

Human Hand Motion Analysis and Synthesis of Optimal Power Grasps for a Robotic Hand

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Abstract Biologically inspired robotic systems can find important applications in biomedical robotics, since studying and replicating human behaviour can provide new insights into motor recovery, functional substitution and human-robot interaction. The analysis of human hand motion is essential for collecting information about human hand movements useful for generalizing reaching and grasping actions on a robotic system. This paper focuses on the definition and extraction of quantitative indicators for describing optimal hand grasping postures and replicating them on an anthropomorphic robotic hand. A motion analysis has been carried out on six healthy human subjects performing a transverse volar grasp. The extracted indicators point to invariant grasping behaviours between the involved subjects, thus providing some constraints for identifying the optimal grasping configuration. Hence, an optimization algorithm based on the Nelder-Mead simplex method has been developed for determining the optimal grasp configuration of a robotic hand, grounded on the aforementioned constraints. It is characterized by a reduced computational cost. The grasp stability has been tested by introducing a quality index that satisfies the form-closure property. The grasping strategy has been validated by means of simulation tests

and experimental trials on an arm-hand robotic system. The obtained results have shown the effectiveness of the extracted indicators to reduce the non-linear optimization problem complexity and lead to the synthesis of a grasping posture able to replicate the human behaviour while ensuring grasp stability. The experimental results have also highlighted the limitations of the adopted robotic platform (mainly due to the mechanical structure) to achieve the optimal grasp configuration.

Keywords Human Hand Motion Analysis, Grasping Indicators, Hand Kinematics, Human-like Grasping Strategy, Arm-hand Robotic System

1. Introduction

In recent years, robots have been applied to a wide range of areas, coming into closer and closer contact with human beings [1] – [4]. It has been predicted that in the next decade a robot will be in every home, thus becoming part of humans' everyday life [5]. In this scenario, the usefulness of endowing robots with the same manipulation skills as that of human beings has

been highlighted. Attempts in this direction include the development of robotic hands as similar as possible to the human hand from both the aesthetic as well as the functional point of view [1] and, consequently, new approaches for reproducing human hand motion. They can resort to observation and analysis of hand motion [6], [7] or else, to learning-by-demonstration approaches [8].

Several approaches to robotic hand grasp planning, able to fulfil dexterity, stability and closure properties, have been proposed. In particular, a grasp is defined stable when the object immobility is ensured. The work in [9], [10] proposed grasping synthesis algorithms for the determination of force-closure grasps through the optimization of objective functions. The main drawback of these methods is the high computational cost. In [11], after heuristically generating a set of feasible grasp candidates on the basis of the characteristics of the object, grasp quality measures have been used to choose the best grasp. In [12], the best location of the robotic hand in the space of feasible grasp configurations is researched. The main limitations of this approach are the high dimension of the solution space in the grasp optimization and the need for computing the hand inverse kinematics in order to guarantee that the object contact points are physically reachable by the robotic hand. Empirical approaches are based on the imitation of human grasping strategies by choosing the hand configuration that fits the task constraints as well as the object characteristics. Learning by demonstration approaches belong to this category and are based on: i) observation of the human subject performing the task and replication through robotic systems; ii) object observation: the robotic system learns the association between object relevant characteristics and different hand configurations, contained in a database, in order to compute natural grasping configurations appropriate to the task. In order to reduce the high dimension of the grasp space and the hand control complexity, it has been investigated whether humans use a combination of basic grasp configurations for prehensile postures [13], [14], [15]. This research has shown that a wide range of grasping tasks can be achieved through a reduced number of basic hand configurations. In [16], the authors have used linear combinations of *eigengrasps* to obtain a wide range of hand postures for grasping tasks; however, they have not studied the problem of deriving the optimal posture subspaces. Shape-matching approaches are proposed in [17], where the best matching between object contact points and a small database of known human hand poses is searched for. However, the algorithm can also produce in output unusual grasp configurations.

From the aforementioned research, it is possible to conclude that the best grasp configuration depends on hand kinematics, on the task to be performed and on the physical characteristics of the object to be manipulated. Hence, the objective of this paper is twofold: (1) to observe human motion for extracting hand kinematic parameters and indicators related to a particular grasping task and to describe the task in a quantitative way; (2) to introduce these constraints in an optimization grasping algorithm

for defining the optimal configuration of a robotic hand to ensure a stable grasp when performing the same task studied with humans. The specific case of the power transverse volar grasp is investigated. Therefore, a general rule for synthesizing a stable, human-like cylindrical grasp with a robotic hand is proposed in order to provide the basis for finding an optimal grasp configuration always applicable to certain grasping conditions. An optoelectronic motion analysis system has been used for collecting information about the thumb and fingers of the human subjects during grasping. A protocol for the reconstruction of hand joint motion has been proposed. A set of quantitative indicators has been defined for the description of human behaviour and the development of the grasping algorithm able to replicate the same observed behaviour on a robotic hand. They account for:

- The form-closure property defined in [18] (i.e., the ability of the hand to prevent motions of the grasped object, relying only on unilateral, frictionless contact constraints). It is a necessary and sufficient condition for a stable grasp. By analogy with the work in [19], the form-closure property [18] is applied to the human case as a quality index to assess the stability of the performed human grasp as well as the output of the proposed grasping algorithm.
- The thumb behaviour. Despite the fundamental role of the thumb played during the grasping action, there is a sizeable lack of information in the robotic literature about its behaviour. Despite there being several studies about the identification of a valid thumb kinematic model [20], [21], nevertheless, adequate information regarding the analysis of thumb functional aspects is lacking and a motion analysis on human subjects has been performed to retrieve this information.

The extracted quantitative indicators have been chosen in accordance with the neuroscientific study in [22], to support in a measurable way the results on the optimal configuration of the 4 long fingers (i.e., from index to little finger) for a diagonal volar grasp. Furthermore, the chosen indicators identify an invariant behaviour between different subjects, thus allowing the detection of invariants in the grasping configuration. These invariants provide constraints for the grasping algorithm and for reducing its complexity. Here, the approach in [22] has been extended to the transverse volar grasp (which is more commonly used than the diagonal volar grasp) and the optimal thumb configuration has been searched for. To this purpose, the behaviour of six human subjects has been investigated during the execution of both diagonal and transverse volar grasps, the approach in [22] has been verified for the 4 long fingers and the thumb configuration has been studied (Fig. 1).



Figure 1. Diagonal volar grasp (left) and transverse volar grasp (right)

The validity of the proposed grasp synthesis algorithm in terms of grasp stability has been tested in three different ways: i) by comparing joint angles and positions obtained from the grasping algorithm with the data directly measured on the human subjects; ii) by evaluating the aforementioned form-closure quality index; iii) by testing the algorithm on a real arm-hand robotic platform composed of the MIT-Manus robot arm and the DLR-HIT-Hand II.

