when pointing to a fixed visual target, slow their limbs as they approach the target, we observed the hand motion as a step response of linear dynamic system. Such behaviour can be described by a first order linear system. Two time parameters were chosen, for description of movement versus time: tR and tτ. The step response of a first order linear system reaches 10% of its final value after rising time tR and 63% of its final value after time constant tτ.

Time courses of RPY angles and positions were synchronized on the basis of tR of the forearm pitch rotation. All signals related to a movement from the initial to the same reference pose were shifted along time axis in a way that 10% of the forearm rotation was synchronised for all subjects. Translations XYZ along x, y, z axis of the current frame and RPY angles extracted from transformation matrices, were joined together into two values, representing quadratic norm (root sum square) of translations |XYZ| and RPY angles |RPY|. The norm |XYZ| equals the distance from the current to the transposed frame, while there is no physical representation of the norm |RPY|. The quadratic norms were divided by their final values, which were recorded for the pose, when mobile object approached the reference one and the criterion of the task fulfilment was met. The two norms, observed at time instance t, represent the movement of the observed extremity relative to the whole movement, which is necessary to reach a reference pose. We will refer to them as normalised position p and normalised rotation r.

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The translation of the mobile object relative to the reference object was described by RPY angles and the translation vector. The initial values of RPY angles and XYZ translations were subtracted in all cases.

Results

Repeatability of RPY angles (Figure 5 A) and XYZ translations (Figure 5 B), extracted from the matrix describing translation of the mobile object relative to the reference object, was studied for subject i. The movements from initial to selected reference pose j (holding a glass) were not made in a consecutive manner, however, the sequence of initial and reference poses was the same for different trials. The results are represented in Figure 5 as mean value, enveloped by confidence interval of one standard deviation.

When a new pose is displayed within virtual environment, the subject hast first to recognize the pose. During the recognition phase no action is taken. The movement from the initial to the observed reference pose follows. It is evident from Figure 5 that trajectory of the mobile object is similar for different trials. Standard deviations are reduced during approach of the mobile object to the reference one. This holds for orientation and position. Larger standard deviations during the central part of the movement can be observed.

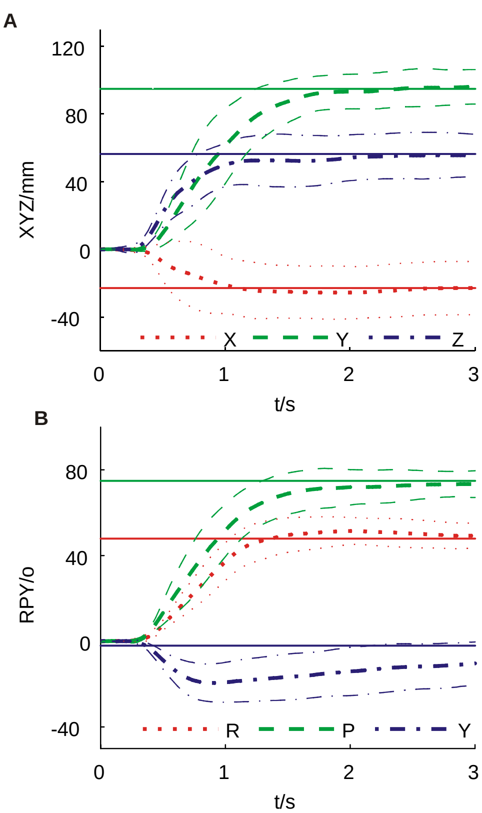

Figure 5: Repeatability of object trajectory of twelve movements from the initial to selected reference pose, performed by one subject.

All subjects were able to reach reference poses shown in virtual environment. This was not the case when the online adjustment of poses to length of hand extremities was not performed. A trajectory of the mobile object approaching to a reference pose is similar for different subjects too, although the variability is slightly higher than in repeated object movements observed for one subject. Standard deviations of XYZ translations and RPY rotations assessed in all subjects did not exceed 20 mm and 17° during the movement towards holding a glass posture and did not exceed 15 mm and 6° when the mobile object reached vicinity of the reference object.

Time courses of RPY angles and XYZ translations, extracted from transformation matrices describing elbow – forearm (TEFij), forearm - hand dorsum (TFDij), and hand dorsum – object (TDOij) frame transformation, were also observed. They represent the contribution of the forearm rotation, wrist and finger joints to the total movement. They are repeatable for different subjects while approaching towards the same reference pose. Normalised positions p and rotations r were calculated from quadratic norms of XYZ translations and RPY rotations extracted from the transformation matrices. They are presented in Figure 6 and Figure 7 for screw, and unscrew movements respectively.

Time courses of normalised positions p and normalised rotations r of one subject are plotted on figure panels A and B. Contribution of the forearm rotation, wrist and finger joints is plotted with dotted, dashed and full lines respectively. Vertical dotted lines denote the time tτ, when forearm reaches 63% of its final pitch rotation in reference posture.

