On the Shared Control of an EMG-Controlled Prosthetic Hand: Analysis of User–Prosthesis Interaction

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***Abstract*—An anthropomorphic underactuated prosthetic hand, endowed with position and force sensors and controlled by means of myoelectric commands, is used to perform experiments of hierarchical shared control. Three different hierarchical control strategies combined with a vibrotactile feedback system have been developed and tested by able-bodied subjects through grasping tasks used in activities of daily living (ADLs). The first goal is to find a good tradeoff between good grasping capabilities and low attention required by the user to complete grasping tasks, without addressing advanced algorithm for electromyographic processing. The second goal is to understand whether a vibrotactile feedback system is subjectively or objectively useful and how it changes users' performance. Experiments showed that users were able to successfully operate the device in the three control strategies, and that the grasp success increased with more interactive control. Practice has proven that when too much effort is required, subjects do not do their best, preferring, instead, a less-interactive control strategy. Moreover, the experiments showed that when grasping tasks are performed under visual control, the enhanced proprioception offered by a vibrotactile system is practically not exploited. Nevertheless, in subjective opinion, feedback seems to be quite important.**

***Index Terms*—Biorobotics, electromyographic (EMG) classification, prosthetic hand, shared control, vibrotactile feedback.**

I. Introduction

AN IMPORTANT requirement in designing reliable and acceptable prosthetic hands is that the control system must be simple, direct, and user-friendly. Current sophisticated commercial prostheses are controlled by means of electromyographic (EMG) signals recorded using surface electrodes, detecting electrical activity related to the patient's arm muscles [1], [2], making it possible to interpret a voluntary intention of the subject who acts on the hand by appropriate muscle contraction. Experience shows that even though a few subjects may be able to control a multiple DOF prosthesis with dexterity through many input EMG channels, most of them show early fatigue and desire hands requiring lesser effort in controlling movements. As it requires a high level of concentration to control many inputs simultaneously, only simple "single-channel hands" seem to be acceptable so far. This is reflected in the design of current commercial hand prosthesis [3]: because of the excessive effort required to reliably use more than two EMG signals extracted from the residual upper extremity muscle contractions [4]–[6], current prosthetic hands (such as OttoBock hands [1]) have only one or two DOFs [1]; therefore, they are not dexterous. Their mechanical design is aimed at providing basic functionality and reliability for grasping and some elementary manipulation. A novel multiarticulated prosthetic hand, i.e., the i-LIMB hand [2] was recently introduced in the market. This hand is the first-to-market prosthetic device with five individually powered digits. It is manufactured using high-strength plastics and looks like a real human hand. It has two main improvements compared to other commercial prostheses: first, speed and grip-strength sensors allow the control system to independently stop each digit; second, the possibility of moving the opposition plane of the thumb by means of a passive joint. The result is that the hand is capable of different grasping patterns such as precision (tridigit), power, and lateral grips. Nevertheless, concerning the control strategy, the device still uses a traditional two-input EMG system to open and close the hand's fingers that does not differ from those available in other commercial prosthetic hands.

An additional drawback of actual prosthetic hands is that no tactile or proprioceptive feedback is provided to the subject; grasping tasks are essentially carried out automatically by the mechanism over a specific and simple high-level command. The only sensory feedback available is based on the user's direct vision with which the subject can stop or reset hand operation if the grasping task is not successful. The aforementioned illustrated limitations affect subjects' acceptability in a significant way: surveys on using such artificial hands reveal that 30–50% of the upper extremity amputees do not use their prosthetic hand regularly [7], [8]. The main drawbacks pointed out by these subjects include reduced functionality, poor cosmetic appearance, and limited controllability [9]. Users would like to increase grasping functions in order to carry out more activities of daily living (ADLs) [10]. This turns out to be fundamental for an acceptable quality of life. Moreover, subjects would also like to have a sensory feedback in order to be able to grasp independently from visual control [11], [12] and to feel the hand as part of their own body.

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Despite amputee community demands, technology and working principles of commercially available hands have not changed in the last 30 years. However, in the last decades, classical robotic knowledge has been applied to improve some of the basic components of prosthetic hands and several research groups are currently investigating new and more complex systems aimed at matching users' desires and expectations.

Research areas in this field regard the development of prosthetic hands with better performance, dexterity, anthropomorphism, and cosmetics as well as the development of more intuitive or unconscious interfaces between the user and the device for better controllability.

In the field of sensory substitution, many studies have been carried out to provide sensory feedback, essentially by means of vibrotactile or electrotactile stimulation [13]–[16]. As a result of this research, guidelines and engineering parameters have been investigated to achieve the optimum stimulation.

The conventional approach for prosthesis control is the use of electromyography for pattern recognition and classification allowing a direct interaction between the user and the device. In contrast to simple EMG classifiers available in commercial prosthetic hands, a great number of powerful EMG classifiers are under investigation. Novel advanced systems are designed to guarantee up to six different classes [17], [18], even though these classifiers are usually tested on bench so that their reliability is not so guaranteed on a "real" moving system such as the human forearm. Moreover, using more than two EMG electrodes, these systems seem to be less reliable and intuitive than the commercial ones.

Besides the "classical" prosthesis control approach, another important field of research, involving engineers and neuroscientists, is aimed at developing neural interfaces with the ultimate goal of enabling a natural and unconscious control of the hand in respect of the traditional indirect EMG-based high-level control. To this aim, the authors are studying a cybernetic prosthesis (CyberHand, [19]) that is intended to be interfaced to the peripheral nervous system (PNS) by means of an implanted neural interface in order to improve control capabilities by processing the efferent electroneurographic (ENG) signals and to provide sensory feedback by means of stimulation of the PNS according to exteroceptive signals generated by the artificial sensory system [19]–[25]. Preliminary results of first experiments on neural interface have been obtained in the framework of the CyberHand project, in particular, animal afferent ENG signals have been recorded and classified; results are described in [26]. The work is ongoing toward the development of an implantable and reliable neural interface for recording and stimulating the peripheral nerves; it is expected that in a short time, the essential component of the CyberHand, the neural interface, will be ready for its first implant in human subjects.

Parallel to the advances in the research of human–prosthesis interfaces, innovative and improved functional anthropomorphic artificial hands have been investigated to provide adaptive grasps using low number of actuators [27]–[30].

Despite the important effort on the development of prosthetic hands, the new dexterous devices are not yet used in clinical trials because of the lack of adequate interfaces with the user [31]. In order to overcome this problem, Kyberd *et al.* proposed in [3] an EMG hierarchical grip control to drive a 2-DOF prosthetic hand. They demonstrated the possibility of controlling a number of degrees with little direct intervention by the operator if the control is arranged in a hierarchical manner and the detailed control of the lower levels is performed by a microprocessor.

