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Evaluation of Prosthetic Hands Prehension Using Grasp Quality Measures

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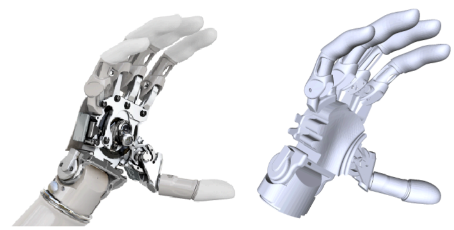
Abstract— **Prosthetic hands have evolved and improved over the years, helping people gaining manipulation capabilities. Having a simulation tool able to obtain quantitative evaluation of the grasp capabilities of such hands could give insights as how to improve the design of hand prostheses or robotic hands by means of obtaining better quality scores. The purpose of this work is to present a framework developed to evaluate the grasp capabilities of a prosthetic hand using a selected set of grasp quality measures, and compare the results with the ones obtained for the human hand using a biomechanical model. Experiments grasping an object with different postures and varying aspects of the prosthetic hand model were performed showing the functionality of the proposed framework to evaluate the grasp quality.**



(a) Real (b) Simulated model

Fig. 1. Otto bock Michelangelo hand: real (Photo courtesy of Otto bock) and model implemented in OpenRAVE

I. INTRODUCTION

Much effort in the field of upper-extremity prostheses research is directed towards the creation of prostheses as true limb replacements. Unfortunately current prosthetic components and interface techniques are still a long way from realizing this goal [1]. In order to make them clinically viable, most prosthetic hands are designed with non-articulated fingers and thumb, and connected to the palm through a single axis of rotation controlled by two EMG signals that are used to simultaneously open and close all the fingers.

One of the main desired features of prosthetic hands is their grasping capability. Keller et al. [2] evaluated different prehensile patterns and found that the *tri-digital pinch* was the most frequently used for static grasping. Guided by this finding, most prosthetic terminal devices have frequently being designed with a single DOF to incorporate this as the dominant grasp pattern [3].

Evaluating the grasp quality of a prosthetic hand performing this prehensile pattern could have several applications. First of all, the design of hand prostheses could be improved if the quality of the grasp performed by a given mechanical hand could be measured and compared to the physiological hand. Additionally, the design of hand-held products could be improved to accommodate to the prosthetic hands.

For many years, the robotics community has studied the autonomous handling of objects by robots. In order to help the selection of the proper robotic grasp for handling an object, many grasp quality measures have been developed that allow the comparison of different aspects of the robotic grasp [4]. In previous work, we have developed a framework to evaluate human grasp [5] adapting the most common robotic grasp quality measures to the evaluation of the grasp of the human hand in simulation and proposing complementary quality indices that might consider biomechanical aspects. In addition, through a correlation analysis, we proposed the minimum set of indices that allow for the evaluation of the different aspects of the grasp. A set of experiments was designed to explore a wide range of possibilities of the human grasp. We selected 36 grasps of a cylinder varying different parameters of the experiments such as the grasping posture, the grasping position or the number of fingers used to perform the grasp. These postures were measured with the registration of human subjects and reproduced in simulation. Our purpose in this paper is to show that, making use of this framework, prosthetic hand grasps can also be evaluated and compared with the results obtained for the human hand.

In this work, we used one of the latest developed prostheses by Otto Bock, the Michelangelo hand (Fig. 1), to show the use of quality measures to evaluate prostheses grasps and compare the results with the values obtained for the human hand. Additionally, variations to the original design were studied evaluating their grasp quality, which can give insights as how to improve the prosthesis design in order to obtain better quality scores.

II. MATERIALS AND METHODS

A. The Michelangelo hand

The Michelangelo hand is a five-finger prosthetic hand which fingers are non-articulated and designed with a slight flexion at a position approximating the interphalangeal joint. The fingers and thumb have a single axis of rotation to

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flex until contacting the object or reaching their mechanical limits. Additionally, it has the ability to separately position the thumb using muscle signals, which allows seven different hand positions.

This prosthesis has three active fingers: the thumb, the index finger and the middle finger; the last two fingers are for cosmetic reasons. The index and middle fingers are mechanically coupled via a cable, so that usually they both come into contact with the object and produce the same force. If the index finger come into contact with the object first, the middle finger still continue to move, until also the middle finger is in contact. Once the index and middle fingers stop, the ring finger and little finger do not continue to move.

