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A Force-and-slippage control strategy for a poliarticulated prosthetic hand

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Abstract— **One of the main problems in the prosthetic hand design is to provide the hand with a reliable system for force and slippage control. The real-time detection of an object slippage during grasping plays a fundamental role in performing a stable grasp. Aim of this paper is to propose and test (i) a system for object slippage detection during grasping, (ii) a control strategy for grasping force regulation and slippage prevention and (iii) a finger coordination method for replicating on the prosthesis system a human-like behaviour. The approach has been validated on a real prosthetic hand, i.e. the IH2 Azzurra (developed by Prensilia), on which tips force sensing resistors have been placed. The preliminary experimental results have demonstrated the feasibility of the methods for slipping detection and for force/slippage control and have shown that the prosthetic hand is able to perform a stable pinch grasp of different objects guaranteeing finger coordination.**

I. INTRODUCTION

The problem of automatically controlling grasp also avoiding object slippage is a very important issue in hand prosthetic systems to light the attention level and the cognitive burden for the user. In order to firmly grasp the objects, the prosthesis wearers need to provide a constant visual attention during the task execution for adjusting grasping force and preventing object slippage. The discomfort in this situation is outlined by the studies on prosthesis user needs, where the wish of performing actions in a more coordinated manner and with less visual attention is always pointed out [1].The integration in the prosthesis of a control system able to command hand actuators managing the forces acquired by an embedded tactile system could guarantee the grasp of different objects with less visual attention with respect to the majority of commercially available prosthesis hands where the force regulation during grasping is managed only by a visual control from the user.

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In the literature, some efforts in force and slippage control during grasping have been proposed.

Myoelectric prosthetic devices have a limited number of actuators in order to keep low the hand weight and size, and the computational cost of myoelectric control solutions. This inevitably leads to a worse controllability with respect to robotic hands characterized by a high number of actuators (dexterous hands) and consequently by many active Degrees of Freedom (DoFs) allowing them to perform very complex manipulation tasks. Anyway, hand prostheses control treasures the experience achieved with control of robotic hands as discussed in [2], [3], where reviews of the prosthetic hands controls have been proposed for grasp tasks.

Empirical approaches based on the imitation of human grasping strategies have been proposed [4] to reduce the computational cost of the grasping control algorithms for robotic hands. In particular, it has been investigated whether humans use a combination of basic grasp configurations for prehensile postures [5] in order to replicate a human-like behaviour on robotic devices [6], [7]. The relationship between the grasping forces and the joint torques has been modeled by means the grasp matrix, adopted also for evaluating the grasp stability [8].

Latest literature works have highlighted the importance of a force control strategy to ensure stability during grasp. In [9], a PI force control has been implemented with a velocity inner loop, while in [10] an inner loop based on fuzzy position control has been proposed keeping a PI force control as outer loop. In [11] a force control strategy based on a neural network, aimed at compensating sensors and hardware non-linearities, has been developed.

In [12], improvements on grasp stability by introducing slippage prevention algorithms in the control has been obtained. In particular, the results obtained with a slip prevention controller based on an integral sliding mode has been compared to the results obtained with a PD shear force feedback control and with a sliding mode control with no slip prevention. The former produced the least amount of deformation with respect to the latter controllers, simultaneously guarantying a stable grasp. The controller proposed in [13] has been divided in a preshaping phase relying on a position control and a further fuzzy logic algorithm phase to prevent the object from slipping.

Slippage detection algorithms for prosthetic hands usually rely on Fourier transform, wavelet or derivative techniques applied to the force signals [12]. In [14], tangential and normal forces acquired by BioTac sensors have been used for the slippage detection by means of the friction cone

definition, a frequency analysis, and random forest classificators. The main drawback is the difficulty of discerning between slipping events and false positives. In [15], a sensor made of a pressure conductive rubber has been developed for detecting slippage. In particular, in unloaded conditions, the electrical resistance is infinity, whereas, in presence of tangential forces, the electrical resistance randomly changes.