The paper is structured as follows: in Section 2, the protocol developed for hand motion tracking is described; Section 3 is focused on the analysis of the human behaviour and on the quantitative indicator choice, describing the experimental setup, the experimental protocol and the obtained results; Section 4 introduces the optimal grasping algorithm developed for the five fingers, based on the results on humans; the comparison between measurements on human subjects and output of the grasping algorithm is proposed in Section 5, through the same set of parameters. The stability of the approach is proved in Section 5.2 by introducing the grasp quality index; in Section 5.3, the experimental results on a real robotic platform are illustrated. Finally, Section 6 addresses conclusions and future work.

2. Kinematic Model and Protocol for Hand Motion Tracking

Since one of the paper's objectives is to determine quantitative indicators for developing a synthesis grasping strategy for a robotic hand, a protocol for tracking hand motion and reconstructing joint angles starting from the marker positions acquired with an optoelectronic motion analysis system is proposed.

For describing human hand kinematics, different kinematic models have been proposed in the literature [23]. They differ for simplifying assumptions especially related to the number of DOFs and the position and orientation of the Axis of Rotation (AoR) [24], [25], [26], [27]. Therefore, a first effort consisted of determining an appropriate model for describing finger behaviour during grasping. The kinematic model that fits with the purpose of this work consists of 21 DOFs [28]: five for the thumb and four for each of the long fingers. Each finger is regarded as a single open kinematic chain. A motion analysis technique has been used to measure joint angles. Joint angle values have been determined placing 25 reflective markers of 6 mm diameter on the volunteer's right hand, as shown in Fig. 2(a). The protocol for positioning markers on the hand has been chosen in order to minimize artefacts, due for example to skin movements or marker occlusion, and obtain information about wrist position (which is a reference point for the grasping algorithm in Sect. 4).

Three markers (called $b1$, $b2$, $b3$) have been positioned on the hand dorsum, i.e., the part of the hand that suffers less from skin movements; they constitute the system reference frame (in green in Fig. 2(b)). In this study, the axes of rotation of the long finger MCP joint and thumb

TM and MCP joints are defined as shown in Fig. 2(b) and F/E axes of PIP, DIP and TIP joints are hypothesized parallel to each other.

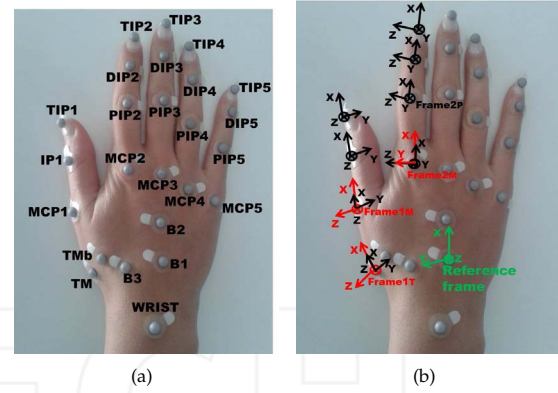


Figure 2. (a) The adopted protocol for marker positioning. Joint labels are outlined in black. (b) Joint reference frames. The system reference frame, positioned on the hand palm and outlined in green, has the X-axis along the line connecting the marker $b1$ with the marker $b2$, the Y-axis perpendicular to the palm plane and the Z-axis defined with the right hand rule.

Given our hypothesis that the AoR of TM joint and MCP joints are incident and perpendicular, it is possible to resort to the protocol introduced in [29] for the upper-limb to evaluate hand joint angles. In particular, the protocol in [29] allows determining upper-limb joint angles (shoulder, elbow, wrist) starting from the position of markers conveniently placed on the arm and resorting to Euler angles representation. Analogously, in this paper, the action of long finger MCP joints and of the thumb TM joint is represented by a sequence of three elementary rotations (with respect to X, Y and Z axes) expressed by a set of Euler angles. Actually, for each image frame, the 3D marker positions acquired with the optoelectronic system are used for obtaining unit vectors representing the axes of joint reference frames.

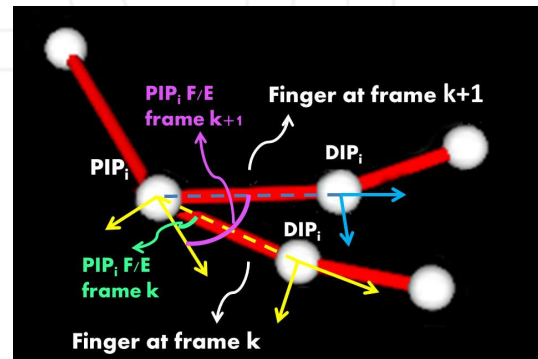


Figure 3. Finger position in two different frames. The DIP joint reference frame is outlined in yellow at frame k , whereas it is in blue at frame $k+1$. The proposed protocol determines joint rotation frames at each video frame. The relative position of two consecutive joint rotation frames gives joint angle values. PIP F/E angle is in green at frame k , in violet at frame $k+1$.

With reference to Fig. 3, the orientation of $Frame_i^j$ with respect to $Frame_{i-1}^j$ (where $i = 1, \dots, 5$ enumerates fingers and $j = 1, \dots, 4$ enumerates the finger joints, from MCP—TM for the thumb—to TIP) are parameterized via ZYX Euler angles representation. In the analysed case, the rotation around X is set equal to zero. The A/A angle is evaluated as the rotation around Y-axis, while the F/E angle is given by the rotation around the Z-axis.

3. Hand Motion Analysis

3.1. Experimental Setup

The proposed protocol for reconstructing hand joint motion has been used for analysing data obtained from tests on healthy subjects and extracting some indicators of the human hand joint behaviour during grasping. The indicators allow us to quantitatively describe the hand joint configuration during grasping. They are partly chosen in order to verify some assumptions made in our previous work [30] (where a simplified version of the grasping algorithm, valid only for 4 fingers, has been introduced) and partly grounded on geometrical considerations on the hand configuration.