B. OpenHand Framework

OpenHand is a framework developed for modelling, simulating and analysing the grasp performed by human hands [6]. It includes low-level computational tools that are invoked using different applications. At the lower level, it uses OpenRAVE [7] for kinematic definition and visualization.

A previously-validated 3D, scalable, biomechanical model of the complete human hand [8] was implemented in this framework as a new plugin. It has the definition of the kinematic model enabling users to scale it with the hand breadth and the hand length anthropometric parameters.

Each grasping experiment is defined through a Grasping module using MATLAB. The OpenRAVE environment is initialized, the most open posture and tentative grasping posture are defined, then the simulator interfaces with the collision engine to obtain contact information for the hand closing algorithm. After the grasp is performed, the contact information is used to calculate several implemented grasping quality measures.

The Michelangelo hand was also implemented for OpenRAVE and the same grasping framework was used to create its closing algorithm and obtain its contact information. The model without the cosmetic glove (Fig. 1) used for the experiments was provided by the *Vision4Robotics Group*[1] with permission from Otto Bock.

C. Independent Grasp Quality Measures

In previous work, we have reviewed, selected and adopted a set of grasp quality measures to study the human grasp [5]. These quality measures were selected to evaluate independent aspects of the grasp and normalized to make them comparable so that they have a best value of 1 and a worst value of 0. The biomechanical aspect measuring the *muscular fatigue* has no meaning for a prosthesis without muscles and therefore it was discarded.

Q_1 - Restriction of the grip: It looks for a uniform contribution of the contact forces to the total wrench exerted on the object [9]. It is calculated as:

$$Q_1 = \frac{\sigma_{min}(G)}{\sigma_{max}(G)} \tag{1}$$

where σ_{min} and σ_{max} denote the minimum and maximum singular values of the Grasp Matrix [10]. This measure has to be maximized and has no units.

Q_2 - Dynamic effects: It aims to minimize the effect of gravitational and inertia forces during the motion of the robot, measuring the distance between the centre of mass p of the grasped object and the centroid of the contact points p_c [11]. Then the measure is calculated as:

$$Q_2 = \mathit{distance}(p, p_c) \tag{2}$$

This measure has to be minimized and has units of length.

Q_3 - Ability to resist forces: It is defined as the largest perturbation wrench that the grasp can resist with independence of its direction [12]. Only the directions of forces are used and their magnitudes are upper-bounded to 1. Defining GWS as the set of all possible wrenches w acting on the object, the maximum of $w \in GWS$ lies on the boundary approximated as the convex hull over the discretized friction cones (CW). Then the quality metric is the radius of the largest sphere centred at the origin, which is contained in GWS:

$$Q_3 = \min_{w \in CW} \|w\| \tag{3}$$

This measure has to be maximized and it has $[force]$ units if the torque in w is divided by a parameter ρ with units of $[length]$. The index depends on the choice of the origin of the reference system used to compute torques. In this work, we use the centre of mass of the object.

Q_4 - Comfort: This index measures how far each joint i is from its maximum limits [13]. The aspect of *Comfort* measured by this index does not refer, as with the human hand, to the discomfort produced by stresses in the articular soft tissues when they come stretched close to the joints operating limits, but now must be understood as a reduction of manipulability, as possible changes in the grasp posture are limited. It is calculated as:

$$Q_4 = 1/n_q \sum_{i=1}^{n_q} \left(\frac{y_i - a_i}{R_i} \right)^2 \tag{4}$$

where n_q is the number of hand joints and R_i is the joint angle range between the middle-range position a_i and either the upper or lower angle limit, used to normalize the index:

$$R_i = \begin{cases} a_i - y_{im} & \text{if } y_i < a_i \\ y_{iM} - a_i & \text{if } y_i > a_i \end{cases} \tag{5}$$

where y_{iM} and y_{im} are the maximum and minimum angle limits of the i^{th} joint. The index has to be minimized, so that the grasp is optimal when all joints are at the middle-range position, having a quality measure of zero, and it goes to one when all its joints are at their maximum angle limits.

Q_5 - Manipulability: The inverse condition number of the Jacobian matrix gives a measure of the sensitivity of the magnitude of the end-effector velocity to the direction of the joint velocity vector. It is a dexterity measure that considers the capability of the hand to move an object in

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any direction with the same gain, which implies a good manipulation ability [4]:

$$Q_5 = \frac{\sigma_{min}(G_J)}{\sigma_{max}(G_J)} \tag{6}$$

where σ_{min} and σ_{max} are the smallest and largest singular values of the grasp Jacobian matrix G_J [14]. This measure has to be maximized and has no units.