The main purpose of this work is to propose and experimentally test (i) a system for object slippage detection during grasping, (ii) a control strategy for grasping force regulation and slippage prevention and (iii) a finger coordination method for replicating on the prosthesis system a human-like behaviour. A human-like behaviour, in terms of real-time reaction to slippage events and of finger coordination, has been achieved by means of (i) a force control with inner position loop, (ii) a sensorization system giving information about the applied normal forces, (iii) an algorithm for detecting and managing in real-time the object slippage and (iv) an approach for controlling the fingers in a coordinated manner on the basis of the virtual finger concept [16]. Furthermore, the grasping action performed by the human beings has been studied for obtaining a force reference for the controller.

The proposed approach has been experimentally validated on a real poliarticulated underactuated prosthetic hand, namely the IH2 Azzurra, performing pinch grasp on objects of various dimensions. The hand has 5 fingers and 5 active DoFs, i.e. MetaCarpo-Phalangeal (MCP) Flexion/Extension (F/E) of the five fingers (1 DoF is related to the coupled movement of the ring and the little fingers) and Trapezio-Metacarpal (TM) Abduction/Adduction (A/A) of the thumb.

The paper is structured as follows: in Section II, the slippage detection, the control and the force balancing approaches are described; Section III is focused on the experimental setup and on the analysis of the human force behaviour during grasping. Experimental results on the real poliarticulated hand are illustrated in Section IV. Finally, conclusions and future works are reported in Section V.

II. FORCE/SLIPPAGE CONTROL ALGORITHM

The main goal of the controller is to use the information, about normal force and object slippage, derived from the force sensors positioned on the prosthetic hand tips for performing a stable grasp, by online compensating for possible object slippage.

A. Force/slippage control law

The concept of the *virtual finger* [17] has been introduced for modeling the hand fingers opposing forces on the grasped object. In particular, considering pad opposition grasp configurations [5] (i.e. the hand postures where the thumb pad is opposed to the long finger pads), the long fingers (i.e. the index, middle, ring and little) have been modeled as a virtual finger opposing forces to the thumb [16]. The choice of combining the behaviour of different fingers modeling them as a single finger has the twofold purpose of replicating on the prosthetic hand the behaviour of the human hand during grasping (i.e. the normal force applied by the virtual finger should be equal and opposite to the normal force applied by the thumb [16]) and of reducing the prosthetic control need, handling different fingers and different grasp configuration identically.

In Fig. 1 the control block scheme of the thumb and of the *virtual finger* is shown. In particular, the control architecture is composed of the virtual finger control, the thumb control and the coordination among the two fingers achieved by the force compensation block. It is worth outlining that the approach has been adapted for underactuated fingers, i.e. the finger F/E is obtained through a linear motion of a slider which, pulling a cable, determines the finger flexion. The finger extension is obtained through torsion springs embedded in the joints.

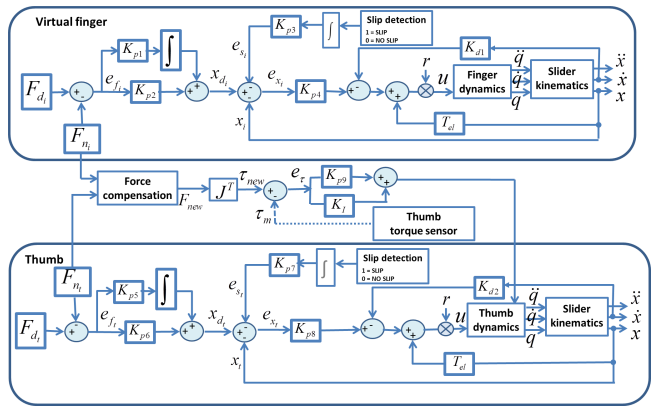


Fig. 1. Control block scheme of the thumb and the virtual finger.

