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Optimal Grasping in Humans

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Abstract—**The key idea in this work was to observe fingers of a human hand while changing the orientation of an object, in order to gain some knowledge, which could be of interest in control of multi-fingered robotic grippers. We sought for an answer, whether the grasps, optimal for a human are also optimal from analytic point of view. Motion tracking device was used to asses grasp configuration of a human hand while manipulating three different objects. Two grasp dexterity measures, condition number and velocity of the grasped object, were used to evaluate human grasps. A minimum-maximum relation of those two measures was expected for optimal grasps. However, this relation was not observed. The grasp matrix estimation, proposed in literature, should be in our opinion adapted for human grasp, as fine manipulation is not performed by fingertips but finger-pulps.**

Index Terms— **grasp dexterity measure, human grasp, multi-fingered grasp, optimal grasp**

I. INTRODUCTION

Humans are able to accomplish fine manipulation by relatively fast and small motion of fingers which configure into a proper grasp for a variety of different objects [1]. A multi-fingered robotic hand, which would be capable to emulate human-like movements, could replace an array of special purpose grippers used in industry and benefit people with functional disabilities in hand. Besides, the coordination of multiple serial mechanisms within a single manufacturing cell can also be treated in a similar way.

The research in algorithms for achieving important properties of multi-fingered robotic hands has been restricted to fingertip grasps and so is this article. A control scheme of a good grasp, which would be able to perform everyday tasks similar to those performed by humans, should possess dexterity, equilibrium, stability, and desired dynamic behaviour [2]. We focused on dexterity.

Human grasp kinematics is redundant, which gives the basis for dexterity definition. It is an ability of a grasp to achieve one or more useful secondary objectives, satisfying the primary objective, the kinematic relationship between internal and external coordinates. Secondary objectives can be: avoidance of joint limitations, force or velocity maximization in a desired direction or avoidance of singularities and obstacles.

Grasp dexterity measures were extended from studying manipulability of redundant robotic arms. One of the most fundamental questions arising from the study of multi-fingered robotic hands is the determination of an appropriate grasp, which would suite to a given object together with a task to be performed. There have been attempts to use grasp dexterity measures for contact location synthesis, but no algorithm has been widely adopted [3]. A simulation system for contact determination, that allows a user to evaluate a grasp with numeric quality measures, was proposed by Miller and Allen [4].

Some researchers argued that robot hands are fundamentally different from the human hand [5]. The key idea of this work was to observe a human performing a task to establish whether the grasp optimal for human and from analytic point of view corresponds to the same criterion. The aim of this work was to evaluate human grasp of various objects with two grasp dexterity measures.

II. METHODS

We assumed that fingers had already grasped the object and that their location was kept fixed during manipulation of an object. The last assumption is justified as sliding is rare in robotic applications.

A quality of grasp was estimated from the grasp matrix G. The computation of the grasp matrix was described within [6]. It requires the knowledge of contact locations, fingertip orientation and kinematics of fingertip contact. Three infra red (IR) markers were placed onto each finger and three onto an object as shown in Fig. 1. Sticks made of aluminium were attached to the distal phalanges for more precise acquisition of fingertip orientations. The sticks were bent in a way that a good visibility of markers was achieved and collinearity of markers avoided. A motion tracking device (Optotrak,

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Northern Digital Inc.) was used to acquire three-dimensional positions of IR markers. Fingertip manipulation of three different objects was recorded: a sphere (r=20 mm), a cylinder (r=25 mm; h=140 mm) and a prism (a=115 mm; b=50 mm; c=30 mm) at wrist flexion. Five subjects took part in this study and several recordings were made for each subject. The acquired data was processed offline.

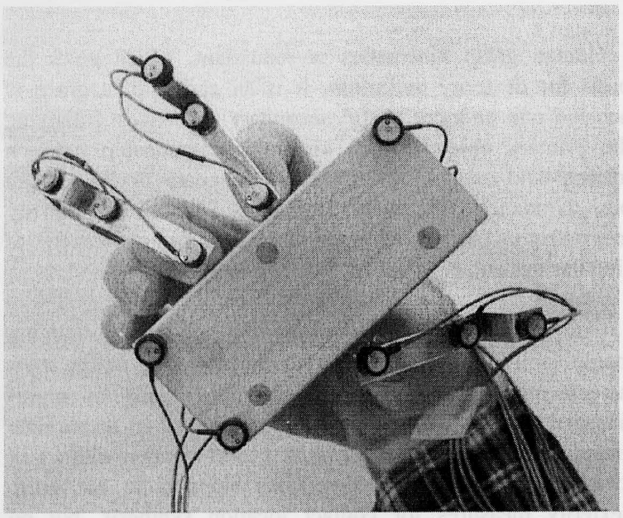

Fig. 1. Attachment of infra red (IR) markers onto fingers and object.