In previous work [6], we performed a series of experiments designed to vary different aspects influencing the grasp to identify ranges of variation which are better-adapted to human grasping. This enabled us to find more realistic ranges of variation of the measures than those obtained with the mathematical limits. These values are presented in Table I and are used to normalize the measures in order to make the values comparable with the ones obtained using the human hand model.

TABLE I

NORMALIZED RANGE FOR EACH MEASURE

	Restriction of the grip	Dynamic effects	Ability to resist forces	Comfort	Manipulability
Min	0.00	0.07	0.00	0.51	0.00
Max	0.30	1.00	0.09	0.90	0.02

D. Hand postures

In order to evaluate the grasp quality of the Michelangelo hand, we used postures evaluated with the human hand model and attempted to reproduce them using the prosthesis. A nylon cylinder, 200 mm in length and with a 50 mm diameter, was chosen for the experiments. Only grasps involving the distal phalanxes of the fingers and thumb were considered, taking into account that the frequency of grasping objects with the finger's distal phalanxes while performing common daily activities has been found to be three times the frequency of grasping objects with contacts along the fingers and the palm [15]. As this prosthetic hand has predefined thumb positions and only one degree of freedom, several of the grasps achieved with the human hand were not possible to be reproduced with the prosthesis. Therefore, only 12 cylindrical grasps were considered using the *tripod pinch* posture (considered the most frequently used as mentioned previously), using 3 and 5 fingers and varying the position and orientation of the grasped object (Fig. 2).

In order to reproduce the same postures, the wrist was located in the position registered for the human hand using a VICON motion capture system [16] for the human subjects. At this position, the closure algorithm was executed until all fingers contacted the object or reached their maximum limits. The collision algorithm is used to determine the contact points and normals and all the selected quality measures were evaluated. All three-finger grasps were performed closing all fingers as the Michelangelo hand can not independently control the number of fingers used to perform the grasp. However, as only the thumb, index and middle are active fingers, they are the only ones that produce contact forces.

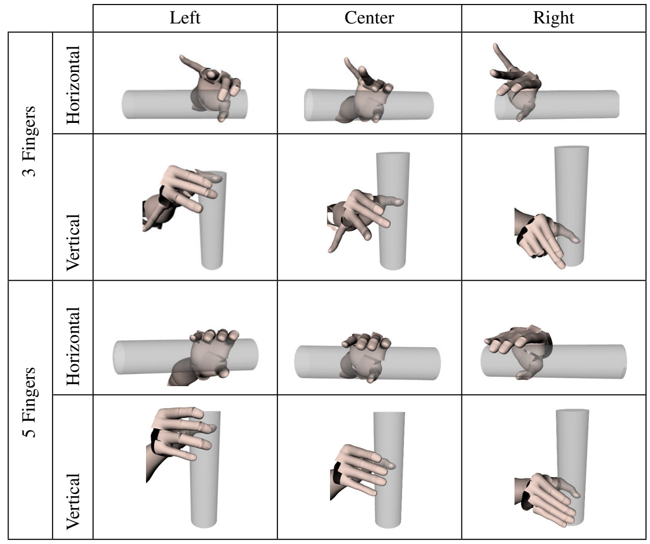


Fig. 2. Selected grasp postures (Cylinder: 50mm diameter, 200mm length and 460g)

The ring and the small finger produce only small forces when grasping an object, nevertheless these fingers can also help to stabilise an object, depending on their shape.

Therefore, when trying to simulate three-finger grasps, grasps with 3, 4 or 5 fingers were achieved, depending if the ring and small fingers reached the object. But only the three fingers selected to perform the grasp produced active forces. On the other hand, when trying to simulate five-finger grasps, sometimes the prosthesis achieved grasps with four fingers, and again, only three of the contacting fingers produced active grasping forces. We have - in both cases - calculated two values for each quality measure: i) one only using the three active fingers and ii) using the contacts actually produced; and we present these two values as a range among which the grasp quality measure actually lies.

E. Experiments evaluating grasp quality

Different experiments were designed in order to evaluate the grasp quality of the Michelangelo hand.

1) Original design: The quality of the grasp for each of the 12 selected postures is evaluated using the proposed measures for the original design of the Michelangelo hand. The results were compared with the ones obtained performing the grasp with the human hand model.