Based on Kyberd assumptions, this paper presents the research developed on the control of a five-fingered underactuated hand endowed with 16 DOFs actuated by six motors: the CyberHand [24], [25]. The proposed control architecture has been developed to assess whether a simple but reliable EMG classifier exploiting two electrodes and recognizing four different commands, combined with a hierarchical grip control strategy and a vibrotactile feedback system, make it possible to activate different prehension patterns useful in everyday life in order to overcome current reduced practical reliability of powerful on-bench EMG classifiers. Three control strategies implementing different ratios of shared control between the high-level controller (directly depending on the subject intentions) and the prosthesis-embedded low-level controller (depending on the sensors and algorithms), have been developed and tested by able-bodied subjects. The control strategies differed in how the four EMG-based commands were exploited: it was possible to obtain more interactive control or more automatic control, thus, affecting the interaction and attention required by the subject to command the hand.

Experimental trials have been carried out to assess whether grasping performance, user acceptability, and satisfaction are affected by shared control changes, and how this variation is related to the required attention and the fatigue that may occur while using the prosthetic hand during different grasping tasks. A comparative analysis on performance, usability, and acceptability of different EMG hierarchical control strategies has been carried out. Finally, the important problem of force feedback in order to provide the perception of the hand as part of the body has been investigated. In particular, our aim was to understand whether the vibrotactile system is (objectively or subjectively) useful for enhancing the proprioception of the hand for the user.

This paper describes the mechatronic platform of a prosthetic hand endowed both with efferent EMG-based controllers and afferent vibrotactile feedback allowing the user to close the loop in grasping tasks. The control architecture, the simple vibrotactile sensory feedback system developed, the four-command EMG classifier, and the three different control strategies that are intended to progressively increase the user interaction and attention, are presented. Finally, a description of the performed grasping experiments is provided, and the collected objective and subjective experimental results are illustrated and discussed to be useful for future development on hand control.

II. Mechatronic Resources

A. Mechanical Design

The CyberHand is actuated by six DC motors, one for each finger (cable driving) plus one for the thumb opposition [25]. The thumb opposition motor is inside the palm, while the motors

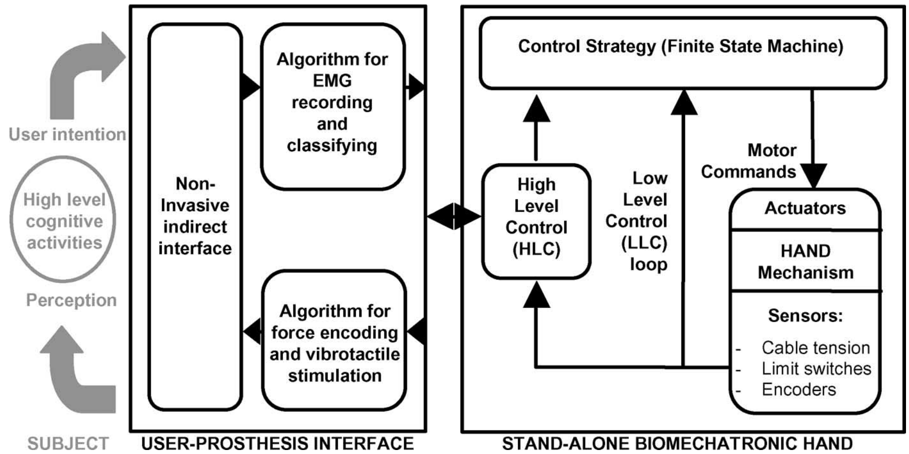


Fig. 1. Scheme of the developed prosthetic hand system. The stand-alone, modular biomechatronic hand consists of the mechanisms, the actuators, and the sensors. It is controlled by means of an LLC loop primarily responsible for grasp stability and an HLC system loop responsible for selecting the grasp configuration and force level requested by the user. The noninvasive indirect interface consists of two commercial EMG electrodes and the vibrotactile system developed; the user-prosthesis interface is responsible for exchanging signals to encode sensor information retrieved from the hand and to decode efferent EMG commands to control the hand action. Modified from [25].

for the flexion of the fingers are all located outside on a mechanical platform; the size of it is quite close to the prosthetic socket even if, in this first implementation, some additional room has been used for tuning and maintenance of the actuation system [32]. The hand has tendon transmission and uses Bowden cables in which routing has been optimized [33]. The underactuation system of the prosthesis allows the flexion of the three joints of the finger with a single DC motor providing an adaptive wrapping grasp around the unknown object. The goal, indeed, is to obtain a stable grasp with objects of different sizes and shapes, without increasing the complexity of the mechanism and control. This feature is particularly important in prosthetic hands where the constraints include weight and dimension, low-power consumption, and low EMG signal availability. Further details of the bioinspired design and pictures of the CyberHand are presented in [25].

B. Control Architecture

As stated in [25], the action of the prosthetic hand is controlled by a control architecture composed of two main parts: a low-level control (LLC) and an high-level control (HLC) (Fig. 1). The LLC loop is responsible for grasp stability, whereas the HLC has been designed both to interpret the subject's intentions gathered from the user–prosthesis interface (UPI), for launching appropriate action patterns, and to provide the UPI itself with appropriate signals for afferent stimulation. Both control levels are crucially dependent on a sensory system comprising five cable tension sensors, for finger-force sensing (one for each finger), motor encoders, and motor-limit switches (for a description, refer to [32]). Hand operation has, thus, been designed to be controlled as a finite-state machine (FSM), where the transitions between the different states are identified and detected as crucial events by the LLC (depending on the sensory system) or by the HLC (detecting recognized commands coming from the UPI, i.e., from the user). If the transitions between the different states are identified by the LLC, we have automatic control; whereas, if they are identified by the HLC, we have interactive control based on user intentions. Briefly, depending on the control strategy (i.e., the FSM), it is possible to obtain different ratios of shared control between the user and the embedded controller of the prosthesis.

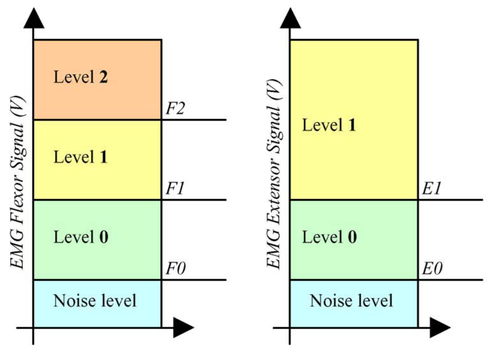
The noninvasive indirect interface consists in this case, of two commercial EMG electrodes and the vibrotactile system developed. However, the modular design of the hand makes it possible to exploit and validate not only different noninvasive indirect interfaces (as shown in Fig. 1) but also neural interfaces by simply changing the high-level controller [25]; the ultimate goal, in fact, is to connect a future version of the CyberHand via a neural interface implanted in peripheral nerves of amputees [22].

C. Electronic Hardware

The control architecture of the prosthetic hand is physically implemented on a personal computer (PC, AMD ATHLON XP 2.8 GHz, 512-MB RAM), equipped with two National Instruments input/output boards: a 12-bit high-speed analog output board (model: PCI-6713E), and a high-performance data acquisition board (model: DAQ PCI-6071E). The PC is also connected to six stand-alone motion controllers (one for each motor) by means of a serial communication. The core of these controllers is a Microchip microcontroller (PIC18F2431), which reads the motor encoders, and limit switches, and drives output power circuitry using a pulse-width modulation (PWM) technique. The six stand-alone motion controllers are capable of implementing position control by using proportional-integral-derivative (PID) algorithms, and to drive power to the motor, proportionally to an external voltage applied (driver modality). The input/output boards are used both to drive the motors in the driver modality and to acquire the cable tension sensor signals after they have been properly conditioned. Further details on the hardware architecture are described in [25] and [32].