Six right-handed human subjects (two men and four women), aged 28.6 on average (Standard Deviation 5.35) volunteered to participate in this study. Subjects were asked to grasp three cylindrical objects characterized by different diameters and heights but with a homogeneous weight (Fig. 4). The participants had to grasp each object with a transverse volar grasp. Each grasping action was repeated 6 times. They were seated in front of a table on which the cylindrical objects were located in an a-priori known position (outlined with the green cross on the table in Fig. 4). Hand starting position (white cross in Fig. 4) and initial posture were the same for all the participants. The shoulder was abducted of 0° in the frontal plane and flexed with an angle of 0° in the sagittal plane. The elbow was flexed with an angle of 90° in the sagittal plane. The wrist was in a neutral position with 0° for flexion/extension and 0° for radio-ulnar deviation. In the hand starting configuration the four fingers were fully extended and the thumb was adducted. The marker positions were acquired with the optoelectronic system BTS SMART-D Motion Capture System. This is a seven-camera motion analysis system with an acquisition rate of 60 Hz. In particular, the BTS Smart Analyzer software package was used to reconstruct the marker Cartesian positions and a link model of the hand was constructed. The marker



Figure 4. Objects to be grasped. Object A is 60 mm diameter and 150 mm height; Object B is 66 mm diameter and 340 mm height; Object C is 40 mm diameter and 235 mm height.

positions were recorded in the starting position and during the whole trial until the hand grasped the object. Three markers were positioned on the objects, as shown in Fig. 4: the first one was positioned at the top centre, the second and the third one on the opposite sides of the cylinders respectively on the upper and lower extremities. Therefore, from markers Cartesian positions it is possible to extract the position of the object with respect to the camera and the hand reference frames, the object radius, the height, and the centre of mass (which is supposed to be located at the centre of the object). After grasping, the subject held the object for a while, until an auditory cue announced the acquisition end. Before starting the data acquisition, each participant was asked to grasp the object five times, for familiarizing with the grasping action.

3.2. Data Analysis

Due to our aim of extracting quantitative indicators for describing hand optimal behaviour, the accuracy of the proposed joint reconstruction method needs to be assessed. In fact, joint angles are used to compute the indicators and to extend the results to a robotic hand. Therefore, data analysis has the twofold purpose of (i) verifying the accuracy of the motion reconstruction protocol; (ii) searching for a general rule capable of describing the human strategy for grasping cylindrical objects with a transverse volar grasp.

On issue (i), the validation of the reconstruction protocol has been carried out as proposed in [25], [31], by comparing the marker positions directly measured by the optoelectronic system and those reconstructed by the angles computed with the protocol. Once data on marker Cartesian positions have been collected with the BTS system, Denavit-Hartenberg parameters have been extracted and the joint angles have been determined as explained in Sect. 2. To verify the accuracy of the joint reconstruction, marker positions have been calculated by applying the forward kinematics to the obtained joint angles.

The error between the marker Cartesian components provided by the BTS system and those obtained from the forward kinematics has been evaluated for each hand joint and for all the trials performed by each subject. Error values for the PIP, DIP and TIP Cartesian positions of each finger are reported in Fig. 5 for one subject and one object, for the sake of brevity. A similar behaviour has been observed for the other subjects and the other objects.

In order to evaluate the accuracy of the reconstruction model, the indicators proposed in [25] have also been computed. The invariance of the behaviour of each subject has been evaluated through six repetitions of the same task. Thus, mean and standard deviations of the indicators over more trials of the same subject and over all the subjects have been computed; the invariance is mainly assessed through the standard deviation. Two parameters have been evaluated to measure subject accuracy on one complete task and over multiple repetitions of the same

task. They are calculated as follows for each performed task:

$$\Delta_r = \sqrt{\frac{\sum_i |P_i^* - P_i|}{N}} \quad \Delta = \sqrt{\frac{\sum_r (\Delta_r)^2}{M}} \quad (1)$$

where P_i^* and P_i are the reconstructed and measured position of the marker i , N is the number of frames, M is the number of repetitions of the same task. In particular, Δ_r represent the reconstruction accuracy during one trial performed by one subject, whereas Δ is the reconstruction accuracy during M repetitions of the same motion patterns. In Fig. 6, Δ_r parameter is reported. In particular, it has been evaluated during all the trials for each finger TIP of each subject. In Fig. 6, mean and standard deviations of Δ_r over six trials for each subject and for each finger are shown.

The values of these two parameters is always less than 4 mm and the values of the error between the marker positions directly provided by the BTS system and those obtained with the forward kinematics are also small. The highest position error is on the z-component and is at maximum equal to 9 mm. Note that this is due to two factors: (a) the finger anatomy is slightly different from the modelled one: fingers actually are not cylinders, but truncated cones slightly curved along the z-axis. (2) There is an error propagation along the kinematic chain of approximately 5 mm; this corresponds to the difference between the error on TIP joints (its average value is 5 mm) and the error on PIP joints (which is null). These values satisfy the expected accuracy for the purpose of the kinematic reconstruction.

On the second issue (ii), subject behaviour has been investigated to search for a general rule able to synthesize a stable transverse volar grasp. In order to reduce the complexity of the search for the optimal grasp configuration, some constraints have been imposed. These constraints are expressed by means of indicators retrieved with the proposed protocol for hand motion analysis and able to quantitatively describe hand behaviour. They are used for verifying the assumption in [22] that during a volar grasp the sum of the distances between the hand finger joints and the object CoM is minimal. Additionally, they are also used to describe the thumb behaviour, neglected in [22]. The set of extracted indicators is as follows:

1. The distances between the hand joints and the object Centre of Mass (CoM).
2. X-coordinate of the MCP joint of the little finger (this represents a reference point for the algorithm presented in Sect. 4).
3. The radius of curvature of every finger: this is the radius of the osculator circle tangent, at each joint, to the spline passing throughout the finger joints.
4. The aperture angle of the hand: this is calculated as the angle between the link connecting the MCP joint of the thumb to the wrist and the link connecting the MCP joint of the index finger to the wrist.
5. The thumb TM joint position with respect to the wrist Cartesian coordinates.
6. The thumb opposition angle.

In order to compute the thumb opposition angle, two additional indicators have been calculated:

- the angle between the X-axis and the projection onto the xy -plane of the link connecting the MCP joint of the index finger and the TM joint of the thumb;
- the angle between the projection of the link connecting the thumb TM and MCP joints onto the Y-axis and the link.

The above indicators are expected to provide useful information about the configuration of all the fingers during grasping. The first two indicators are used to support the assumptions introduced in Sect. 4 for the proposed grasping algorithm. The third indicator allows verifying the results on the long fingers reported in [22] during diagonal volar grasp and extending them to the transverse volar grasp. The fourth indicator is useful for understanding the position of the thumb during grasping, while the fifth one (computed via the last two indicators) is used for assessing the experimental results on the robotic hand and comparing them with the human case.

3.3. Results on Human Subjects

Data on human subjects have been processed and the indicators listed above have been computed, as explained in the following.