2) Varying hand design: Variation on the grasp quality changing the hand design by modifying the abduction position of the fingers. Four new designs are evaluated and compared with the performance of the original hand. They are detailed in Table II and shown in Fig. 3.

III. RESULTS

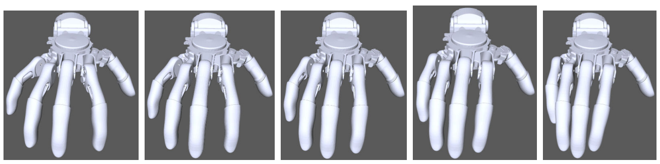
A. Original design

The results of calculating the independent grasp aspects for the 12 cylindrical postures are presented in Fig. 4 taking into account both: only the 3 active fingers and the real number of contacts. They are presented alongside the picture

TABLE II

VARIATION OF THE FINGER'S ABDUCTION FOR EACH NEW DESIGN WITH RESPECT THE ORIGINAL HAND

Posture	Index	Middle	Ring	Little
Max Abd	20º	0º	-5º	-5º
Mid Open	10º	0º	-2.5º	-2.5º
Original	0º	0º	0º	0º
Mid Close	-4º	0º	5.5º	2.5º
Min Abd	-8º	0º	11º	5º



(a) Max Abd (b) Mid Open (c) Original (d) Mid Close (e) Min Abd

Fig. 3. Design of hands varying finger's abduction

of the respective human hand grasp and radar plots present the selected 5 independent aspects evaluated for each grasp and both hands.

1) Variation between three active fingers and all fingers contacted: The *ability to resist forces* was the aspect with greater variation (up to 19%) given that if the number of fingers increases, the ability of a grasp to resist external forces also increases, and vice versa. The *dynamic effects* aspect presents variations (up to 15%) as the centroid of the grasp polygon varied between three and five fingers, reducing or increasing its distance to the object center of mass. The *restriction of the grip* varied less than 1% of the total normalized range [0-1]. The *comfort* was not altered given that, as the fingers move according to one degree of freedom, all the fingers were at the same position in the joint range of motion.

2) Variation between prosthetic and human hand: The *Manipulability* is the aspect that clearly gives a large advantage to grips performed with the human hand since this measure always gives zero values for the prosthesis. This is because the prosthetic hand has only one degree of freedom and therefore one of the singular values of the grasp Jacobian matrix (G_J) is always zero. This shows that, once achieving the grasp posture, the hand can not produce other movements to the object, which have to be produced by the wrist or arm, producing a manipulability of the hand equal to zero.

The grasp *comfort* is measured taking into account how far are the hand joints from their limits. As it was mentioned before, it should be understood as a measure of manipulability in terms of the hand ability to move the joints after performing the grasp. Since the object had a medium size, the prosthesis is grasping it at approximately the center of its joints' range of motion thus getting always a very high performance in this aspect. This is more accentuated when the human hand is performing grasps with three fingers in which it moves the ring and small fingers to their limits to put them out of the way. In this cases, it should be considered to modify this measure to only take into account the joints' values of fingers that contact the object.

The *ability to resist forces* gave equal or better results in most of the cases (5 over 6) for the grasp performed with the Michelangelo hand for three finger grasps. In these cases, the grasp was performed with three fingers with the human hand for which the Michelangelo hand used 5, allowing it to increase its ability to resist forces. It can be visualized that when the measure is evaluated for the 3 active fingers of the Michelangelo hand, it is equal or less than for the human hand. In contrast, it gave generally (5 over 6) better results for the grasp performed with the human hand for five finger grasps, given that in many of these cases only 4 fingers of the Michelangelo hand actually contacted the object.

The *dynamic effects*, measured with the distance from the grasp polygon to the center of mass, gave similar results for both hands since the wrists were located in the same position. The results clearly show that grasps performed close to the object centre are rated better than in the extremes. In some cases, there are small differences given that the human or Michelangelo hand positioned the fingers differently.

Lastly, the values obtained measuring the *restriction of the grip* are similar for both hands, only giving better values for the human hand in the horizontal three-finger posture grasping the cylinder in the center.

B. Varying hand design

The results of changing the abduction of the fingers are shown in Fig. 5. The results of the evaluation of the 12 grasps are shown for each measure with the different hand designs. As the manipulability index (Q_5) is always zero, its results are not shown in the graph.