III. UPI

The UPI developed is responsible for exchanging signals to encode sensor information retrieved from the hand and to decode



Flexor level	*Extensor level*	*EMG COMMAND*
0	0	**C0**
1	X	**C1**
2	X	**C2**
0	1	**C3**

Fig. 2. EMG signal classification. Upper graphs. The flexor and extensor carpi radialis signals, acquired by the PC by means of two commercial EMG electrodes and the data acquisition board, are processed and classified depending on their amplitude. If the amplitude is lower than the noise levels (thresholds F0 and E0), signals are sampled at the maximum resulting system control rate (650 Hz). If one of these signals is higher than thresholds F0 or E0, small windows (100 ms at the rate of 100 Hz) of EMG signals are processed and associated to a level (0, 1, or 2 for the flexor signal and 0 or 1 for the extensor). Lower tabular portion. Depending on the flexor and extensor levels associated to the input signals, an EMG command (C0, C1, C2, or C3) recognized by the HLC is generated; X labels mean that cocontraction always produces a C1 or C2 response.

efferent EMG commands to control the hand action. In this paper, it consists of an EMG four-command classifier and a vibrotactile system described in the following sections.

A. EMG Four-Command Classifier

A simple but reliable classifier was developed by recording the EMG signals from antagonist flexor and extensor carpi radialis in able-bodied subjects using two commercial active electrodes (Ottobock Company Group: 13E125). The active electrodes are designed with a built-in filter and a built-in adjustable gain. The signals have been acquired using the data acquisition board (NI PCI 6071E) and then processed on-line on the PC using a C routine. Four EMG commands are generated by implementing the following pattern recognition schema.

1) Supervised Training Phase: The subject performs a powerful flexor contraction, a powerful extensor contraction followed by muscle relaxation. In this phase, large windows of EMG (1 s at the rate of 200 Hz) are processed and three thresholds for flexion (F0–F2) and two for extension (E0 and E1) are set. These thresholds are employed to generate the four EMG commands as described in Fig. 2. Thresholds F0 and E0 are essential for EMG noise signal discrimination.

2) On-Line Pattern Recognition and Classification: During this phase, EMG flexor and extensor signals are acquired. If one of these signals is higher than thresholds F0 or E0, small windows (100 ms at the rate of 100 Hz) of EMG signals are processed and associated to an EMG command (C0–C3) mentioned in the lower portion of Fig. 2. On the contrary, if the signals are lower than thresholds F0 or E0, no EMG 100-ms temporal windows are processed and the resulting control rate becomes higher (650 Hz).

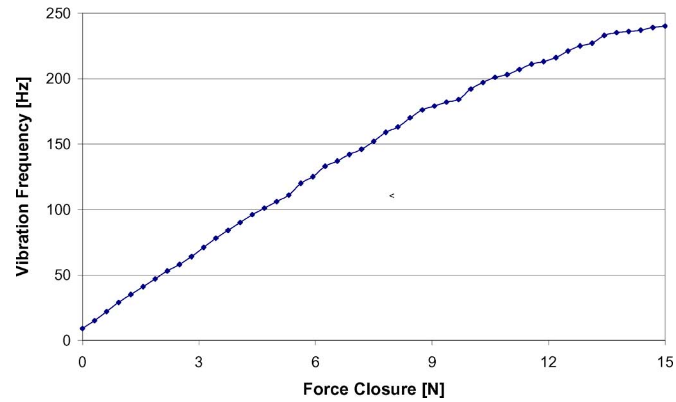


Fig. 3. Vibrotactile vibration frequency versus force closure characteristic. The force closure is measured by five cable tension sensors embedded in the actuation units of the hand [32]. A proportional relation between frequency and force is imposed to deliver feedback to the subject about force closure.

Command C1 is obtainable by performing a light flexor contraction, C2 by a strong flexor contraction, and C3 by an extensor contraction. Command C0 is used in the experiments as the quiet state and is obtainable by relaxing the muscles. The developed classifier is simple, fast, and reliable (90% of success ratio). Once generated, the four commands are processed by the HLC and the prosthetic hand moves depending on the FSM that regulates the system.

B. Vibrotactile Feedback Sensory System

As defined in [14], vibrotactile stimulation is when tactile sensation is evoked by a mechanical vibration of the skin, typically at frequencies of 10–500 Hz.

A simple vibrotactile system was built to deliver sensory feedback to the user in order to provide him/her with extended perception. Among the different principles of force feedback, a vibrotactile system was chosen, because of its high acceptability [14]. The developed system consists of a DC motor (MFA/Como Drills model RE-380) with eccentric (mass $= 0.6$ g; eccentricity $= 6$ mm), driven using the PWM technique by a power n-MOS, where the gate is directly connected to the NI output board PCI-6713E. The PWM duty-cycle equation (i.e., the algorithm for force encoding and vibrotactile stimulation shown in Fig. 1) was tuned in order to provide a frequency skin vibration proportional to the grasping *force closure* (defined later in Section IV), that is measured by the five cable tension sensors available (Fig. 1 and [32]). The graph in Fig. 3 shows the resulting characteristic.

IV. Definitions

Although the natural hand contributes about 90% of the function to the upper limb to perform common ADLs [34], the upper extremity is an entire system, where the coordinated movements create overall mobility and dexterity. To distinguish the functionality of the hand, it must be assessed as an isolated manipulator (i.e., decoupled from the rest of the upper limb: shoulder, elbow, and wrist) wherever possible [35]. In order to describe the

TABLE I
DEFINITIONS OF BASIC PARAMETERS USED TO DESCRIBE A GRASP OF A FIVE-FINGER ANTHROPOMORPHIC HAND. BASED ON [36]

Hand pre-shaping	It is defined as the displacement in the space of each link of the hand immediately before the enclosure phase occurs. This parameter depends on the object shape and on the task requirements.
Force closure	It is the force value that the hand exerts to perform a stable grasp of an object, i.e. when the object position is fixed without slipping with respect to finger joints while they are locked. In the CyberHand it is measured by cable tension sensors on tendons.
Grasp stability	It is generally defined as the ability of the grasp to resist external forces without slippage, and its capability to return to its initial configuration after being disturbed by an external force or moment.
Grasp security	In this paper refers to the resistance to slipping [36]; it depends on the configuration of the grasp (i.e., *hand shape*), on contact area and on friction between the object and the fingertips. Note that grasp security is strongly related to grasp stability.

operation of the CyberHand, it is sufficient to provide four general parameters: *hand preshaping*, *force closure*, *grasp stability*, and *grasp security*, as listed in Table I.

Other analytical measures such as *compliance*, *connectivity*, *form closure*, *grasp isotropy*, *internal forces*, and *manipulability* were introduced by [37] and [38]. They principally refer to the grasping "manipulator system," on the objects and on the ability of the grasp to impart arbitrary motions to them. Once the grasping "manipulator system" is defined, *compliance* and *connectivity* depend exclusively on the grasped object. The present four-parameter set is defined to describe a simple clamping task with no manipulation capabilities, in order to compare the human hand-clamping capabilities with the ones available in an underactuated anthropomorphic prosthesis; for this reason, *form closure*, *grasp isotropy*, *internal forces*, and *manipulability* are not considered, even if important for further studies.