1. According to the neuroscientific study proposed in [22], during a diagonal volar grasp the sum of the distances between the hand finger joints and the object CoM is minimal. With the purpose of verifying this assumption, the distances between hand joints and object CoM have been computed; they have been compared to the sum of the finger thicknesses plus the object radius. It has been supposed that this sum is the minimum distance between the finger joint and the object CoM during power grasps. In Table 1, the error between the above two quantities during the grasp of the cylinder of 40 mm in diameter is reported for the sake of brevity only for the index finger (on the left of Table 1) and the thumb (on the right of Table 1). A similar behaviour has also been obtained for the other finger joints.
2. The X-coordinate of the little finger MCP joint is an important value for the algorithm development. In fact it is hypothesized that this coordinate is equal to the X-coordinate of the object CoM. By analysing the acquired data it is possible to note that the difference between these values is equal to 2-3 mm on average.

Long fingers			Thumb		
Joint #	Mean [mm]	SDV	Joint #	Mean [mm]	SDV
MCP	-2.03	±0.34	MCP	4.72	±0.68
PIP	2.27	±0.48	IP	5.9	±0.59
DIP	3.16	±0.81			
TIP	3.23	±0.69	TIP	2.73	±0.31

Table 1. Error between the distance of the finger joints from the CoM and the sum of the finger joint thicknesses and the object radius

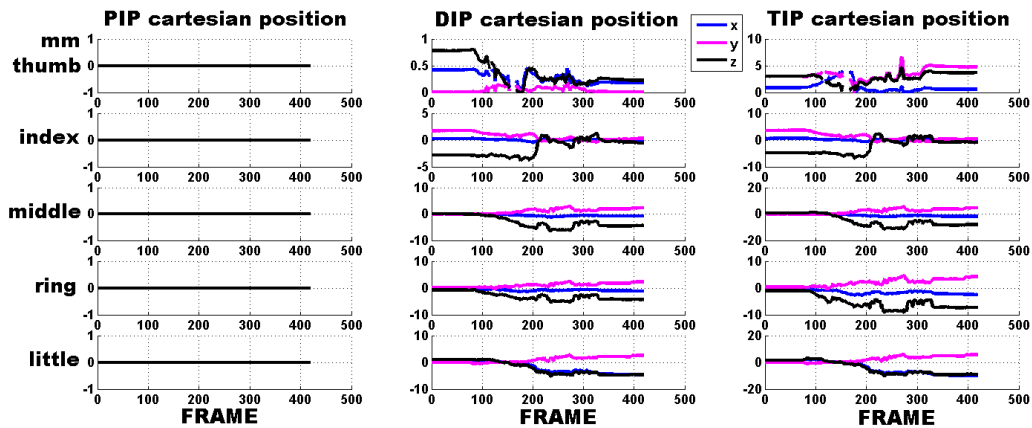


Figure 5. Errors between the marker positions directly measured with the BTS and reconstructed with the kinematic model. The data are concerning one subject performing the transverse volar grasp of the 40 mm diameter cylinder.

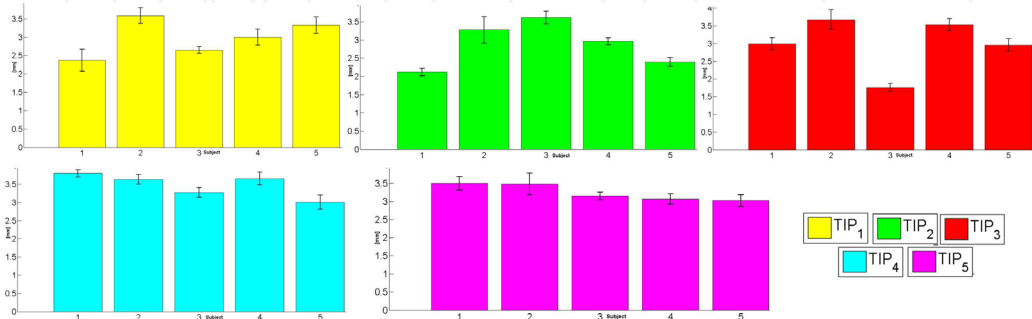


Figure 6. Δ_r indicator values.

3. By analysing the radius of curvature of every long finger (see Fig. 7), it is possible to observe a very similar behaviour, for the same subject, for the two power grasp configurations, i.e., diagonal and transverse volar grasps. This finding supports the extension of the optimization algorithm to the transverse volar grasp. In other words, one subject grasps a cylindrical object with the same long finger configuration independently on the grasp type. The difference between them lies only in the thumb.
4. The aperture angle is an important parameter for estimating the position of the thumb MCP joint in the optimal grasp. The analysis of the data acquired with the BTS has pointed to an almost constant value of this angle among subjects, for the same type of grasp and for the same object. In Tab. 2, mean and standard deviations of hand aperture angle during the six trials are listed for the transverse volar grasps. For the sake of brevity, the listed values are related only to the object with diameter of 40 mm, but the angle invariance among subjects is verified also for the other two objects. In Tab. 3, the mean value and the standard deviations of the aperture angle calculated on all the subjects are reported for each object. Looking at the standard deviation values, the invariance of the angle among subjects can be observed. Hence, the aperture angle plays an important role in the definition of an effective transverse volar grasp and will contribute to describing a general rule about the thumb configuration, together with the position of the TM joint with respect to the wrist.

5. As shown in Fig. 8, the position of the TM joint during the analysed reach-and-grasp actions is also quite invariant. This means that TM joint position with respect to the wrist depends only on the hand kinematic parameters.
6. The thumb opposition angle allows determining the A/A angle of the thumb MCP joint.

Subject #	Mean [rad]	SDV
1	0.9341	± 0.0602
2	0.8971	± 0.0391
3	0.8557	± 0.0166
4	0.9725	± 0.0272
5	0.9837	± 0.0117

Table 2. Mean and standard deviations of hand aperture angle in transverse volar grasp

Object diameter	Mean [rad]	SDV
40 mm	0.9287	± 0.0531
60 mm	1.0524	± 0.0372
66 mm	1.0441	± 0.0737

Table 3. Mean and standard deviations of hand aperture angle in transverse volar grasp for each object