A soft-finger contact model was chosen to describe fingertip kinematics. This model can be used when noticeable friction exists between the object and fingers. In this case fingers are able to exert forces f_1, f_2, and f_3, in any direction and torque f_4 around the z axis, directed perpendicularly toward the object surface as shown in Fig. 2. Fingertip locations are kept fixed if forces remain within friction cone ($f_1^2+f_2^2<\mu f_3^2$; $|f_4|<\gamma f_3$), where μ and γ denote Coulomb and torsion coefficients of friction respectively. The contact wrench F_{Ci}, applied by finger i, can be described as stated within (1), where B_{Ci} denotes wrench basis, and f_{Ci} the magnitudes of forces f_1, f_2, and f_3, and torque f_4 around z axis.

$$F_{C_i} = B_{C_i} f_{C_i} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \end{bmatrix} \tag{1}$$

Matrix $\boldsymbol{G}$ can be obtained by resolving each fingertip wrench F_{Ci} to a common coordinate frame embedded within the object, as stated within equation (2).

$$F_{oi} = Adg^T_{OC_i} B_{C_i} f_{C_i} \tag{2}$$

Adg_{OCi} denotes the wrench transformation matrix, which maps a contact wrench F_{Ci} to the object wrench F_{Oi}. It can be calculated as stated within (3). Matrix R_{OCi} and vector p_{OCi} denote fingertip orientation and position relative to the object frame, respectively.

$$Adg_{OC_i} = \begin{bmatrix} R_{OC_i} & 0 \\ p_{OC_i} R_{OC_i} & R_{OC_i} \end{bmatrix} \tag{3}$$

A sum over all wrenches applied to the object results in (4).

$$F_0 = G_1 f_{C_1} + \ldots + G_n f_{C_n} = \begin{bmatrix} G_1 & \ldots & G_n \end{bmatrix} \cdot \begin{bmatrix} f_{C_1} \\ \vdots \\ f_{C_n} \end{bmatrix} = G \cdot \begin{bmatrix} f_{C_1} \\ \vdots \\ f_{C_n} \end{bmatrix} \tag{4}$$

The first chosen grasp dexterity measure ω is given in (5). It had been proposed for non-redundant spherical wrist manipulators and later extended to redundant arms with non-square grasp matrices. When ω becomes the largest, the volume of manipulability ellipsoid is maximized. This physically implies the largest velocity of the grasped object.

$$\omega = \sqrt{\det GG^T} \tag{5}$$

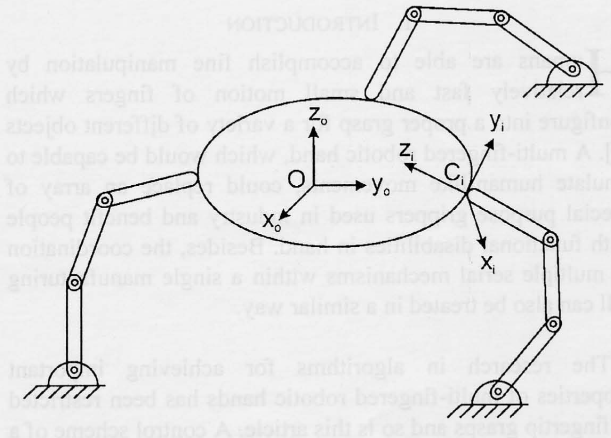

Fig. 2. Position and orientation of frames attached to fingertips relative to the object frame.

The second chosen measure of manipulability is the condition number of grasp matrix $n_C(G)$, given in (6). This measure acts as an indicator of uniformity of transformation from the space of internal to the space of external coordinates. It is a measure of magnitude and direction of column vectors. When all magnitudes are equal and column vectors orthogonal, this measure equals 1. In this case each joint velocity contributes equally to the object velocity.

$$n_C(G) = \left\| G^T \right\| \cdot \left\| G^{-T} \right\| \tag{6}$$

Grasp dexterity measures were studied for three objects of distinct shapes and sizes. They were joined together into single value and plotted as mean enveloped by a confidence interval of one standard deviation versus normalised angle of object rotation ρ_n.

III. RESULTS

All rotations were recorded at wrist flexion. Maximal sphere rotation came in average to 106°. Maximal cylinder rotation was slightly smaller. It reached in average 89°. The smallest object rotation was observed for prism, which was in average rotated from its initial orientation for 62°.

Mean values of condition number n_C and of the grasp dexterity measure related to velocity of a grasped object ω, were plotted for all cases. They were presented as functions of normalised angle ρ_n of object rotation. Normalised angle ρ_n represent the proportion of object rotation, relative to its maximal rotation, recorded for a chosen trial. This approach was necessary because different values of object rotations were observed for different subjects and object shapes. In this way the comparison of the measures assessed in individuals was enabled.