V. NATURAL GRASPING STRATEGY AND THE GRASP PRIMITIVE APPROACH

Grasp stability is the result of selecting appropriate grasp sites on an object, defining hand *preshaping* and transporting the hand to enable the digits to contact the object, and, once in contact with the object, avoiding slippage by applying sufficient *force closure* in relation to any destabilizing surface-tangential forces at the individual finger–object interfaces [25]. Common objects are identified by vision for automatic retrieval of relevant internal models, which are used to parametrically adapt the motor commands prior to their execution, in anticipation of the upcoming force requirements. The different ways of grasping an object are called *affordances* [39]. Johansson in [40] describes how grasp stability is ensured. The swift coordination of fingertip forces during self-paced everyday manipulation of ordinary "passive" objects cannot be explained with feedback control, due to its long time delays, and must be explained by other mechanisms. Indeed, the brain relies on feedforward control mechanisms and takes advantage of the stable and predictable physical properties of these objects by parametrically adapting

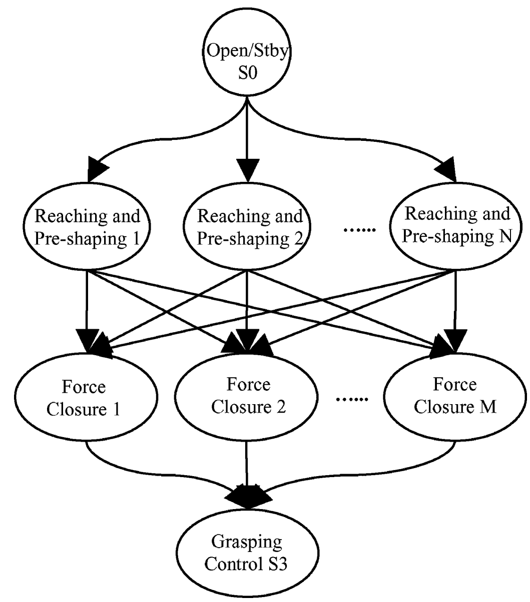


Fig. 4. Natural grasping strategy model. The natural hand reaches, preshapes, and grasps the object, according to affordances provided by internal models after visual perception [41]. Once the object is held, the brain relies on feedforward grasping control mechanisms, i.e., load force ratio required for a stable grasp is controlled by a "low-level" controller, which is digit specific [42].

force motor commands to the relevant physical properties of the target object. After lifting and replacing object trials, Johansson demonstrated that the grip force in each instant is constrained by the active sensorimotor program to increase and decrease with no time delay parallel to the vertical load force. This coordinative constraint ensures grasp stability, i.e., the grip force at any given load force exceeds the corresponding minimum grip force to prevent slippage by a certain safety margin [40]. Consequently, the natural hand grasping strategy can be graphically described by the model in Fig. 4.

In artificial hands, the same hand control scheme, described in Fig. 4, can be obtained by means of EMG classification, having a large variability of commands recognized by the HLC (i.e., *grasp primitives*), correlated with affordances. By driving an anthropomorphic prosthesis with the right grasp primitive, all the objects can be held as in the natural case (grasping primitives approach). Nevertheless, current smart classifiers do not provide more than six recognized classes (or primitives) [17], [18], and their practical reliability must be evaluated; moreover, their controllability in prostheses application is neither natural nor intuitive.

A reliable system based on the "natural-based" grasping primitive approach, currently used in commercial prostheses, can be described by the FSM general diagram in Fig. 5.

Traditional prostheses allow the amputee to intentionally move from one state to another of the upper graph in order to open and close their prosthetic hand, by using at most two input channels (one EMG electrode or electrical switch, or two EMG electrodes, or one EMG electrode plus one switch). Current systems include force sensor-based control in order to avoid object slippage by automatically selecting the *force closure*. Depending on the prosthesis and on its working modality, two different

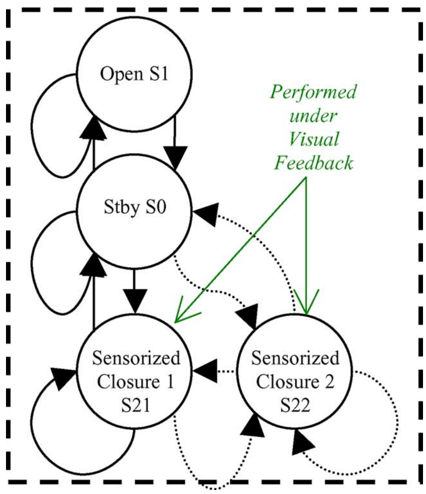


Fig. 5. Commercial prostheses grasping strategy state diagram, based on the grasping primitive approach. The prosthesis is controlled by means of an FSM; each circle represents a possible state. S0 is the standby state: the hand is still. S1 is the open state: the hand opens until it reaches its mechanical stop. S21 and S22 are sensorized closure states, i.e., the hand closes and manages a force closure level, set during device calibration.

force closure grasps may be available. For successful grasps, the subject must look at the prosthesis during its operation and open it in risky situations (visual feedback). The novel advanced commercial i-LIMB [2] prosthesis is still controlled by a traditional two-input EMG control system. Its control scheme is neither described in literature nor illustrated. It is important to point out that the control approach described in this paper is general and could also be implemented in such a sophisticated hand.

Even if the amputee can decide *when* to start a grasp, he/she cannot decide *how*. In fact, the *preshaping* is fixed by the mechanical design, the *force closure* levels (if more levels are permitted by means of different grasp primitives) are set by the system calibration, and *grasp stability* and *grasp security* are established by the success of the grasp and by the shape of the object. The grasping primitive approach, in a control issue, implements an FSM where the transitions between the different states are identified and detected as crucial events by the embedded LLC (Fig. 1). As a consequence, by using this approach, the amputee does not have complete control of the prosthesis; whenever the prosthesis fails, the user must restart the task. A graphical description of this behavior is given in Fig. 6(A). The figure illustrates that all the grasping parameters depend on the LLC (white slices); none on the HLC.