Q_3 shows that hands with the fingers more abducted have better ability to resist forces with a variation of up to 25% of its range. The *dynamic effects* of changing the hand design, in general (8 over 12), gave incrementally better results when hands had their fingers more adducted.

There is not much variability between hand designs using the Q_1 and Q_4 measures. The *restriction of the grip* only shows small variations in the vertical orientation when grasping the cylinder up. The *comfort* is clearly the same as the hands are driven by the same closing algorithm and their joints will be at the same angle with respect with their limits.

IV. CONCLUSIONS

In this paper, we demonstrated one of the possible uses of a framework for evaluating grasps through its various independent aspects. We showed how the grasp ability of a prosthetic hand can be compared to the one that the human hand has.

Although prosthetic hands have evolved and improved over the years, they have large deficiencies in their appearance and their functionalities are very limited. These deficiencies are largely related with the quality of the grasps they can perform. Specifically, the Michelangelo hand largely looses dexterity and versatility compared to the human hand,

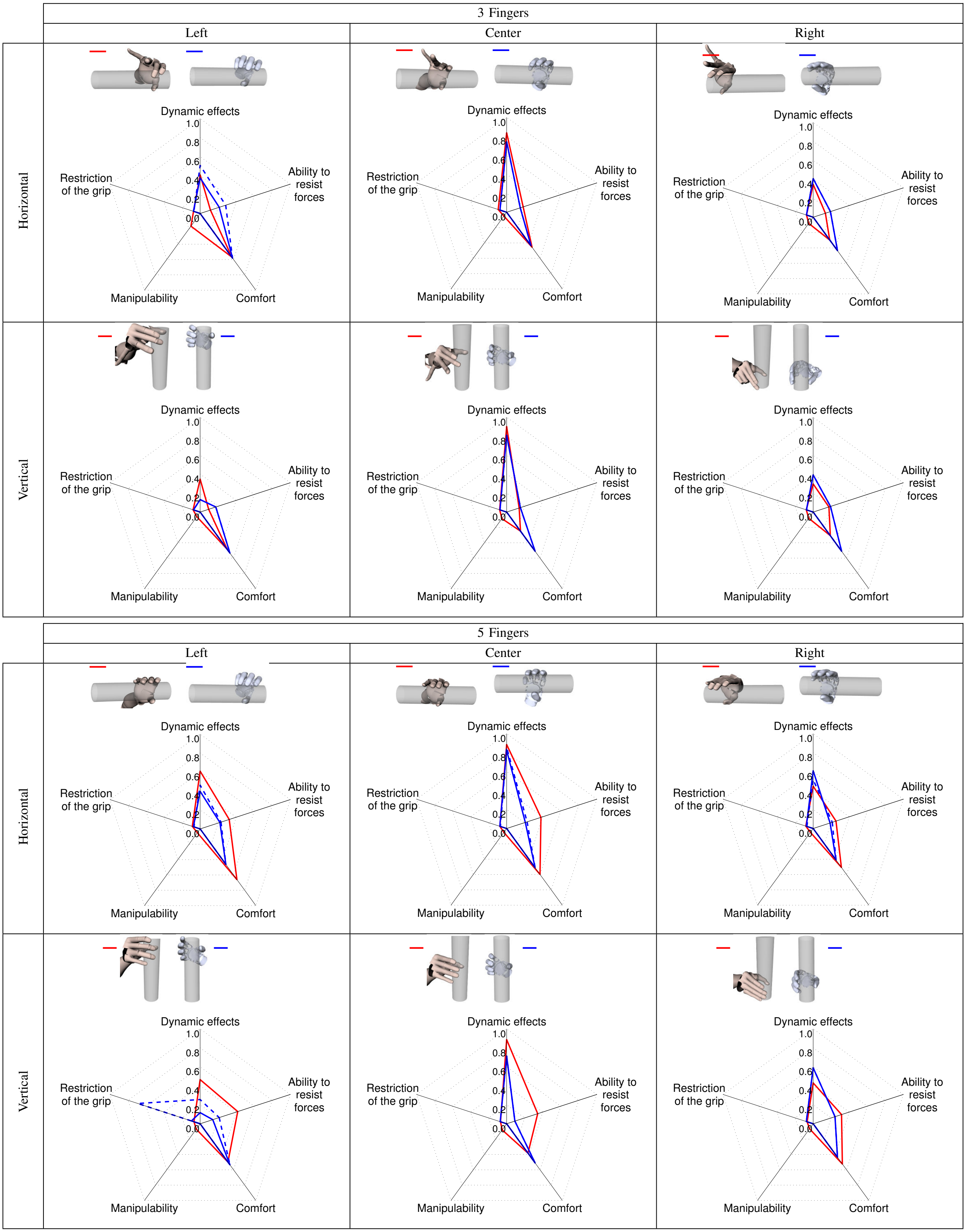


Fig. 4. Independent grasp aspects for the human and Michelangelo hands (red line: Human, continuous blue line: Michelangelo calculated with all fingers contacted and dotted blue line: Michelangelo calculated with only the 3 active fingers)