The fingers have been controlled with a force control with inner position loop. The reference grasping forces of the thumb F_{d_t} and of the virtual finger F_{d_i} have been determined by analyzing the human beings performing the same actions executed with the prosthetic hand, as described in Sect. III-B. The normal forces, F_{n_t} and F_{n_i}, applied by the prosthetic hand fingers on the object surface have been acquired by the force sensors and have been subtracted to the reference force in order to obtain a force error, e_{f_t}, e_{f_i} that have to be minimized by the control. Then, the reference position x_{d_k} for the k-th finger slider has been obtained from a Proportional-Integrative (PI) force control

$$x_{d_k} = K_{p1} \int_0^{t_f} (F_{d_k} - F_{n_k}) dt + K_{p2}(F_{d_k} - F_{n_k}) \quad (1)$$

and has been compared with the actual position x_k derived from the hand position sensors. K_{p1} and K_{p2} are the controller gains and t_f is the final integration time. In order to manage slippage events, a slip-dependent additional contribution e_{s_k} has been considered [12]. Therefore, the position error of the k-th finger is

$$e_{x_k} = x_{d_k} - x_k - e_{s_k}, \quad (2)$$

where

$$e_{s_k} = K_{p3} \int_0^{t_f} \alpha dt. \quad (3)$$

α is the binary signal equal to 0 when slip does not occur and 1 if slip occurs, K_{p3} is a constant regulating the e_s weight

in the control. The integration of this signal will guarantee a smooth increment of the applied grasping force in presence of slippage, as demonstrated in [12]. The so obtained position error e_{x_k} should be led to zero by a Proportional-Derivative (PD) control in the slider space described by the equation

$$u = r[-K_D\dot{x} + K_P(x_{d_k} - x_k - e_{s_k}) + T_{el}] \quad (4)$$

T_{el} is the cable tension compensating for the spring elastic forces, r is the vector of the pulley radii and $x, \dot{x}, \ddot{x}$ are the slider position, velocity and acceleration, respectively [20].

Under the hypothesis of rigid object and rigid finger pads, in order to guarantee the grasp stability, the normal force applied on the object surface by the virtual finger should be equal and opposite to the normal force applied by the thumb, neglecting the force contribution due to the grasped object weight [16]. It has been guaranteed by the introduction, in the proposed control law, of a force compensation block taking in input the normal forces acquired by the sensors on the fingertips. In order to be compared, the acquired forces should be expressed in a common reference frame that has been supposed coincident with the wrist joint. Therefore, the measured forces applied by the hand tips have been computed in the wrist frame

$$F_{TIP}^{wrist} = R_{tip}^{wrist} F_{TIP}^{tip}, \quad (5)$$

where R_{tip}^{wrist} is the rotation matrix of the fingertip reference frame with respect to the wrist reference frame, F_{TIP}^{wrist} is the force applied by the TIP in the wrist reference frame and F_{TIP}^{tip} is the fingertip force expressed in the fingertip reference frame. Then, the obtained forces of the thumb and of the virtual finger have been compared and equalized in the wrist reference frame. These are the forces the fingers should apply on the object surface in order to firmly grasp it. By means the transformation matrices, they have been brought back to the fingertip reference frame. The application of the desired force on the object has been guaranteed by driving the finger motors to apply the corresponding torque τ_{new} obtained by means of the hand finger Jacobian and of the balanced forces F_{new}:

$$\tau_{new} = J_p^T F_{new_{TIP}}^{wrist}, \quad (6)$$

where $F_{new_{TIP}}^{wrist}$ is the force the TIP should apply in the wrist reference frame and J_p^T is the transposed Jacobian matrix related to the linear velocity. Only the torque pertaining the thumb A/A has been considered and compared with the actual thumb A/A torque τ_m obtained from the hand sensors. A PI controller has been added to guarantee the convergence to zero of the torque error e_τ. The so obtained A/A torque has been given in input to the thumb dynamics.

B. Slippage detection

In order to acquire information about the interaction forces between the prosthetic hand and the grasped object, commercially available force sensors, i.e. the FSR sensors (Model 400 by Interlink Electronics [18]), able to provide information about the normal force, and to meet the application requirements (such as, the measurable force range, until $20N$ with a discriminant threshold of $0.2N$ and the easiness to be embedded under a cosmetic glove), have been placed on the hand fingertips.

The simplicity of the acquisition circuit and data processing allows the easy use of this methodology on different types of hand. In fact, the same setup has also been adopted to evaluate the grasping forces exerted by the human subjects to determine the reference level of strength, as described in detail in Sect. III-B. The proposed approach is not limited by the chosen force sensor, but can be applied to several type of sensors able to provide information about the normal force.