The basic idea of the work presented in this paper is to distribute responsibility of the grasping task in a different way, giving the subject the possibility to interact with the prosthesis, and, eventually, developing different, more-balanced, and bioinspired grasping strategies. This is possible by implementing an FSM where the state transitions are determined not only by the LLC but also by the HLC (strongly dependent on the user intentions). This modification could allow the user to decide not only *when* to start a grasp but also *how to perform it*: how to *preshape* the prosthesis, how much *force closure* to apply; in other words, to select the right affordance. Therefore, subject participation in the task is enhanced. It is clear, however, that this approach

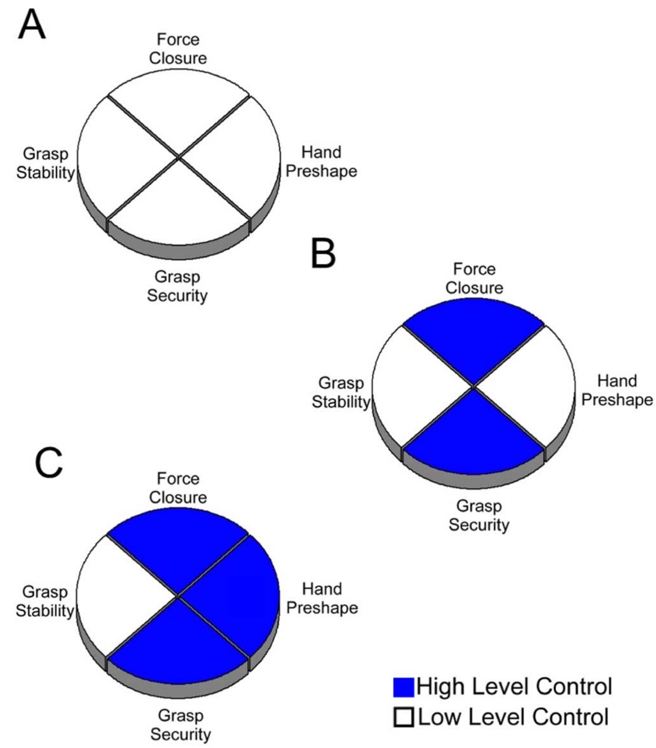


Fig. 6. Grasping parameters' dependence graph. White slices refer to grasping parameters dependent on the LLC; gray slices refer to grasping parameters dependent on the HLC. (a) Exploiting the grasping primitive approach, all grasping parameters are established by the embedded LLC. (b) Grasping parameters established by the HLC and by the embedded LLC in control strategy $\mathrm{M}2$. (c) Grasping parameters established by the HLC and by the embedded LLC in control strategy $\mathrm{M}3$.

inevitably increases the subject concentration required to perform the grasping task and may, possibly, cause early fatigue; however, if this growth of concentration is awarded by a higher number of graspable objects, users' satisfaction may be higher.

VI. Methods and Experiments

According to the approach described in the previous section, a classifier was developed for the CyberHand, in order to assess and compare different strategies. Three different control strategies were developed in the hand controller: they are formally defined as modalities $\mathrm{M}1$, $\mathrm{M}2$, and $\mathrm{M}3$. In $\mathrm{M}1$, the grasping parameters defined in Table I are completely managed by the embedded LLC of the prosthesis (grasp primitive approach, Fig. 5). In $\mathrm{M}2$, the control is slightly shifted from the LLC to the HLC: thanks to the visual feedback, and assisted by the vibrotactile feedback, the user is able to stop the closure as desired, and, for this reason, is capable of selecting the *force closure*. In $\mathrm{M}3$, the grasp is completely controlled by the HLC (the user), which is able to select both the hand *preshape*, by moving the thumb opposition axis as desired, and the *force closure*, by stopping the grasp.

A. Control Strategy $\mathrm{M}1$

The grasping parameters, defined in Section IV, are completely managed by the prosthesis LLC such as that in the

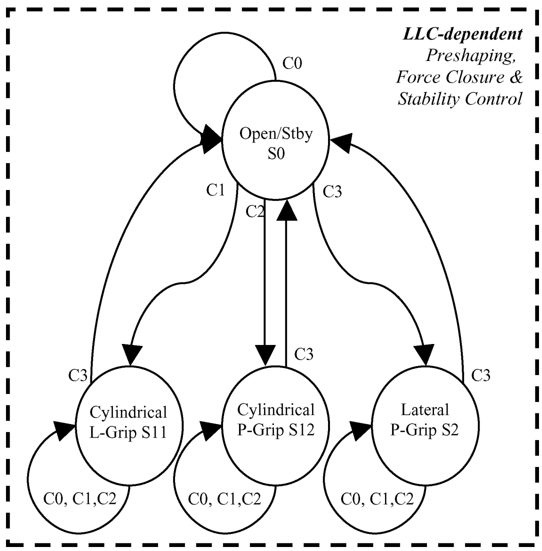


Fig. 7. Control strategy M1, FSM diagram. Circles represent states. C0–C3 are the EMG commands, defined in Fig. 2. A light cylindrical grasp (state S11) or power cylindrical grasp (S12) are selectable by light (command C1) or power (C2) flexor contraction; the power lateral grip (S2) by an extensor contraction (C3). The hand reopens (S0) after an extensor contraction (C3). The grasping parameters are all managed by the hand LLC.

grasping primitive approach [Figs. 5 and 6(a)]. Fig. 7 depicts the FSM diagram of the control strategy M1. By means of muscle contractions (selecting the appropriate EMG command, Fig. 2) the user can choose among a light cylindrical grasp (state S11), a power cylindrical grasp (S12), and a power lateral grip (S2); the fixed force closure values are 2.5 N, 15 N, and 3 N respectively. Napier suggests in [43] a taxonomy scheme in which grasps are divided into "power grasps" and "precision grasps." However, it is important to point out that due to the underactuated mechanisms of the CyberHand, it is impossible to control each finger joint, and, thus, the set of grasps has been focused on "light" rather on "precision" grasps, according to the total force applied. For this reason, the cylindrical force closure values were selected to obtain power and light grasps, in order to grip many different shape and weight objects [32]. Moreover, according to Cutkosky's grasp taxonomy [36], the lateral grasp belongs to the power branch of the *grasp tree*; for this reason, its force closure value is fixed at a power level.

When the classifier recognizes an EMG command, the prosthetic hand executes the prehension pattern as following: in the first phase, the hand is driven in its preshaping posture. In the second phase, the hand closes the involved fingers according to the fixed force; grasping stability is guaranteed by a cable tension-based force control algorithm (for a detailed description of the algorithm, refer to [32]). In order to ensure system controllability, the EMG signals are not recorded during the preshaping and reopening phases.

While performing the grasp, users' concentration and interaction are limited: only a single muscle contraction plus visual check are required. Anyway, users' capability to decide how to perform a grasp is very low: only three fixed affordances are available to the user. In order to understand what is the effect of this issue in terms of grasping capabilities, the grasp taxonomy, defined by Cutkosky [36], can be used (Fig. 8).

Combining the features of an underactuated prosthetic hand with the grasping algorithm that achieves a balanced distribution of the forces within the hand, both prismatic and circular grasps can be obtained, beginning with a cylindrical preshaping of the hand [32].

The underactuated hand is able to adapt itself to the shape of the object thanks to the mechanism of each finger. The dynamics of the finger, with or without the contact with the grasped object, is strictly dependent on the pulley radius, the torsional spring stiffness, the torsional spring preload, and the mechanical stops. During the enclosure phase, the fingers come into contact with the object, generating a resultant force pointing toward the palm. The grasp is always stable, but it cannot be considered a pinch grasp, and a small object is totally enveloped. However, choosing a value of force closure sufficiently low (for the light prismatic/circular grip), it is possible to reduce the resultant of the distal phalange contact force pointing toward the palm, obtaining a stable pinch grasp with small light objects. This is possible only with relatively light, small objects, through the friction between the object and the fingers: objects where the load force is higher than friction will inevitably fall. As a consequence, a fixed low value of force closure (as it is in control strategy M1) implies a limited subset of possibly achievable precision grasps (e.g., grasps 12 and 6 in Fig. 8). For power prismatic/circular grasps, instead, there is no limitation on the value of force closure and, for this reason, using the M1 control strategy, all grasps with fixed thumb opposition are possible (grasps 1, 2, 10, and 11 in Fig. 8).