Mean values of condition number n_C (left panels) and the measure of object velocity ω (right panels), enveloped by one standard deviation are presented in Fig. 3, for rotation of a sphere (A, B), prism (C, D) and cylinder (E, F). The grasp is optimal when condition number n_C becomes the lowest, and object velocity measure ω reaches its maximum. It can be noticed from figure panels C and E that noticeable minima of condition number n_C were reached for cylinder and prism rotation at $\rho_n=0.55$ and $\rho_n=0.23$ of normalised rotation respectively. The smallest value of condition number can be observed for prism ($n_C=280$) which is notably higher for cylinder rotation ($n_C=420$). On the contrary, there is no global minimum of condition number n_C for sphere manipulation, although subjects reached the angle of sphere rotation at which the grasp was in their opinion the most comfortable and stable. Local maximum can be noticed instead at $\rho_n=0.27$

Global maximum of object velocity measure ω is not found in any of the observed situations. On the contrary! Distinct minima of ω can be observed at $\rho_n=0.11$, $\rho_n=0.23$, and $\rho_n=0.36$ of normalized rotation, for a sphere, prism, and cylinder, respectively.

IV. CONCLUSION

The aim of this work was to evaluate human grasp of various objects with two grasp dexterity measures. Our results show that angle of object maximal rotation depends on object shape. After examining a variety of human grasps, Cutkosky reported [7], that the choice of grasp was dictated less by the size and shape of the object than by the tasks to be performed. In our case grasp dexterity depended on object shape.

Two grasp dexterity measures were compared. A minimum-maximum relation of condition number and measure of object velocity was expected for optimal grasps. However, this relation was not observed, although subjects reached the angle of rotation where grasp was most comfortable to them. On the contrary, minimum-minimum relation was observed for prism and cylinder rotation and maximum-minimum relation for sphere manipulation.

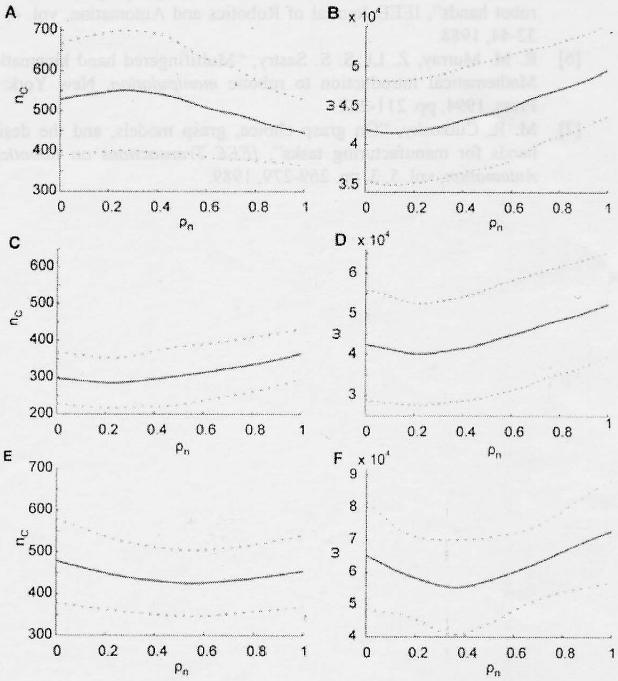

Fig. 3. Mean values of condition number nC (left panels) and the measure of object velocity ω (right panels), enveloped by one standard deviation, for finger rotation of a sphere (A, B), prism (C, D) and cylinder (E, F).

The results are opposite to our expectations. The method for grasp matrix estimation, proposed in [6] should be in our opinion changed for human grasp evaluation. We noticed that fine manipulation is in general not performed with fingertips but finger-pulps, which appose the approach shown on Fig. 2. The acquisition should be further improved by forearm fixation. A visual feedback such as virtual environment could be introduced into the method to guide object rotation, which would guarantee that the same movement was repeated in all observations.

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REFERENCES

[1] Z. Li, S. S. Sastry, "Issues in dexterous robot hands", in Dexterous Robot Hands, S.T. Venkataraman, T. Iberall, Springer, 1990, pp. 154-186.

[2] K. B. Shimoga, "Robot grasp synthesis: A survey", The International Journal of Robotics Research, vol. 15, pp. 230-266, 1996.

[3] A. M. Okamura, N. Smaby, M. R. Cutkovsky, "An overview of dexterous manipulation", in Proceedings of the 2000 IEEE *International Conference on Robotics & Automation,* San Francisco, 2000, pp. 255-262.

[4] A. Miller, P. Allen, "From robotic hands to human hands: a visualization and simulation engine for grasping research", Industrial Robotics, vol. 32, 1, pp. 55–63, 2005.

[5] Z. Li, S. S. Sastry, "Task oriented optimal grasping by multifingered robot hands", IEEE Journal of Robotics and Automation, vol. 4, 1, pp. 32-44, 1988.

[6] R. M. Murray, Z. Li, S. S. Sastry, "Multifingered hand kinematics" in Mathematical introduction to robotic *manipulation*, New York: CRC Press, 1994, pp. 211-223.

[7] M. R. Cutkosky, "On grasp choice, grasp models, and the design of hands for manufacturing tasks", *IEEE Transactions on Robotics and Automation*, vol. 5, 3, pp. 269-279, 1989.