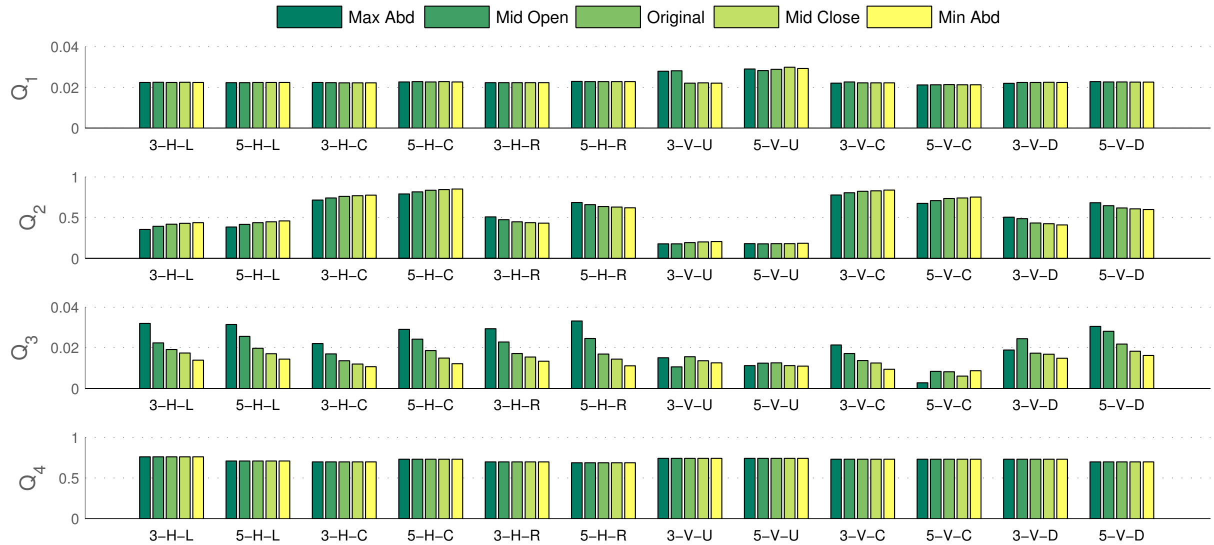


Fig. 5. Quality measures evaluated for 12 simulated grasps. Postures described by: number of fingers (3,5) - orientation (H:Horizontal, V:Vertical) - position (L:Left,C:Center,R:Right,U:Up,D:Down) (Cont.)

reducing from 23 to only one degree of freedom. For this reason, out of 36 grasps that were studied for the human hand only 33% were able to be evaluated for the prosthesis. Additionally, the number of quality measures that are meaningful for the Michelangelo hand is reduced, excluding specially the proposed biomechanical indices as they do not make sense for hands without muscles.

The results given by the manipulability measure (Q_5) are specially relevant for this hand. Although it was possible to calculate the singular values of the grasp Jacobian matrix, the inverse of the condition number always gave zero values. This demonstrates that once achieving the grasp posture, the hand can not produce other movements to the object, which have to be produced by the wrist or arm. This clearly shows one of the major deficiencies with the prosthetic hands: loss of manipulability.

As future work, additional measures might be proposed to take into account the fact that although the prosthesis is a five-finger hand, only three of its fingers are active and therefore able to produce significant forces to the grasped object. Specifically, the role of the passive forces generated by the ring and little fingers should be studied.

The experiment changing the abduction of the fingers is presented as an example of the potential use of the proposed framework to modify the prosthesis design. Future studies can investigate how adding different degrees of freedom to prosthetic hands can improve their ability to perform better grasps. This can be used by the robotics community since more and more robotic hands tend to be more similar to the human hand trying to achieve its dexterity to perform grasps and manipulate objects.

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