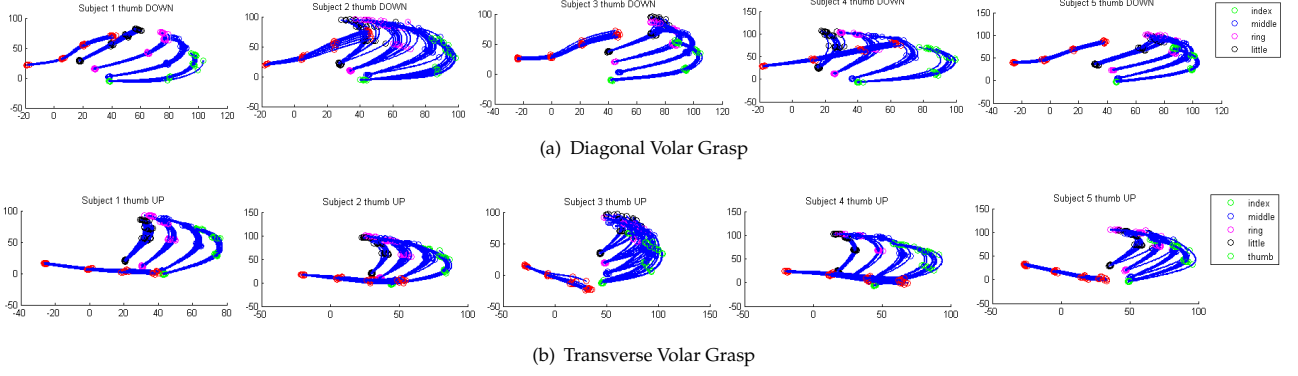


Figure 7. Curvature of the fingers during diagonal and volar grasp

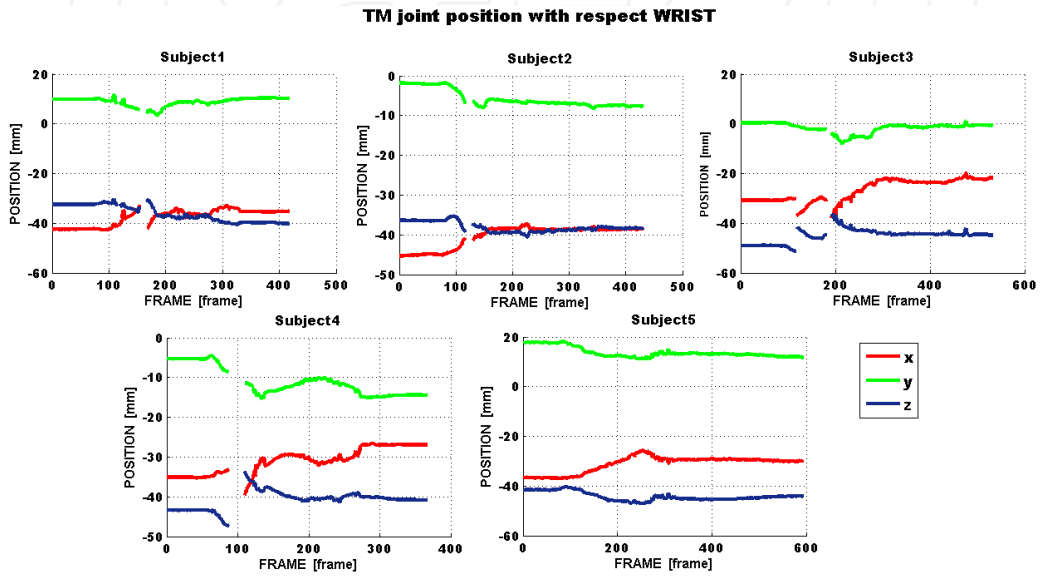


Figure 8. Position of the TM joint with respect to the wrist during the entire grasping action. The behaviour of all subjects grasping the object with a diameter of 40 mm is reported.

As evident from the reported values, the chosen indicators satisfy the property of being invariant intra-subjects and between different subjects during the grasping action.

4. Bio-inspired Grasping Algorithm for a Robotic Hand

Data reported in Sect. 3 and obtained from the analysis of the human hand behaviour are used for developing an algorithm for the synthesis of the optimal power grasp for a robotic hand. This has the purpose of predicting the optimal configuration of a robotic hand for stably grasping a cylindrical object, given the size and the weight of the object and its location in the space. In the case of unknown objects, additional sensors should be considered for an in-depth description of the object characteristics (e.g., force/tactile sensors and/or vision systems). The approach has already been explained in our previous work [30] only for the 4 long fingers, based on two assumptions:

- It has been supposed that the x coordinate of the little finger MCP joint is coincident with the coordinate of the object CoM. This assumption has

been experimentally verified in Sect. 3.1 when the x -coordinate of this joint has been computed.

- In order to establish the height at which subjects grasp the cylindrical objects, it has been hypothesized that the y coordinate of the middle finger MCP joint is coincident with the coordinate of the object CoM, which is located at half of the object height (since objects with a homogeneous weight have been considered) accordingly with studies on human beings in [32].

The results of the human motion analysis in Sect. 3 provide evidence for the validity of the aforementioned assumptions and allow us to introduce the thumb behaviour.

The position of the wrist joint that guarantees a stable grasp configuration for the long fingers can be obtained by minimizing the following expression [22], [33]:

$$f = \sum_{i=1}^4 \sum_{j=1}^3 \text{dist}_j^i(x, \alpha), \quad (2)$$

where

- j is the joint index, ranging from 1 (the MCP joint) to 3 (the DIP joint);
- $dist_j^i(x, \alpha)$ is the distance of the j -th joint of the i -th finger from the object surface. This distance is a function of x , i.e., the wrist x -coordinate in the palm reference frame, and of α , i.e., the inclination angle of the hand reference frame z -axis with respect to the object rotation axis;
- r_{obj} is the object radius.

In particular, for each joint (i.e., MCP, PIP and DIP), the distances from the object surface can be expressed as

$$dist_{MCP}^i = \sqrt{(x_{MCP_i} - x_{obj})^2 + (r_{obj} + t_0)^2} \quad (3)$$

$$dist_{PIP}^i = \sqrt{(a_i - \sqrt{(dist_{MCP}^i)^2 - (r_{obj} + t_1)^2})^2 + (r_{obj} + t_1)^2} \quad (4)$$

$$dist_{DIP}^i = \sqrt{(a_i - \sqrt{(dist_{PIP}^i)^2 - (r_{obj} + t_2)^2})^2 + (r_{obj} + t_2)^2} \quad (5)$$

where

- a_i is the finger length projection on the plane perpendicular to the object rotation axis (plane xy). In this way it is possible to work in this plane, simplifying the approach and considering fingers parallel to each other. Actually, fingers during grasping are inclined by certain angles, therefore, joint Cartesian coordinates determined in the projection plane are brought back to the original planes where each finger lies through a rotation matrix, known as the inclination angle;
- t_i is the finger thickness;
- x_{MCP_i} is the x -coordinate of the MCP joint of the i -th finger in the optimal configuration. Its value depends on the x -coordinate of the initial configuration (i.e., $x_{MCP_i}^{start}$) and on the inclination angle α given by the optimization procedure as follows:

$$x_{MCP_i} = x + (x_{MCP_i}^{start} - x_{MCP_4}^{start}) + (y_{MCP_i}^{start} - y_{MCP_4}^{start}) * \tan \alpha. \quad (6)$$

By minimizing eq. (2), in addition to some geometrical considerations, all the joint coordinates are computed for the four long fingers. In Fig. 9, the procedure for determining all joint positions and angles is schematized.