Finally, grasping capabilities exploiting the M1 control strategy are limited by the set force closure values and by the fixed preshaping of the hand; the set of permitted grasps (circled with a dashed line in Fig. 8) comprises: lateral pinch (grasp 16), power prismatic/circular (grasps 1, 2, 10, and 11), and light prismatic/circular grips (e.g., grasps 12 and 6 in Fig. 8).

B. *Control Strategy* M2

The second modality, M2, slightly shifts the shared control from the LLC to the HLC; in other terms, from the prosthesis to the user, who is able to establish the force closure deciding whenever to stop the closure thanks to the visual and vibrotactile feedback.

Fig. 9 depicts the FSM diagram of M2; by a first muscle contraction, the user may choose between a cylindrical (state S1) or a lateral (S2) grip. When the classifier recognizes the starting EMG command (C1 or C2 for cylindrical grasp, or C3 for lateral grip), a prehension pattern is achieved as following: at first, the hand preshapes and, soon after, the involved fingers start closing. During hand closure, visual and vibrotactile feedback are essential to decide when to stop the grasp: the hand stops closing by meaning of a second flexor contraction (C1 or C2) that drives the FSM in its user-force grasp control state, formally S3. Final stability is, then, guaranteed by the cable tension-based force control algorithm [32]. In order to ensure system

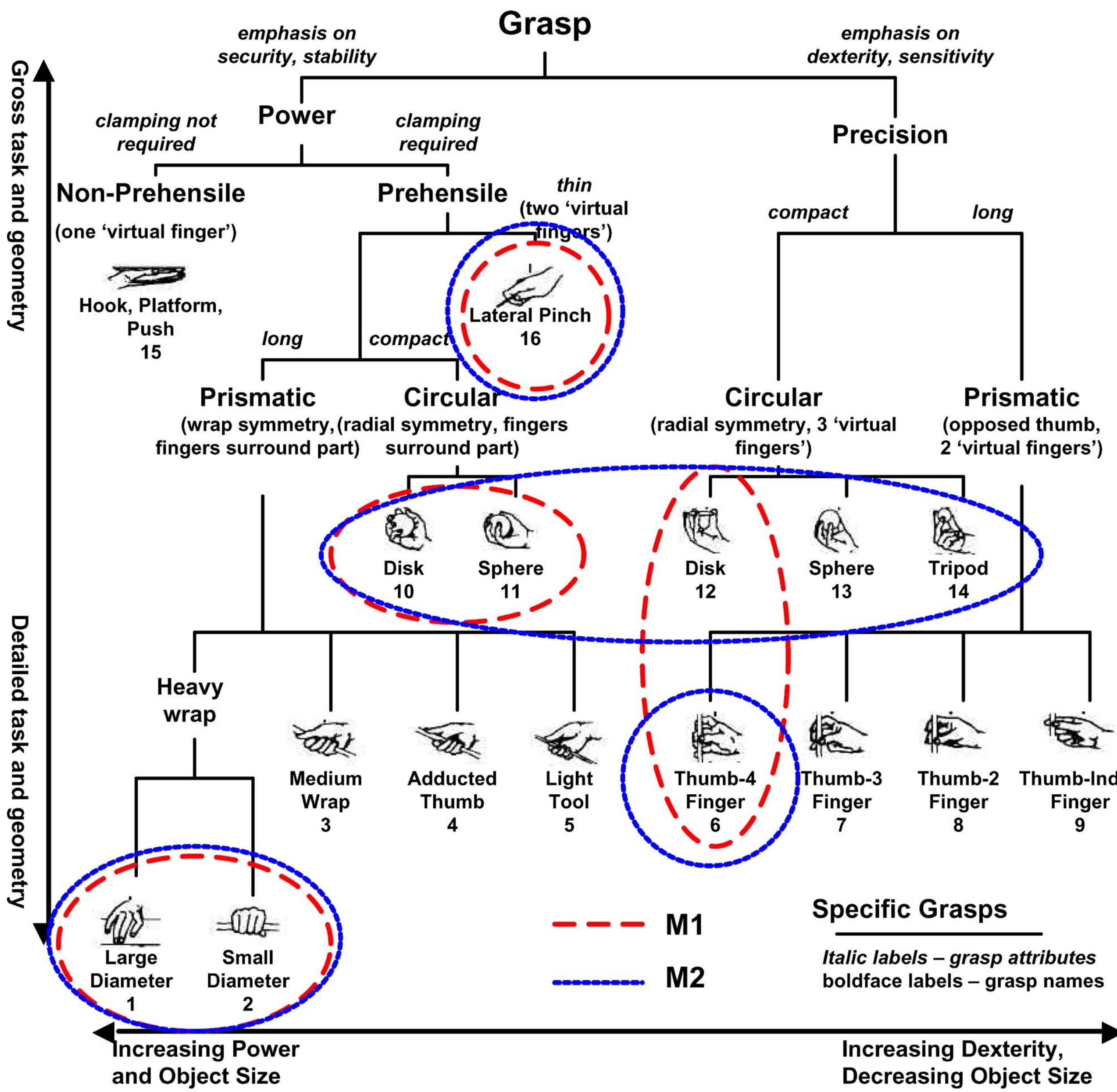


Fig. 8. Available grasps based on Cutkosky's grasp taxonomy [36]. A small set of grasps is permitted by using strategy M1 (dashed line circles), i.e., lateral pinch, power prismatic/circular, and light prismatic/circular. M2 (dotted line circles) permits a larger set of grasps by selecting the force closure. M3 theoretically allows to perform all the grasps of the taxonomy.

controllability, the EMG signals are not processed during the preshaping phase and the reopening of the prosthesis.

While the preshaping of the hand is fixed "*a priori*," the desired force closure is directly chosen by the user (through the HLC) once he/she decides to stop the grasp. This event interrupts the cable tension-based force control algorithm; the current force closure, FC, is measured and set in the grasping algorithm control loop as the desired one (Fig. 10).

The desired finger force $F_{(f)}$ is calculated in cylindrical grasps by using the following equation:

$$F_{(f)} = \begin{cases} \frac{\mathrm{FC}}{6}, & f \in [2, 3, 4, 5] \\ \frac{\mathrm{FC}}{3}, & f = 1 \end{cases} \tag{1}$$

where FC is the force closure and f is an index that refers to fingers: 1 for the thumb, 2 for the index finger, 3 for the middle finger, 4 for the ring finger, and 5 for the little finger.