Three normalised positions p and normalised rotations r, which belong to the time instance tτ, can be extracted from the matrices TEFij, TFDij, and TDOij for each subject. In this way 3 sets of normalised positions and normalised rotations, are obtained. They are presented as box plots. Dark grey, light grey and white colours are used to display the contribution of forearm rotation, wrist and finger joints respectively. Normalised positions are depicted on figure panels C and normalised rotations on figure panels D. Horizontal lines of a box plot denote the 25th, 50th and 75th percentile, while the whiskers confine an interval containing all values.

The wrist and elbow joint are close to their limitations, when performing a screw movement from the initial pose (Figure 3 A to Figure 3 C). Therefore, the rotation of the object, by moving the fingers take place first and it is followed by rotation of the forearm and dorsum, which occur in hand with each other (Figure 6, B). Likewise, the translation of forearm and dorsum lacks behind translation of the object (Figure 6 A). At time instant t_τ, median values of normalised positions recorded for all subjects came to about 60% of their final values for forearm and hand dorsum (Figure 6 C). This value was higher for object and it reached 85%. Median of normalised rotation of the object went up to

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88 %, while the values obtained for forearm and hand dorsum were smaller for more than 20 % (Figure 6 D).

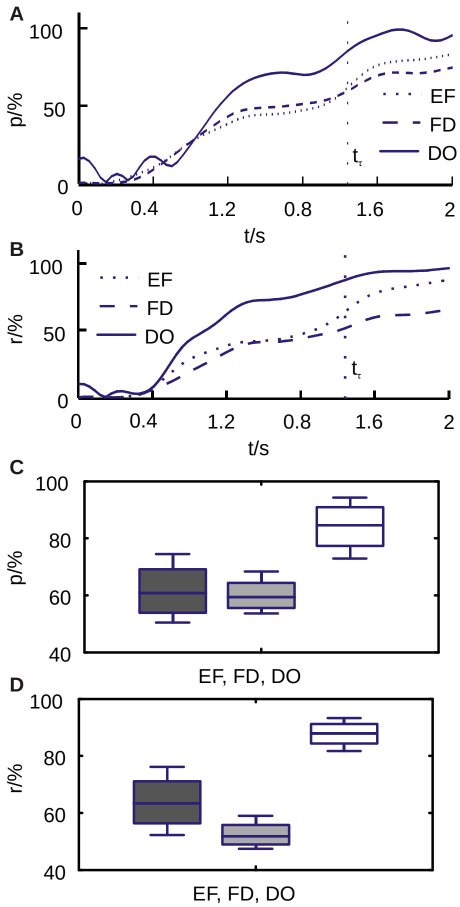

Figure 6: Screw posture. Time courses of normalised positions *p* (A) and normalised rotations *r* (B) of one subject. Normalised positions (C) and normalised rotations (D) for all subjects at time t_τ

During the unscrew movement (Figure 7) all rotations grew up to about the same value after time t_τ (B). This can also be observed for all subjects (D). From this time on they change at the same rate. In contrast to rotations, the forearm translation comes about first and it is followed by dorsum translation. The change of the distance between hand dorsum and object is significantly delayed after forearm and dorsum translation (A). Medians of normalised positions, at time t_τ, reached 93, 64, and 33 % of forearm, hand dorsum, and object final position respectively.

Discussion

The first aim of our study was to develop a method for studying hand dexterity and to validate it against the experimental data. We have shown good repeatability of object trajectory for one subject, when approaching a single reference pose. This holds both for time course of object orientations and positions as well as for different subjects and reference poses (not presented within this paper). Larger standard deviations which were observed for the central part of the movement can be noticed on account of different velocities during the trials.

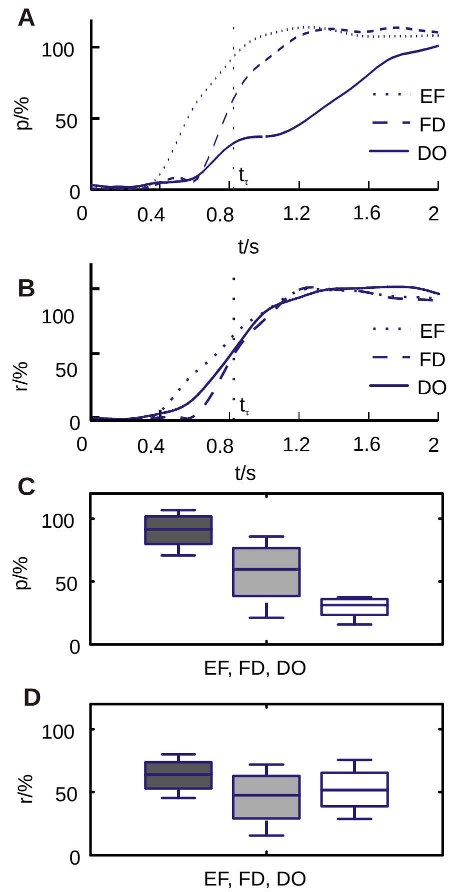

Figure 7: Unscrew posture. Time courses of normalised positions *p* (A) and normalised rotations *r* (B) of one subject. Normalised positions (C) and normalised rotations (D) for all subjects at time t_τ.