A Wheatstone bridge with three nominally identical resistance has been adopted for transducing the sensor resistance value R_s into voltage. Then, the obtained voltage value has been amplified by means of an operational amplifier (TL074, Texas Instrument, Inc.) in differential configuration with a nominal gain of 2 and has been finally converted in a force. The so acquired data have been used for detecting the object slippage in real-time by performing the following steps:

- Voltage signal amplification. The amplification constant has been empirically determined;
- Force extraction from the amplified voltage;
- Force square root evaluation;
- Computation of the absolute value of the normal force square root derivative at each sample point in order to quantify the force rate of change;
- Identification of the onset of the slippage by means of a threshold empirically determined. This threshold has been established grasping the objects with the prosthetic hand and measuring the force values in correspondence of which the object slippage starts.

A slippage event has been simulated on a calibrated FSR sensor by applying, with a probe, a constant force normally to the sensor. After a while the probe has been slid on the sensor sensible area. The output signals of one trial is shown in Fig. 2, where the force signal is outlined in blue, the processed signal, from which the slippage event can be extracted by imposing an appropriate threshold, is shown in red and the threshold in black.

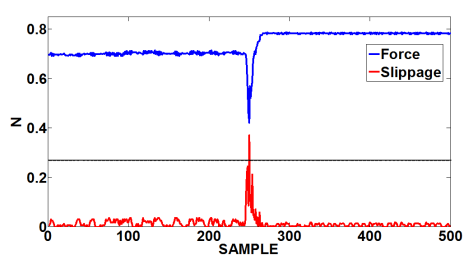


Fig. 2. Output of the slippage detection method.

The algorithm output will be a binary value: 1 in correspondence of a slippage event, reported with the dashed black line in Fig. 2 and 0 in correspondence of a non-slippage event. For the sake of brevity, only the results obtained in one trial have been reported, but similar results have been obtained for five consecutive experiments.

III. ALGORITHM IMPLEMENTATION ON THE PROSTHETIC HAND

A. Experimental Setup

The IH2 anthropomorphic robotic hand [19], is a 5-finger robotic hand with a weight (640 g) and a size similar to the human ones (Fig. 3). The hand has 11 DoFs, of which

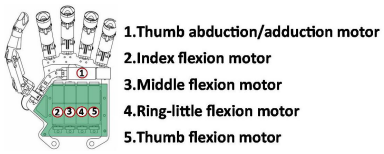


Fig. 3. The IH2 Azzurra prosthetic hand. The location of the motors in the hand palm is outlined.

5 active. Each underactuated finger is composed of two phalanxes and a tendon wrapped around the pulley placed in the joints. The underactuated mechanism let the fingers automatically adapt to the object shape while closing. The F/E of each finger is managed by means of a slider located in the hand palm, whereas a universal joint is used for linking the thumb A/A motor, positioned in the palm, to the TM joint. An incremental encoder is adopted for measuring the finger position, i.e. a value equal to 0 correspond to a totally open hand, whereas 255 correspond to a totally closed hand.

The F/E angles of the MCP and PIP joints (i.e. q_{mcp} and q_{pip} respectively) are linked to the slider position x by means of the joint pulleys radii (r_{mcp} and r_{pip}) and the starting joint angles ($q_{0_{mcp}}$ and $q_{0_{pip}}$, supposed equal to 0) [20]:

$$x = r_{mcp}(q_{mcp} - q_{0_{mcp}}) + r_{pip}(q_{pip} - q_{0_{pip}}). \quad (7)$$

The long fingers kinematic chain is the one of two-link planar manipulators, whereas the thumb kinematic chain is equal to the one of an anthropomorphic manipulator. The dynamic model of the manipulators is given by

$$B(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) + \tau_{el} = \tau, \quad (8)$$

where $B(q)$ is the joint inertia matrix, $C(q,\dot{q})\dot{q}$ is the vector of centrifugal and Coriolis torques, $q, \dot{q}, \ddot{q}$ are respectively the joint position, velocity and acceleration vectors, $g(q)$ is the gravitational torque vector.

