

Validation of a Power Grasping Algorithm for an Anthropomorphic Robotic Hand on the Basis of Human Grasping Action

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Abstract It is generally acknowledged that performing a natural and reliable grasp with a robotic hand is a challenging task not yet completely solved. Further, the robotic hands designed until now do not have the same kinematic characteristics of a human hand, especially regarding the thumb. The main purpose of this paper is to use information obtained from the analysis of the human grasping action for validating and improving a reach-and-grasp algorithm we proposed for determining the optimal hand position for grasping a cylindrical object. Algorithm effectiveness has been tested on a real arm-hand robotic system.

Key words: Robotic grasping, hand kinematics

1 Introduction

The human hand represents the most dexterous part of the human body, both for its complex mechanical structure and for the versatility of its possible activities. In particular, grasping is one of the human skills that robotic researchers mostly attempt at imitating. One possible approach to reduce the complexity of the control that ensures stability of grasping consists of optimizing grasping configuration. During the pre-shaping phase, on the basis of the physical characteristics of the object to be grasped, such as shape and weight, the hand, while approaching the object, attains the most suitable configuration for seizing. Thus, pre-shaping plays a fundamental role in order to guarantee a stable grasp.

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Many approaches can be found in the literature to the purpose of searching an optimization criterion for selecting the optimal grasp configuration for a given object. In [1] a review of various techniques has been proposed for identifying the optimal grasp within the space of feasible grasps for a given set of task constraints, like object shape, type of task, hand degrees of freedom (DOFs), maximum force to be applied, etc. The main difficulty of this approach is the choice of the parameters to be used as constraints and to be included in the objective function [2]. A different approach consists in determining the hand-object contact points that guarantee a firm grip. Joint positions and forces that a robotic hand should apply for a stable grasp could be provided by a neural system [3] implying a high computational cost. Contact points can also be determined by means of grasp quality measures, which are used to evaluate grasp performance. In [4] two groups of grasp quality measurements have been considered and the authors propose a method for satisfying them. In [5], after heuristically generating a set of feasible grasp candidates, grasp quality measures, computed with an ad hoc method, have been used to choose the best grasp. Finally, methods for finding an optimal grasp configuration based on grasping force determination can be mentioned. They rely on the concepts of wrench matrix and friction cone [6].

By analyzing the robotic literature, it is evident a sizeable lack of information about the thumb behavior, despite its fundamental role during the grasping action. In fact, the robotic hands designed so far [7–9] are not able to replicate the motor capabilities of the human hand.

From the analysis of the grasping action performed by human beings and from the study of the anatomy of the human hand and of its behavior during grasping, it is possible to obtain useful information for developing human-like grasping algorithms so as to improve knowledge about hand kinematics on which this work is based. Objective of this work is to validate a recently proposed algorithm [10] that guarantees a stable power grasp and to pave the way for future works devoted to improving knowledge about the thumb behavior, giving some hints for enhancing the existing robotic hands. An optoelectronic motion analysis system has been used for collecting information about finger behavior during grasping. The obtained results have been used for improving and validating the optimization algorithm that has been also tested on a real robotic arm-hand system during reach-and-grasp tasks of cylindrical objects.

2 Experimental Analysis of Human Grasping Action

The Vicon optoelectronic motion analysis system has been used for collecting information about the fingers during grasping. The system is composed of 7 InfraRed (IR) cameras, with a frame rate of 100 Hz.

Seven human subjects, 31.7 years old in the average (8.75 Standard Deviation), five men and two women, all right handed, volunteered to participate in this study. Subjects were asked to grasp a cylindrical object of 6 cm diameter with a diagonal