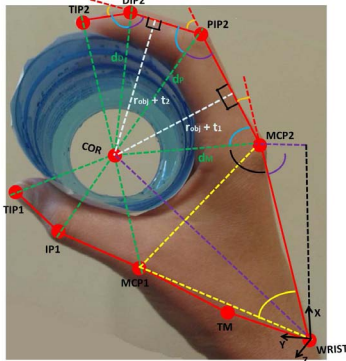


Figure 9. Schematic representation of the scenario in which the algorithm has been developed

Thumb configuration can be obtained by recalling that the hand aperture angle is quite invariant from subject to subject when a transverse volar grasp is performed (see Table 2) and the position of the TM joint with respect to the wrist is almost constant during the grasping movement (Fig. 8). Hence, the thumb MCP joint position can be found with respect to the TM joint and the position of the other thumb joints can be obtained by minimizing the distances from the thumb joints and the object surface by means of eqs. (3)–(6). The opposition angle allows determining the A/A angle of the thumb MCP joint.

The convergence of the proposed non-linear optimization algorithm depends on the choice of the initial condition. By analogy with the typical approach followed by the optimization algorithm, and also considering that for the purposes of our study the hand is not very far from the object to grasp [34], an initial condition close to the expected solution has been chosen. The Nelder-Mead simplex method has been used for solving the optimization problem.

5. Validation of the Bio-inspired Grasping Algorithm

The validity of the bio-inspired grasping configuration obtained from the proposed algorithm has been proved in three different ways: i) a comparison between the data on human subjects collected with the BTS system and the corresponding data obtained from the optimization algorithm in simulation; ii) a measure of the grasp stability by means of a suitable quality index; iii) the experimental validation on a real anthropomorphic robotic hand.

5.1. Comparison between Algorithm Outcome and Acquired Data

In order to validate the goodness of the approach, joint angles and positions obtained with the grasping algorithm applied to simulated hands have been compared with the data directly measured on the human subjects by means of the optoelectronic system. The algorithm has been tested on five different simulated hands characterized by the same kinematic parameters of the volunteers' hands involved in the experiments with the BTS system. For the sake of brevity, only the data related to one subject grasping the cylindrical object of 40 mm in diameter are reported in the following. Therefore, the following comparisons have been done between the data acquired with the BTS system on one subject and the data obtained with the algorithm on the corresponding simulated hand. Special attention is paid to the object with diameter of 40 mm since it is the same as that used in the experimental validation with the robotic hand in Section 5.

In order to understand the error between the hand joint positions obtained with the optimization algorithm and the ones obtained with the BTS system, the two configurations are superimposed in Fig. 10. As previously said, only the registered (the joints are coloured dots in Fig. 10) and estimated (the joints are coloured stars in Fig. 10) behaviours of one subject during the grasping of the 40 mm in diameter object are reported, but similar relative configurations are obtained for all the subjects.

In particular, the mean error between the joint Cartesian positions and angles obtained with the algorithm and the corresponding values obtained with the BTS system on the five subjects vary between a minimum of 3 mm $\pm$ 0.4 mm and a maximum of 6 mm $\pm$ 0.3 mm for the position, and a minimum of 0.05 rad $\pm$ 0.008 rad and a maximum of 0.07 rad $\pm$ 0.009 rad for the angle, respectively. The maximum error is obtained for the middle fingertip (ring DIP joint) and is around 8 mm (0.11 rad).

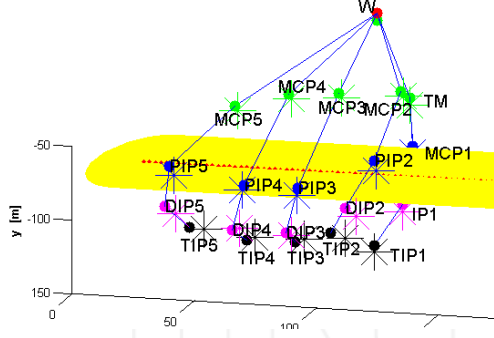


Figure 10. The dots represent the hand joint positions acquired with the BTS system, the stars are the hand joint positions reconstructed with the grasping algorithms

5.2. Evaluation of the Grasp Stability

In order to evaluate stability of grasp configuration, a form-closure quality index [35] is introduced. The form-closure property has been demonstrated to be a necessary and sufficient condition for robot grasp stability and is also stronger than the force closure [8]. In [19], the extension of the form-closure quality index to the human grasp evaluation is proposed and is also used in this paper. In particular, the grasp stability is guaranteed when the distance between the object CoM and the centroid of the contact points is minimized, thus guaranteeing a reduction of gravitational and inertial forces effects during manipulation. The problem is formulated as a non-linear optimization problem:

$$\hat{\theta} = \min(\|y - f(\theta, w)\|) \quad (7)$$

where θ is the set of $n - k$ non-fixed joint variables, i.e., the five thumb joint angles, $\hat{\theta}$ is the set of optimal values of the $n - k$ joint variables, w is the set of the fixed k variables, i.e., hand geometric parameters such as finger segment lengths, $f(\theta, w)$ is the function that, given the finger joint angles of the whole hand, returns the centroid of the contact points and y is object CoM. In particular, the centroid of the contact points can be expressed as

$$f(\theta, w) = \frac{1}{n} \sum_{i=1}^n c_i \quad (8)$$

where c_i is the contact point between the i -th finger and the object (i.e., the finger middle point) and $n = 15$ is the number of contact points.

In [19], the index is normalized with respect to its maximum value (i.e., when the hand is completely open). Therefore, the quality index is given by

$$Q = \text{distance}(y - f(\theta, w)) / \text{distance}_{\max} \quad (9)$$

It varies in the interval $[0, 1]$, where values close to 0 correspond to very stable grasps whereas values close to 1 represent unstable grasps.

In this paper, the index is computed on the data directly acquired on the subjects with the BTS and on the values obtained with the algorithm. The normalized index values are reported in Table 4 and their values range between 0.1 and 0.3 confirming that the optimization algorithm follows the form-closure property. For the sake of brevity, in Table 4 are reported only the mean values for each subject during all the trials and the corresponding standard deviations.