The force applied by the prosthetic hand during grasping have been recorded by positioning on each hand fingertips a FSR whose working principle is based on the transduction of the applied force into a variation of the electrical resistance. By means of a Wheatstone bridge, the sensor resistance value has been transduced into voltage. A static calibration has been performed in order to determine the relationship between voltage and force.

B. Reference force extraction from the human beings

In order to extract a reference force for the controller, the grasping action performed by the human beings has been studied. In particular, it has been asked to 7 subjects, 29.4 ± 3.4 years old on the average, to grasp a glass (diameter $78mm$ and weight $50g$) and two balls (diameter $60mm$ and weight $58g$ and diameter $35mm$ weight $17g$) with a pinch grasp. The forces applied by the fingertips have been acquired by positioning a FSR sensor in correspondence of the subject index and thumb fingertips. The participants have been seated in front of a table on which the objects have been located in a-priori known position. Every subject has been asked to grasp the object, to lift it and stably grasp it until an auditory signal announcing the acquisition end. Before starting the data acquisition, each participant has been asked to grasp the object 5 times, for learning the grasping action. The forces applied by the fingers have been recorded during the whole trial that has been repeated five times for each object. In order to understand if it exists a common behavior among subjects during the grasping action, a comparison among the force data has been carried out.

In Fig. 4 the normal forces acquired on one subject during the five trials are shown. In particular, the forces have been recorded during the pinch grasp of the ball of diameter $60mm$. From Fig. 4 it is evident that the same subject has substantially the same behavior during the five trials. For the sake of brevity, only the results obtained on one subject during the grasping of one object have been reported, but similar results have been obtained for the other subjects and for the other objects. The force values between the two vertical dashed black bars are applied when the grasp is stable. Therefore, their mean value are considered as force reference for the controller.

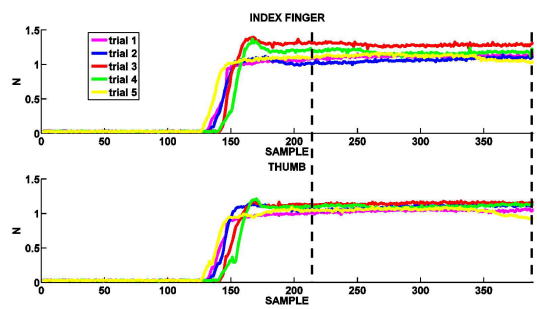


Fig. 4. Normal forces applied by a subject and measured by the sensors on the hand fingertips during the pinch grasp of the 60 mm diameter ball. The behaviour of the forces applied by the index finger and the thumb during the five trials is outlined with different colors.

In Tab. I the mean forces ($\pm$ standard deviation) obtained during the five trials for each subject grasping the different object are listed. The reference forces for the index finger and the thumb controllers are computed as the mean of the forces measured on the 7 subjects. These force values are listed in Tab. II.

IV. EXPERIMENTAL RESULTS

The proposed approach has been experimentally tested on the IH2 Azzurra prosthetic hand. FSR sensors have been embedded on the thumb and on the index fingertips which have been covered with silicon material simulating a cosmetic glove (Fig. 5). The resulting small deformation of the sensors does not compromise the sensor performance. Furthermore, the sensors have been characterized once embedded in the fingertips in order to compensate for possible initial pressure.

TABLE I

MEAN FORCE ($\pm$ STD), IN NEWTON, APPLIED BY THE SUBJECTS PERFORMING THE PINCH GRASP OF THE OBJECTS.

	Ball $60mm$		Ball $35mm$		Glass	
	Index	Thumb	Index	Thumb	Index	Thumb
Subject 1	0.95 ± 0.08	0.98 ± 0.05	0.64 ± 0.08	0.61 ± 0.01	0.59 ± 0.02	0.56 ± 0.04
Subject 2	0.81 ± 0.03	0.78 ± 0.02	0.71 ± 0.03	0.67 ± 0.02	0.56 ± 0.04	0.58 ± 0.01
Subject 3	0.67 ± 0.04	0.74 ± 0.03	0.68 ± 0.01	0.70 ± 0.06	0.61 ± 0.05	0.62 ± 0.04
Subject 4	0.71 ± 0.02	0.73 ± 0.01	0.54 ± 0.03	0.55 ± 0.01	0.63 ± 0.03	0.61 ± 0.02
Subject 5	0.68 ± 0.02	0.64 ± 0.02	0.61 ± 0.06	0.64 ± 0.05	0.6 ± 0.02	0.56 ± 0.08
Subject 6	0.51 ± 0.06	0.52 ± 0.01	0.53 ± 0.04	0.5 ± 0.02	0.53 ± 0.08	0.57 ± 0.03
Subject 7	0.62 ± 0.02	0.6 ± 0.02	0.72 ± 0.02	0.7 ± 0.03	0.65 ± 0.07	0.61 ± 0.07