Equation (1) sets an equal desired force for all the fingers, except for the thumb, where the value is doubled; however, the sum of the finger-desired force is equal to the measured FC. The thumb value is set at a higher level in order to oppose the other fingers' pressure through the object, while it is being grasped. Equation (1) combined with the developed control algorithm, permits an anthropomorphic grasping of objects: once the user decides to end the increasing grasp through a muscle contraction, fingers that touch the object maintain their grip force, whereas nontouching fingers automatically reach total

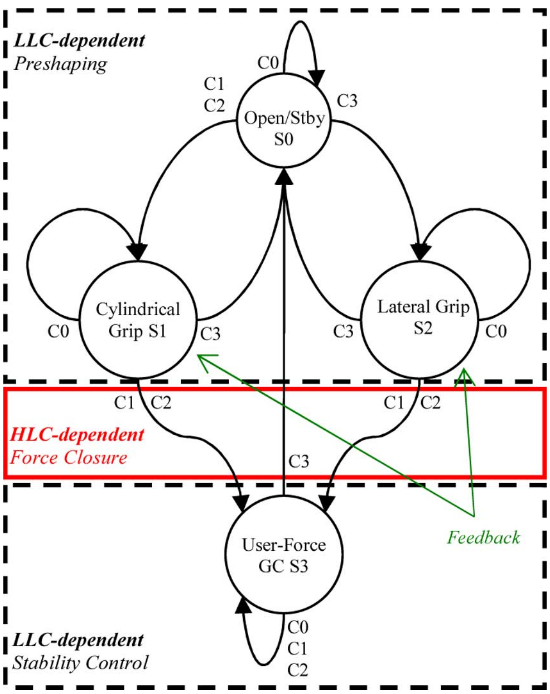


Fig. 9. Control strategy M2, FSM diagram. Circles represent states. C0–C3 are the EMG commands, defined in Fig. 2. A cylindrical grasp (state S1) or a lateral grip (S2) are user selectable by a first flexor contraction (command C1 or C2) or extensor contraction (C3), respectively. A second flexor contraction (C1 or C2) stops closure, and the hand applies and handles a user-dependent force closure value on the object (user-force grasp control, state S3). The hand reopens (S0) after an extensor contraction (C3). Stability and preshaping are managed by the LLC, whereas the force closure is managed by the HLC.

closure [32]. Hence, by a cylindrical preshaping of the hand, it is possible to obtain stable anthropomorphic grasps involving different fingers.

In the lateral grip, only the thumb is involved; when the user decides to stop the grasp, the current thumb grip is measured and set as the desired value in the control algorithm.

In modality M2, the user's level of concentration is higher than in M1 having to contract muscles twice, at the start and at the end of the task. Further, concentration is also required to pay attention to the vibrations produced by the vibrotactile feedback. However, this strategy awards the user with more prehension patterns: the limited grasping capabilities in M1, caused by the fixed force closure value, are now extended. The available grasps are circled with a dotted line in Fig. 8; grasps 1, 2, and 6 are assumed to have equal thumb opposition axis positioning. Grasps 3, 4, 5, 7, 8, and 9 are not obtainable due to the fixed thumb opposition achieved by the preshaping phase. Finally, grasping capabilities in the M2 strategy are only limited by the fixed preshape of the hand. The grasping parameters' dependence graph is shown in Fig. 6(B). Even if the hand preshape still depends on the LLC, by selecting the force closure, the user (operating on the HLC) also influences the *grasp security*; if the chosen force is not enough, the object will probably slip.

C. *Control Strategy* M3

In the third strategy, M3, the grasp is completely controlled by the user who is able to select both the hand preshape by opposing the thumb, as desired, and the force closure, by stopping the grasp, as in M2. Fig. 11 describes the developed state diagram: by means of a light continuous flexor contraction (continuous recognition of EMG command C1) or extensor contraction (continuous recognition of C3), the user can change the thumb opposition axis, accomplishing a sort of preshaping phase (direct control of thumb opposition DOF, cf. Fig. 12).

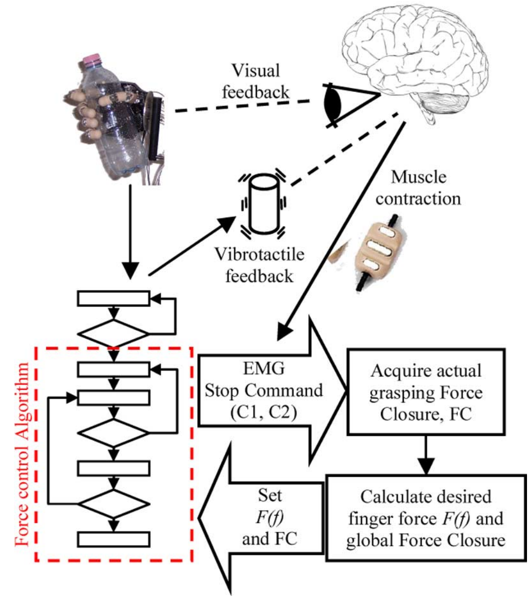


Fig. 10. Desired force closure selection scheme. The force control algorithm is described in [32].

After the thumb has been positioned, the fingers start closing by means of a strong flexor contraction (C2); thumb closure is delayed in order to reach the index when this is already closed (to obtain correct lateral grips). Similar to the strategy M2, the grasping phase is ended by a further flexor contraction. During hand closure, visual and vibrotactile feedbacks help the user to decide when to stop the increasing grasp.

User's concentration and interaction are high: the preshaping selection may require several contractions to finely adjust thumb opposition, as desired; moreover, the grasping phase requires two additional contractions. This growth of concentration is theoretically balanced by an increased number of graspable objects; due to the *opportunity to preshape thumb opposition, as desired*, all the grasps unavailable with M2 (defined grasps 3, 4, 5, 7, 8, and 9 of Fig. 8) are now allowed. This control strategy permits the performance of all the grasps of Cutkosky grasp taxonomy according to the previously described mechanical limitations. The grasping parameters' dependence graph is illustrated in Fig. 6(c): the grasp is strongly user-dependent.

D. *Experimental Setup: Reach, Pick, and Lift Trials*

The prosthetic hand functionality has been tested through experimental grasping trials with the three developed control strategies M1–M3. The prosthetic hand has been assembled onto an orthopedic splint (Fig. 13): the splint in thermoforming plastics supports the prosthetic hand, allowing any reaching movement in which the wrist is not involved. Moreover, it