Subject #	BTS	Algorithm
1	0.1477($\pm$ 0.065)	0.1734($\pm$ 0.054)
2	0.2091($\pm$ 0.037)	0.1962($\pm$ 0.035)
3	0.1892($\pm$ 0.022)	0.2302($\pm$ 0.010)
4	0.1938($\pm$ 0.034)	0.2756($\pm$ 0.021)
5	0.1002($\pm$ 0.071)	0.1439($\pm$ 0.059)

Table 4. Normalized form-closure quality index evaluated on data acquired from the BTS and obtained with the algorithm

Moreover, in Fig. 11, the hand closure configuration is reported for the data extracted from the BTS and those computed with the optimization algorithm. The centroid of the contact point calculated on the data acquired with the BTS system (the green point in Fig. 11) is very close to the one calculated with the algorithm data (the red star in Fig. 11): the difference between these two values is around 2 mm. The thumb link middle point positions (P1, M1 and D1 in Fig. 11) are obtained by applying the forward kinematics to the angles calculated with Eq. 7. They are shown in Fig. 11 and compared to the same values measured with the BTS ($P1_{bts}$, $M1_{bts}$ and $D1_{bts}$ in the same figure) and given by the optimization algorithm ($P1_{alg}$, $M1_{alg}$ and $D1_{alg}$ in Fig. 11). The error in thumb joint position is around 3 mm.

5.3. Experimental Validation on an Anthropomorphic Robotic Hand

5.3.1. Experimental Setup

A real arm-hand robotic system has been considered for validating the grasping configuration obtained with the approach described in Sect. 4. The robotic platform (Fig. 12) is composed of the MIT-Manus planar robot, which acts as the arm responsible for the reaching task, and an anthropomorphic robotic hand (i.e., the DLR-HIT-Hand II) mounted at the MIT-Manus end-effector and responsible for preshaping and grasping. The cylindrical object of 40 mm in diameter used for experiments on human beings has been selected because of its size compatible with robotic hand grasping capabilities.

The MIT-Manus system is a planar robotic arm (typically used for upper-limb rehabilitation) with two rotational degrees of freedom, one for the elbow and one for the shoulder angular motion. It reproduces the planar motion

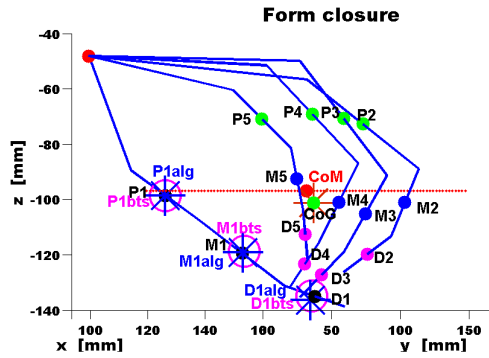


Figure 11. Form-closure configuration



Figure 12. Experimental setup. The DLR-HIT-Hand II and MIT Manus reference frames are shown.

of shoulder and elbow rotational joints of the upper-limb in a workspace of 0.40x0.40 m. It is equipped with two optical absolute encoders and a six-axis JR3 force/torque sensor.

The DLR-HIT-Hand II is a dexterous robotic hand with five identical fingers and an independent palm. Each finger has four DOFs (MCP A/A and MCP, PIP, DIP F/E), of which three DOFs are actuated and one is passive. PIP and DIP joints are 1 : 1 coupled. The thumb is mechanically constrained to assume a fixed opposition of 0.6198 rad in the xy plane with an inclination, with respect to z -axis, of 0.7702 rad; this only enables transverse volar grasps with a fixed thumb inclination. All the active DOFs of the hand are actuated by flat brushless DC motors. Actuators and electronics are embedded in the fingers and palm of the mechanical structure. Furthermore, each finger has three Hall-effect sensors for measuring joint positions, two force/torque sensors and one thermistor as a temperature sensor.

It has been assumed that the shape, weight and position of the object to grasp are known. On the basis of this information, the wrist optimal position and the hand optimal configuration have been obtained by minimizing eq. (2) through the MATLAB function $fminsearch(f, [initialcondition])$. The planar robotic arm has been moved so that the wrist reaches the optimal wrist position in the Cartesian space, given by the algorithm

(i.e., the wrist position given by the grasping algorithm represents the MIT-Manus end-effector position in the Cartesian space. Since the robotic arm and hand cannot change their height and orientation with respect to the table (due to the planar structure of the Mit-Manus), the object has been positioned so that the middle finger MCP joint of the hand grabs the object at half of its height. This choice respects the results reported in Sect. 3.3. In order to move the arm up to the optimal position, a fifth order polynomial function and a proportional-derivative (PD) position control in the Cartesian space have been used. Once the optimal wrist position is reached, the robotic hand is controlled to reach the final MCP, PIP, DIP joint angles, provided by the optimization algorithm. A third degree polynomial function and a PD torque control in the joint space have been used to control the hand for closing the fingers as desired. It is worth noticing that the PIP and DIP joints of the DLR-HIT-Hand II are 1:1 coupled. This represents a constraint for the PIP and TIP positions, which were often slightly different with respect to the desired ones.

The active DOFs involved by the algorithm are reduced to 15, while the hand has been modelled with 21 DOFs. This further reduces the algorithm computational cost which is already quite low due to the simplicity of the minimized function, as shown in Sect. 4.

5.3.2. Experimental Results

In Fig. 13, the trajectories followed by the robotic fingers during grasping are shown. They are commanded to reach the angles given by the optimization algorithm for each joint.

For the arm, a point-to-point movement has been planned in 3.0 s for each trial, starting from the initial position $P_i = [-100 \ 100]^T$ mm to the final position $P_f = [-97.5 \ -124.5]^T$ mm. The final position takes into account the wrist position supplied by the algorithm $wrist = [-97.5 \ -179 \ 150]^T$ mm, as well as the offset between the arm end-effector and the wrist due to the flange connecting the DLR-HIT-Hand II to the MIT-Manus robotic arm. The robotic arm has been controlled for 5.0 s in each trial: (i) three seconds are taken to achieve the final position; (ii) in the last two seconds, the robot holds

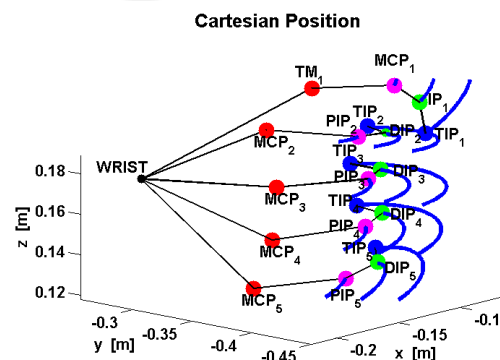


Figure 13. Hand joints trajectory in the Cartesian space for the DLR-HIT-Hand II grasping the cylindrical object with diameter 40 mm

its posture to enable the grasping phase, lasting 1.2 s. The cylindrical object to grasp has been located in $(-51, -257)$ mm in the MIT-Manus reference frame. Once the wrist optimal position has been reached, the hand fingers are moved towards the optimal joint configuration (Fig. 13).