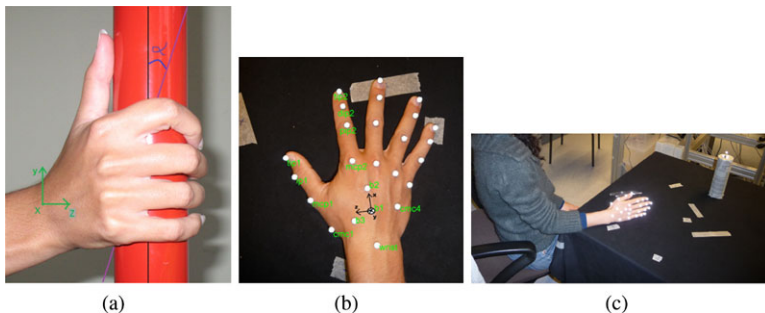


Fig. 1 (a) Human grasp of a cylindrical object with a diagonal volar grasp. (b) Marker configuration with reference frame in black; (c) Subject starting position. The markers on the object allow identifying its position.

volar grasp (Fig. 1(a)) for 10 times each. 25 reflective markers of 6 mm diameter were placed on their right hand as shown in Fig. 1(b). All subjects gave informed consent to participate in the study.

According to results in the literature [11, 12], the protocol for positioning markers on the hand has been chosen in order to minimize artifacts, due to skin movements or marker occlusion, and for obtaining information about the wrist position (a reference point for the grasping algorithm).

The participants were seated in front of a table on which the cylindrical object was located in a-priori known position. Hand starting position and initial posture were the same for all the participants (Fig. 1(c)). The hand starting configuration was the one in which the four fingers were fully extended and the thumb was adducted. The marker positions were recorded in this starting position and during all the trial until the hand grasps the object. The object position was identified by 4 markers placed on the top of the cylindrical object, as shown in Fig. 1(c). Every subject was asked to grasp the object, without lifting it, ten times. Before starting the data acquisition, each participant was asked to grasp the object five times for training.

2.1 Data Analysis and Results

The Vicon Nexus 1.6.1 Software package has been used to reconstruct marker Cartesian positions with the Vicon system and a link model of the hand has been constructed. In order to understand if a common behavior among subjects can be observed during the grasping action, two performance parameters have been extracted from the collected data: (i) the radius of curvature of every finger (i.e. the radius of the osculator circles tangent, at each joint, the spline passing throughout the finger joints); (ii) the adduction/abduction angle between the fingers (i.e. the angle between two adjacent fingers, subtended by the distance between the PIP joints of the two fingers). For calculating the above parameters, the last frame of each trial

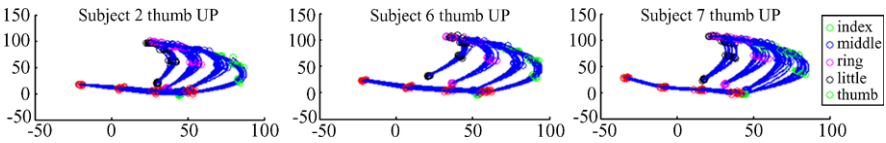


Fig. 2 Curvature of the long fingers during diagonal volar grasp. For space reasons only 3 samples are shown.

Table 1 Mean and standard deviation of radius of curvature in diagonal volar grasp for the index finger.

Subject #	PIP joint		DIP joint	
	Mean (mm)	SDV	Mean (mm)	SDV
1	28.96	3.01	32.83	5.34
2	22.81	0.93	30.97	8.30
3	25.32	1.97	26.36	1.48
4	33.54	2.32	27.19	2.44
5	29.10	1.27	36.35	4.23
6	29.80	1.66	34.06	4.22
7	31.98	3.51	30.95	2.64

Table 2 Mean and standard deviation of the adduction/abduction angle (in degrees) of the MCP joints in diagonal volar grasp.