TABLE II

REFERENCE FORCES, IN NEWTON, AND SDV EXTRACTED FROM THE HUMAN BEINGS FOR THE INDEX AND THUMB CONTROLLERS.

	Ball $60mm$	Ball $35mm$	Glass
F_{index} $[N]$	0.70 ± 0.04	0.63 ± 0.04	0.59 ± 0.04
F_{thumb} $[N]$	0.71 ± 0.02	0.62 ± 0.05	0.57 ± 0.03

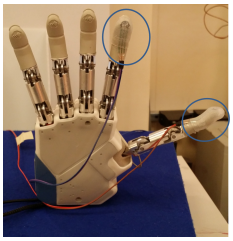


Fig. 5. The IH2 Azzurra hand. The index finger and the thumb has been covered by silicon material. The FSR sensor has been positioned between the finger and the silicon.

Experiments consisting of grasping the same objects grasped by the human beings (i.e. a ball of diameter $60mm$, a glass and a ball of diameter $35mm$) have been performed. Aim of this work is to validate the control approach independently of the adopted interface with the user. Therefore, the prosthetic hand has not been directly commanded by the user, but it has been positioned on a support and commanded by a PC. The objects to be grasped have been located in front of the hand. Once grasped, the object slippage has been induced by applying an impulsive force to the object. The starting A/A angle of the thumb has been imposed on the basis of the human being behaviour [21]. In particular, for the bi-digital grasp, it has been imposed an $AA_{angle} = 86^o$ that guarantee the opposition of the index finger and of the thumb.

The grasping forces obtained in Sect. III-B on the human beings have been given in input, as a reference, to the finger controllers implemented in C++ under Windows 7. The communication between the hand and the PC has been performed by means of an USB port. Referring to Fig. 1, the gains of the force control with inner position loop have been imposed equal to $K_{p1} = K_{p5} = 0.1$, $K_{p2} = K_{p6} = 1$, $K_{p3} = K_{p7} = 4$, $K_{p4} = K_{p8} = 80$, $K_{p9} = 1$, $K_{d1} = K_{d2} = 0.004$ and $K_I = 10$. The threshold imposed for slippage detection has been $0.15N$. During the pinch grasp of the ball, the thumb and index finger flex until the forces F_{n_k} measured by the sensors reach the reference value F_{d_k}. The grasp is maintained stable until an impulsive force is applied to the object determining its slippage.

Figs. 6 and 7 depict the force applied by the fingers, the slippage event detected on the fingers and the joint angles of one representative grasping trial of the $60mm$ diameter ball performed by the prosthetic hand. In particular, in Fig. 6 the normal forces acquired by the sensors positioned on the index and thumb tips are shown in blue and red respectively. The threshold value is outlined in black and the slippage events detected on the fingers are shown in green. When the object slippage is detected, a variation of the F/E angles of the index MCP joint and of the thumb TM joint and of the A/A angle of the thumb TM joint occur, as evident from Fig. 7. It is possible to note the increasing of the fingers flexion angle when the slippage occurs. On the basis of the force compensation approach, when a slippage occurs also a variation of the thumb A/A angle is present. Therefore, the proposed control approach guarantees a firm grasp also in presence of unforeseen events. The finger coordination is pointed out by the contemporary change of the joint angles for compensating the slippage event. The same object has been grasped for 10 times. The 30 grasping trials have been performed with a success rate (i.e. n^o of compensated slippage event/n^o of trials) of 94%. In Tab. III the finger mean reference forces obtained in Sect. III-B and the force mean values applied on the objects by the prosthetic hand fingers during the experimental trials are listed. The finger joint behaviour demonstrates the reliability of the proposed control strategy in following the force reference and in detecting and managing slippage. In Fig. 8, the final grasping configurations are shown. The obtained results are related to the pinch grasp, but the approach can be easily adaptable to the other pad opposition grasps.