The control gains used for MIT-Manus PD control in the Cartesian space and DLR-HIT-Hand II PD control in the joint space are, respectively

- $K_{PA} = \text{diag}\{850, 850\}$ N/m and $K_{DA} = \text{diag}\{50, 50\}$ Ns/m
- $K_{PM} = 0.3$ Nm/rad and $K_{DM} = 0.02$ Nms/rad for the MCP joint of each finger; $K_{PP} = 0.4$ Nm/rad and $K_{DP} = 0.027$ Nms/rad for the PIP joint of each finger.

For each hand joint, a comparison between the Cartesian coordinates reached by the robotic hand and those provided by the optimization algorithm during the transverse volar grasp has been carried out (see Tab. ??). In particular, the comparison has been done between the five human subjects and the DLR-Hand, but, for the sake of brevity, only data related to one subject have been reported in Tab. ??). On the other hand, in Tab. 6, the comparative analysis between the values of the radius of curvature for the robotic hand in the grasping configuration and the values calculated for the human case and for the output of the optimization algorithm is reported. The curvature radii for MCP and TIP joints are very high since for them the spline has an almost null curvature.

The main observation concerns the difference between the Cartesian coordinates (and, consequently, between the finger joint angles) obtained from the algorithm and measured on the robotic hand. This is mainly due to the mechanical structure of the robotic hand that constrains the motion of the thumb and the DIP joints in a way that is different with respect to the human hand. In particular, the robotic thumb is mechanically constrained to a fixed opposition of 0.6198 rad in the xy -plane with an inclination of 0.7702 rad with respect to z -axis; instead, from the analysis of the data obtained with the BTS system on the human subjects, the angle in the xy -plane is on average 0.5585 rad and the angle with respect to z -axis is around 0.6109 rad. In addition, the aperture angle is different: about 0.6458 rad for the robotic hand and 0.9250 rad on average for the human hand. As the optimization algorithm is based on data obtained from the observation of human behaviour, obviously there is a difference in the experimental results, due to the different mechanical structures of the hands performing the task. Nevertheless, interestingly, the values obtained for the radius of curvature of the joints of the DLR-HIT-HAND II are very similar to those computed using the data obtained from the algorithm and from the observation of human beings (Tab. 6).

6. Conclusion

A method for hand motion analysis and pose reconstruction has been presented for the twofold purpose of providing insights into the comprehension of the human

		Cartesian coordinates [mm]					
Finger	Joint	Algorithm			Robotic hand		
index	MCP	10.9	41	105.9	-2.5	36.8	107.8
	PIP	38.6	52	131.4	26	34.3	154.5
	DIP	64.2	47	131.7	51.3	32.1	152.6
	TIP	79	42	123.3	61.2	31.2	129.7
middle	MCP	6.2	15.6	108.9	3.7	10	117.8
	PIP	49.4	21	138.8	43.7	10	145.6
	DIP	77.6	20.3	123.4	65.5	10	133.4
	TIP	84.4	21	105.4	65.9	10	108.4
ring	MCP	9.3	-4.8	110.5	-2.5	16.8	112.6
	PIP	46.8	-0.7	141.8	40.9	-13	146.2
	DIP	76.7	0.3	127.6	64.1	-11	137.1
	TIP	73.6	3.4	109.8	68.5	-10.6	112.5
little	MCP	11.2	-27	95.7	1	-43.4	93.6
	PIP	38.4	-23.2	141.4	31.3	-38	139.1
	DIP	60.7	-18.8	135.4	55.9	-33.7	140.9
	TIP	69.3	-11.7	122.6	72.4	-31	122.3
thumb	TM	35	44.5	61.5	62.2	44.4	78.7
	MCP	71.8	56.9	106.4	79.1	49.6	130.8
	IP	84	70.8	124.6	76.8	44.8	155.2
	TIP	75.3	61.7	143.5	65	34	174.4

Table 5. Joint Cartesian coordinates measured on the robotic hand and extracted from the optimization algorithm in the case of object with diameter = 40 mm

Finger	Joint	Human being	Algorithm	Robotic hand
index	PIP	16.1	23.4	22.5
	DIP	33.5	20.6	1.7
middle	PIP	20.4	22	24
	DIP	47	32.5	18
ring	PIP	17.4	23.8	24
	DIP	23.5	12	18
little	PIP	18.7	14	29
	DIP	34.7	26.1	21
thumb	MCP	45.5	53.4	56
	IP	38.3	26.4	43

Table 6. Values, in mm, of the radius of curvature calculated for the human subjects, extracted from the optimization algorithm and measured on the robotic hand, in the case of object with diameter = 40 mm

grasping strategy and allowing the definition of grasping indicators for describing stable grasp configurations and synthesizing optimal grasp configurations for a robotic hand. The paper has presented the protocol for the observation and analysis of human behaviour through an optoelectronic system, the extraction of the grasp indicators, and the development of an algorithm for the synthesis of optimal grasp configurations for a power grasp, e.g., a transverse volar grasp. The proposed approach can predict the final position of the reaching movement and the optimal finger configuration for a power grasp, once the information on object size and location is provided. The obtained results have been preliminary tested in simulation and validated through i) a

comparison between the data on human subjects collected with the optoelectronic system and the corresponding data obtained with the optimization algorithm; ii) a measure of the grasp stability by means a form-closure quality index; iii) experimental trials with a real arm-hand robotic system, composed of the MIT-Manus robot arm and the DLR-HIT-Hand II. The results have: (a) provided quantitative data on human hand motion during power grasps, with special attention to the thumb behaviour in the transverse volar grasp (neglected in the literature but fundamental to a stable grasp and to manipulating an object); (b) shown the efficacy of the proposed algorithm for the synthesis of optimal joint configuration for all the five fingers of the hand during transverse volar grasps; (c) proven the feasibility and reliability of the approach in robotics with the implementation and the experimental validation on a real arm-hand robotic system. The experimental validation on the robotic hand has also shown that the mechanical structure of the robotic hand can limit the performance of the proposed approach if sufficient similarity with the human structure is not achieved. In particular, the main limitations of the performed experimental trials were related to a fixed thumb opposition of the robotic hand, which did not allow either perfectly achieving the positioning of the thumb predicted by the algorithm or grasping objects with a diameter larger than 40 mm. In our future work, a generalization of the approach to objects of different shapes will be studied and the findings on the human thumb behaviour during grasping will be used to define design criteria for a new robotic hand with a more anthropomorphic configuration of the thumb. Finally, future activities will also address: i) the introduction of grasp dynamics in the synthesis of optimal grasps in order to study the forces involved in the grasping action especially related to grasp stability to win slippage; ii) the extension of the approach to unknown objects by enriching the robotic platform with multimodal sensors for acquiring an in-depth knowledge about the object characteristics.

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