Subject #	MCP ₂₋₃		MCP ₃₋₄		MCP ₄₋₅	
	Mean	SDV	Mean	SDV	Mean	SDV
1	31	2.7	29.11	2.18	25.64	1.49
2	37.8	1.49	24.42	1.28	20.88	1.70
3	36.98	1.38	20.71	0.62	23.34	3.25
4	36.44	4.19	21.31	1.34	21.05	0.85
5	36.88	1.36	20.74	0.18	24.67	0.45
6	32.09	1.52	26.40	0.61	29.76	2.4
7	35.48	3.37	22.98	1.41	28.24	3

has been considered for each subject. They are expected to provide useful information about the configuration of all the fingers during grasping. Figure 2 shows the curvature of all the fingers when grasping the cylindrical object with a diagonal volar grasp. The blue lines are the splines passing throughout the hand joints outlined with different colors, as explained in the figure legend. Furthermore, in Table 1 mean value and standard deviation of finger curvature radii during a diagonal volar grasp are listed. The MetaCarpophalangeal (MCP) and fingertip (TIP) radii values are not reported since they are obviously very high. The mean is calculated for each subject during the 10 trials. A quite similar behavior among different subjects can be observed. In Table 1 only the behavior of the index finger is reported for brevity, but the results are similar also for the other fingers. In Table 2 mean and standard deviation of the adduction/abduction angle (in degrees) of the MCP joints are listed. In particular, MCP_{2-3} , MCP_{3-4} , MCP_{4-5} are the angles between the index finger and the middle finger, between the middle finger and the ring finger and between the ring finger and the little finger, respectively.

These findings allow us to say that subjects with different hand size grasp the cylindrical object with the same long finger configuration independently of the hand dimension. Therefore, it is possible to use the hand joint position for validating the grasping algorithm and for introducing the MCP adduction angles.

3 Bio-Inspired Grasping Algorithm for a Robotic Hand

The wrist plays a fundamental role in the grasping action, i.e. it guides the hand to the grasp position and adjusts the orientation on the basis of the grasping type and task. This is the reason why one marker has been positioned on the hand of the examined human subjects during the motion analysis and why a point on the wrist, called CarpoMetaCarpal (CMC) joint, is considered in the following as reference point for the bio-inspired grasping algorithm for determining the position of the other hand joints.

The algorithm was proposed in our previous work [10] and had the purpose of predicting the optimal hand configuration for stably grasping a cylindrical object, given the size of the object and its location in the space. The starting hypothesis is that the long finger optimal configurations for grasping a cylindrical object with a diagonal volar grasp is the one that minimizes the sum of the distances between the hand joints and the object surface. In particular, the position of the CMC joint that guarantees a stable grasp configuration can be obtained by minimizing the objective function given by the sum of the distances of all finger joints from the object surface. Providing the CMC coordinates and the distances of the joints from the object surface, in addition to some geometrical considerations (such as the adduction/abduction angles obtained from the motion analysis system), all the joint coordinates are computed for the four long fingers with a human-like optimal grasp configuration.

4 Experimental Validation of the Grasping Algorithm

The experimental validation of the algorithm mentioned in Section 3 on a real arm-hand robotic system has been carried out. The experimental platform (Fig. 3(a)) is composed of the MIT-Manus planar robot, acting as the arm to realize the reaching task, and the DLR-HIT-Hand II mounted at the MIT-Manus end-effector, which is responsible for preshaping and grasping.

The five-fingered dexterous robotic hand DLR-HIT-Hand II has five identical modular fingers with four DOFs each. The last two joints (proximal and distal) are 1 : 1 coupled, meaning that the corresponding flexion/extension angles are equal. The thumb is mechanically constrained to assume a fixed opposition of 35.51° in the xy -plane with an inclination, with respect to z -axis, of 44.13° ; this only enables transverse volar grasps with a fixed thumb inclination. Therefore, during the experiments, the thumb has been disabled in order to perform a power grasp with only the four long fingers.

The object to be grasped is a cylinder with given shape, weight and position. The initial configuration of the hand joints, as well as the optimal configuration from the algorithm have been provided in the MIT-Manus reference frame. Being the MIT-Manus planar, the arm and hand height from the table could not be varied. Consequently, the object was properly located in order to allow closing the middle