V. CONCLUSIONS

In this paper a force-and-slippage control approach for prosthetic hand has been proposed and preliminarly tested on a poliarticulated prosthetic hand. A force control with inner position loop has been tested considering as reference the finger forces extracted from the human subjects. FSR sensors positioned on the human and prosthetic hand fingertips have been adopted for measuring the grasping forces. A

TABLE III

REFERENCE FORCE VALUES EXTRACTED FROM THE HUMAN BEINGS AND FORCE APPLIED ON THE OBJECTS BY THE PROSTHETIC HAND FINGERS.

	Ball $60mm$		Ball $35mm$		Glass	
	Human	Prosthesis	Human	Prosthesis	Human	Prosthesis
$F_{index}[N]$	$0.70 \pm 0.04N$	$0.67 \pm 0.07N$	$0.63 \pm 0.04N$	$0.6 \pm 0.08N$	$0.59 \pm 0.04N$	$0.51 \pm 0.05N$
$F_{thumb}[N]$	$0.71 \pm 0.02N$	$0.66 \pm 0.09N$	$0.62 \pm 0.05N$	$0.61 \pm 0.07N$	$0.57 \pm 0.03N$	$0.55 \pm 0.09N$

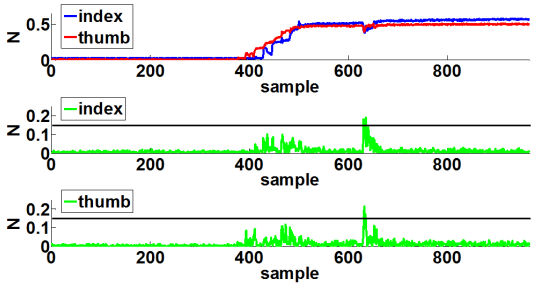


Fig. 6. Normal forces acquired by the sensors positioned on the index and thumb (Top). Slippage event detected by using the sensor positioned on the index fingertip (Center). Slippage event detected by using the sensor positioned on the thumb tip (Bottom).

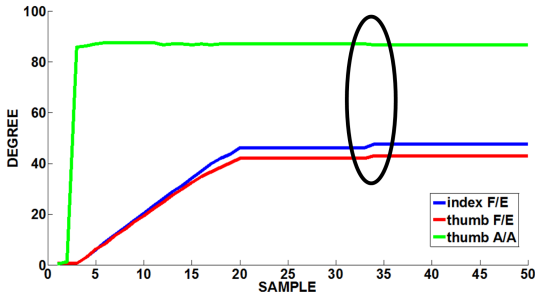
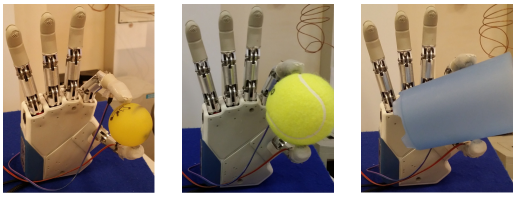


Fig. 7. Angles of the index MCP joint and of the thumb TM joint. The joint angle varation corresponding to the slippage compensation are outlined with the black circle.



(a) ball 35mm (b) ball 60 (c) glass

Fig. 8. Final grasping configurations of (a) the ball of 35 mm diameter, (b) the ball of 60 mm diameter, (c) the glass.

slippage detection algorithm has been proposed and its output has been introduced in the control law. Furthermore, the coordination of the fingers during grasping has been ensured by a force compensation procedure. Information about the forces applied on the objects during grasping, the slippage events, the joint angles have been recorded during the trials in order to demonstrate that the proposed approach can be adopted for improving the grasp stability with prosthesis hands, thus reducing the cognitive burden for the user. The proposed control law let the finger achieve the desired forces. Preliminary results have been obtained for the pinch grasp of several objects, but the approach is easily extendable to the other grasp configurations. Future works will be addressed to test other grasp configurations.

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