The human hand model was considered on the commonly used rigid body assumption. An online adaptation to inter-person variability of hand anthropometry assured reachability for every subject and thus improved the repeatability of dexterity. Furthermore, guiding a hand movement toward reference pose, by displaying the objects into virtual environment, assured the repeatability of the tasks. The subject was able to regulate the motion by visual feedback, while the tactile sensing remained real. By this means a good degree of immersion into virtual environment was achieved. Our results are in agreement to the study reported by Biryukova et al. [8] who stated that spatial tracking system recordings could reliably be used to accurately analyze multi-joint movement in humans.

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The second aim of the present study was to explain some aspects of human hand dexterity for three different hand gestures, recorded while approaching to reference object poses. We were interested in temporal activities of forearm pronation-supination, wrist flexion-extension and abduction-adduction, and collective activity of the fingers, the latter measured by a change of object pose, relative to hand dorsum. The hand movement does not occur progressively, starting with kinematicaly less complicated movements of forearm and wrist and followed by dexterous fingertip manipulation. In some cases collective finger movement precedes forearm and wrist movement while in other cases the leading role is switched. We noticed that the movement is initiated in the joints, which are away from their singularities. When all joints are far from their limit of range of motion, the movements occur simultaneously, as if the motion in joints is coupled. However, the coupling vanishes when a joint approaches to its limitation which enables further motion of other joints.

Roby-Brami et al. [9] claimed that the task-related synergy in human hand, which was in our case observed as simultaneous movement of joints, is used to simplify the control. Namely, coupling of the joints reduces the number of redundant degrees of freedom. Our results confirmed that synergies could indeed be organised at the level of kinematics of the upper limb, as already reported by Scholz, Schoner and Latash [10] and Rosi, Mitnitski and Feldman [11].

We believe that the proposed method could be used, for computer-assisted functional evaluation of a paralysed or injured hand. The approach also enables repetitive task-oriented training of coordination of grasping in handicapped persons. It is easy to add new objects and poses, which makes the method flexible and extendable to all mentioned fields. In robotics the method can be used for planning of multi-fingered hand trajectories by human observation.

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References

[1] SUPUK T., KODEK T., BAJD T. (2005): 'Estimation of Hand Preshaping During Human Grasping', Med. Eng. Phys., in press.

[2] OKAMURA A.M., SMABY N., CUTKOSKY M.R. (2000): 'An Overview of Dexterous Manipulation', Proceedings of the 2000 IEEE International Conference on Robotics & Automation. San Francisco, USA, 2000, p. 255-262.

[3] DOERINGER J.A., HOGAN N. (1998): 'Serial Processing in Human Movement Production', Neural Netw., **11**, pp. 1345-1356.

[4] CAURIN G.A.P., ALBUQUERQUE A.R.L., MIRANDOLA A.L.A. (2004): 'Manipulation Strategy for an Anthropomorphic Robotic Hand', Proceedings of 2004 IEEE/RSJ International Conference on Intelligent Robots and Systems. Sendai, Japan, 2004, p. 75-85.

[5] BICCHI A. (2000): 'Hands for Dexterous Manipulation and Robust Grasping: A Difficult Road Toward Simplicity', IEEE Trans. Robot. Autom., **16**, pp. 652-662.

[6] BUCHHOLZ B., ARMSTRONG T.J. (1992): 'Kinematic Model of the Human Hand to Evaluate its Prehensile Capabilities', J Biomech, **25**, 2, pp. 149-162.

[7] LEE S.W., ZHANG X. (2005): 'Development and Evaluation of an Optimization-based Model for Power-grip Posture Prediction', J Biomech, in press.

[8] BIRYUKOVA E.V., ROBY-BRAMI A., FROLOV A.A., MOKHTARI M. (2000). 'Kinematics of Human Arm Reconstructed from Spatial Tracking System Recordings', J Biomech, **33**, pp. 985-995.

[9] ROBY-BRAMI A., JACOBS S., BENNIS N., LEVIN M.F. (2003). 'Hand Orientation for Grasping and Arm Joint Rotation Patterns in Healthy Subjects and Hemiparetic Stroke Patients', Brain Res, 969, pp. 217–229.

[10] SCHOLZ J.P., SCHONER G., LATASH M.L. (2000). 'Identifying the Control Structure of Multijoint Coordination during Pistol Shooting', Exp Brain Res, 135, 382–404.

[11] ROSSI E., MITNITSKI A., FELDMAN A.G. (2002). 'Sequential Control Signals Determine Arm and Trunk Contributions to Hand Transport during Reaching in Humans', J Physiol, 538, pp. 659–671.

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