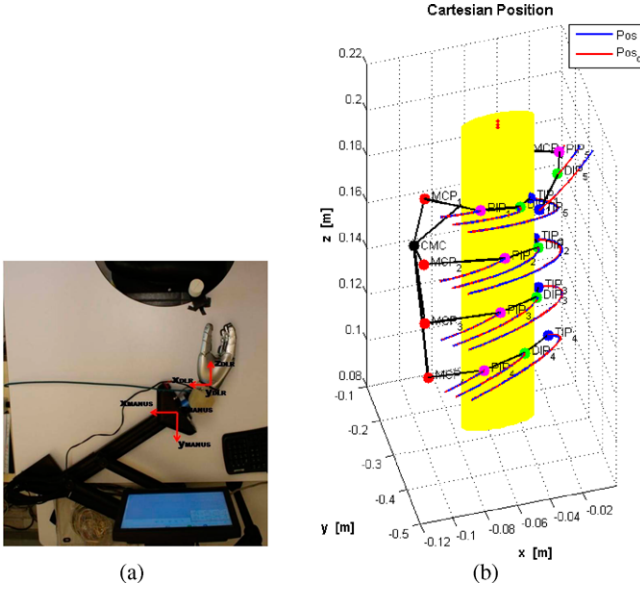


Fig. 3 (a) Experimental setup. The DLR-HIT-Hand II and MIT Manus reference frames are shown. (b) Hand joints trajectory in the Cartesian space for the DLR-HIT-Hand II grasping the cylindrical object with radius 0.020 m.

finger at half of the object height. This assumption was coherent with findings of our experiment.

Given the object position, the optimal CMC Cartesian position and the final hand configuration for grasping the object were obtained through the MATLAB function *fminsearch*(*f*, [*initialcondition*]). During the reaching movement, the hand has been moved by the arm towards the optimal CMC position. Thus, the hand has been controlled in order to reach the final MCP, PIP, DIP joint angles, also provided by the optimization algorithm. During reaching, the hand cannot change orientation, being arm motion planar: z_{DLR} -axis is always parallel to y_{MANUS} .

A fifth order polynomial function has been used to plan the MIT-Manus linear motion from initial position up to final position. Then, a proportional-derivative (PD) torque control in the Cartesian space has been used to control arm position (and consequently CMC position) in the plane.

As regards preshaping, final MCP, PIP and DIP joint positions, provided by the optimization algorithm, have been taken as reference for the DLR-HIT-Hand II motion controller. A third-degree polynomial function has been used to plan joint motion up to the final reference value and a PD torque control in the joint space

enabled reaching the desired final angles. It is worth noticing that, in the DLR-HIT-Hand II, the DIP and PIP joints are coupled with $\theta_{DIP} = \theta_{PIP}$, thus providing a constraint to the final position of PIP and TIP, that was often slightly different with respect to the desired one. The obtained results are shown in Fig. 3, where the joint trajectories are reported in the Cartesian space. For the arm, a point-to-point movement has been performed in 3.0 s for each trial, starting from the initial position $P_i = [-0.1 \quad 0.1]^T$ m to final position $P_f = [-0.0975 \quad -0.1245]^T$ m. The final position, reported only for grasping an object with radius of 0.020 m for sake of brevity, takes into account the CMC position supplied by the algorithm $CMC = [-0.0975 \quad -0.179 \quad 0.15]^T$ m as well as the offset between the arm end-effector and the hand CMC due to the flange that connects the DLR-HIT-Hand II to the MIT-Manus robotic arm. The cylindrical objects to grasp have radii 0.0225 m and 0.020 m and have been located in $(-0.051, -0.257)$ m in the MIT-Manus reference frame.

Table 3 reports the actual Cartesian coordinates for each joint of the robotic hand performing the task of grasping an object with radius of 0.0225 m and compares them with the Cartesian coordinates produced by the optimization algorithm and with those measured by the Vicon system. The values in the last column regard an object with radius of 0.03 m. Moreover, the reference frame is not coincident with the hand wrist, but is positioned as shown in Fig. 1(b). This is the reason why the z -coordinate of the values taken with the Vicon system are different from the values obtained with the other two systems. In particular, the z -coordinate of the hand wrist is -0.056 m in this reference frame. By taking into account this offset, it is possible to note a quite similar behavior among the algorithm output, the robot position and the Vicon results. The small differences in the Cartesian coordinates for the robotic hand are due to its mechanical structure that constrains the DIP joint motion in a different way with respect to the human hand. The obtained results allow us to conclude that the hand configuration obtained with the optimization algorithm is similar to the stable one assumed by the human beings.

Table 3 Joint Cartesian coordinates resulting from the optimization algorithm, measured on the robotic hand and obtained by the Vicon system.

"Cartesian position"						
Finger index	Joint	Algorithm	Robotic hand			Vicon system
	MCP	$[0 \quad 0.045 \quad 0.088]^T$ m	$[-0.0025 \quad 0.0368 \quad 0.1078]^T$ m	$[-0.0143 \quad 0.011 \quad 0.043]^T$ m		
	PIP	$[0.0485 \quad 0.0468 \quad 0.1040]^T$ m	$[0.0264 \quad 0.0343 \quad 0.1545]^T$ m	$[0.029 \quad 0.014 \quad 0.073]^T$ m		
	DIP	$[0.0672 \quad 0.0454 \quad 0.0877]^T$ m	$[0.0513 \quad 0.0321 \quad 0.1526]^T$ m	$[0.057 \quad 0.018 \quad 0.073]^T$ m		
middle	MCP	$[0.0012 \quad 0.0100 \quad 0.0977]^T$ m	$[-0.0037 \quad 0.0100 \quad 0.1178]^T$ m	$[0.0037 \quad -0.009 \quad 0.042]^T$ m		
	PIP	$[0.0541 \quad 0.0100 \quad 0.1126]^T$ m	$[0.0437 \quad 0.0100 \quad 0.1457]^T$ m	$[0.044 \quad -0.008 \quad 0.063]^T$ m		
	DIP	$[0.0716 \quad 0.0100 \quad 0.0947]^T$ m	$[0.0655 \quad 0.0100 \quad 0.1335]^T$ m	$[0.074 \quad 0.008 \quad 0.057]^T$ m		
ring	MCP	$[0 \quad -0.0250 \quad 0.0925]^T$ m	$[-0.0025 \quad -0.0168 \quad 0.1126]^T$ m	$[0.011 \quad -0.026 \quad 0.031]^T$ m		
	PIP	$[0.0515 \quad -0.0268 \quad 0.1093]^T$ m	$[0.0409 \quad -0.0130 \quad 0.1462]^T$ m	$[0.054 \quad -0.019 \quad 0.046]^T$ m		
	DIP	$[0.0695 \quad -0.0253 \quad 0.0922]^T$ m	$[0.0641 \quad -0.0110 \quad 0.1371]^T$ m	$[0.080 \quad -0.061 \quad 0.042]^T$ m		
little	MCP	$[-0.0035 \quad -0.0600 \quad 0.0735]^T$ m	$[0.0010 \quad -0.0434 \quad 0.0936]^T$ m	$[0.021 \quad -0.041 \quad 0.020]^T$ m		
	PIP	$[0.0365 \quad -0.0635 \quad 0.0905]^T$ m	$[0.0313 \quad -0.0380 \quad 0.1391]^T$ m	$[0.056 \quad -0.031 \quad 0.030]^T$ m		
	DIP	$[0.0584 \quad -0.0615 \quad 0.0794]^T$ m	$[0.0559 \quad -0.0337 \quad 0.1409]^T$ m	$[0.073 \quad -0.026 \quad 0.032]^T$ m		

5 Conclusion

Experiments for validating a biologically inspired approach for finding the optimal grasp configuration have been performed. The algorithm has been improved with some geometric considerations obtained from the analysis of the human grasping action. The realized experiments have been described and the obtained data have been analyzed. They allowed us to maintain that the hand configuration obtained by the optimization algorithm is similar to the stable one recorded with the Vicon motion analysis system. The algorithm has been validated through experimental trials on a real arm-hand robotic system, composed of the MIT-Manus robot arm and the DLR-HIT-Hand II. Experimental results on the described robotic platform have proven its feasibility and reliability but have also shown limitations in the grasping tasks due to the constraints imposed by the mechanical structure, not adequately similar to the human structure.

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