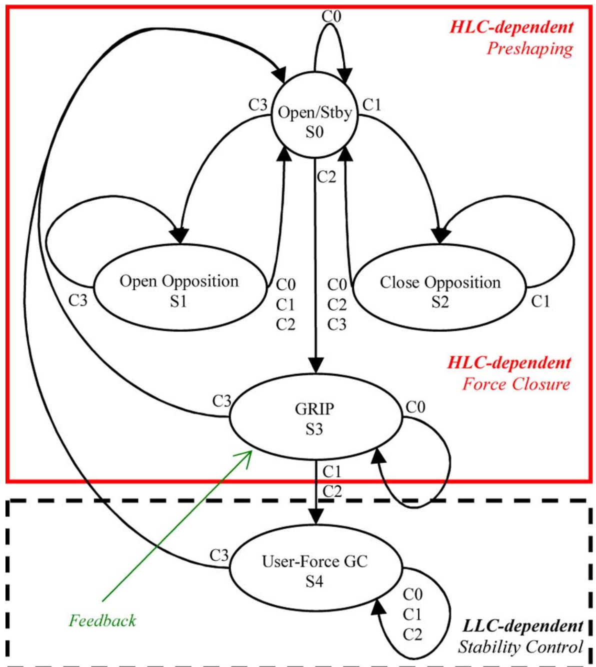


Fig. 11. Control strategy $\mathrm{M3}$, FSM diagram. Circles represent states. $\mathrm{C0}$–$\mathrm{C3}$ are the EMG commands, defined in Fig. 2. By means of a light continuous flexor contraction (continuous recognition of command $\mathrm{C1}$, state S2) or extensor contraction (continuous recognition of $\mathrm{C3}$, state S1), the user can change the thumb opposition axis performing a sort of preshaping phase. After the thumb has been positioned, the fingers start closing (state S3) by means of a strong flexor contraction ($\mathrm{C2}$). A further flexor contraction ($\mathrm{C1}$ or $\mathrm{C2}$) stops closure, and the hand applies and maintains a user-dependent force closure value on the object (user-force grasp control, state S4). The hand reopens (S0) after an extensor contraction ($\mathrm{C3}$). Grasp stability is managed by the LLC, whereas the force closure and preshaping are managed by the HLC.

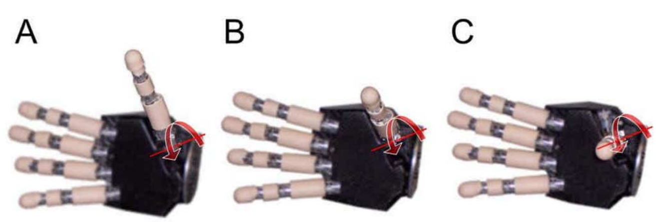


Fig. 12. The hand preshape may be selected by means of users' muscle contractions. (A) The thumb preshaping position permits lateral grips. (B) The thumb is slightly opposed: e.g., thumb-index or thumb-2/3 finger grasps may be obtained. (C) The thumb is completely opposed: e.g., power grasps or thumb-4 finger grasps are achievable.

was fastened onto the forearm by means of Velcro strips. This solution has been adopted in order to perform grasping experiments with able-bodied subjects.

Experiments consisted of two trials of objects pick and lift: 14 able-bodied young subjects whose mean age was 29.0 years (standard deviation 4.7 years), after giving informed consent, had to reach, pick, and lift 17 different objects employing the modalities $\mathrm{M1}$–$\mathrm{M3}$, with or without the vibrotactile feedback system (applied to the subjects biceps by means of Velcro strips). Table II shows the detailed list and the order of execution of the experiments.

Control strategy $\mathrm{M1}$ with no vibrotactile feedback has been assessed within the first experiment: EM1. As a matter of fact, in the $\mathrm{M1}$ control strategy, force closure is set "*a priori*"; for this

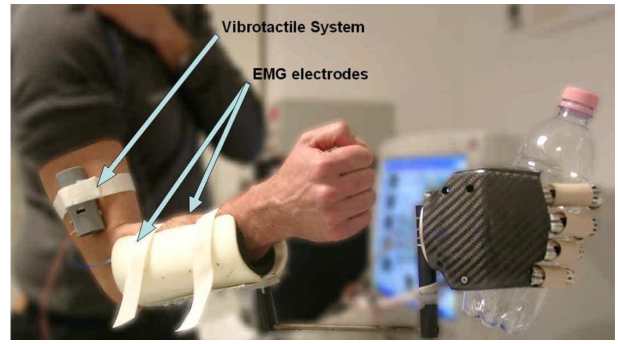


Fig. 13. Prosthetic hand built on the orthopedic splint. The EMG electrodes are applied on antagonist flexor and extensor carpi radialis, whereas the vibrotactile system is applied on subjects' biceps by means of Velcro strips.

TABLE II
LIST OF EXPERIMENTS. EACH EXPERIMENT CONSISTED OF TWO TRIALS OF PICK AND LIFT 17 DIFFERENT OBJECTS, BUT DIFFERED ON THE CONTROL STRATEGY AND ON THE AVAILABLE FEEDBACK

Experiment name	Strategy	Feedback
EM1	M1	Visual
EM2	M2	Visual
EM2 V	M2	Visual + Vibrotactile
EM3 V	M3	Visual + Vibrotactile

reason, vibrotactile feedback is not strictly required for hand control. On the contrary, the control strategy $\mathrm{M2}$ requires user attention for force closure selection. Consequently, $\mathrm{M2}$ has been tested both using only visual feedback (in experiment EM2), and using visual plus vibrotactile feedback (experiment EM2 V), in order to analyze objective and subjective differences in the use of such a system. The $\mathrm{M3}$ control strategy has been assessed only with the vibrotactile feedback system in the last experiment, named EM3 V.

Before starting the experiments, subjects were asked to perform the supervised training phase of the EMG classifier (cf. Section III-A), in order to calibrate the system with their muscular activity levels. After this, they were taught how to generate the four commands, $\mathrm{C0} - \mathrm{C3}$, and left free to use the system for 5–10 min to become familiar with it. Each control strategy was explained before the relative experiment, and five more minutes were left to practice with the specific modality.

Seventeen objects were selected based on the approximate percentage of utilization of the main grips in ADLs and differ by shape and weight (cf. Table III). In the experiments, a spherical grip is required for 10% of the tasks, a tripod/tip grip for 30%, a cylindrical power grip for 25%, and a lateral grip for 20% [35]. Extension grasps (required for 10% of ADLs tasks, [35]) are not considered due to mechanical limitations of the underactuated hand, as described in Section VI-A.

Grasps have been considered successful when the objects were correctly lifted off, i.e., when no slippage event occurred. The *success of the grasp* is the parameter that has been used to objectively evaluate the experiment outcomes. Statistical differences among the experimental results, have been evaluated by using the Kruskal–Wallis nonparametric one-way analysis of variance (ANOVA). A significant level $p < 0.05$ was selected for

TABLE III
OBJECT SET BASED ON APPROXIMATE PERCENTAGE OF ADL TASKS [35]

Grasp Type	Object	Object Id	Size	Weight
Power 25% ADL	Small bottle	P1	D = 6 cm	500 g
	Big bottle	P2	D = 8.5 cm	1.0 Kg
	Cylinder	P3	D = 7 cm	100 g
	Cylinder	P4	D = 5 cm	400 g
	Cylinder	P5	D = 5 cm	50 g
Spherical 10% ADL	Round sponge	S1	D = 10 cm	30 g
	Tennis Ball	S2	D = 6 cm	120 g
Tripod or Tip 30% ADL	Sphere	T1	D = 3.5 cm	20 g
	Sphere	T2	D = 4.5 cm	25 g
	Sphere	T3	D = 5.5 cm	30 g
	Felt-tip pen	T4	D = 2 cm	70 g
	Mobile phone	T5	D = 4 cm	200 g
	Cube	T6	D = 5 cm	80 g
Lateral 20% ADL	Postcard	L1	d = 1mm	10 g
	Key	L2	d = 2mm	80g
	Floppy disk	L3	d = 3mm	40g
	CD	L4	d = 1 mm	30g

the experimental performance comparison. Statistical analysis has been performed by using the MatLab (The MathWorks, Natick, MA, USA) custom scripts.

After the experiments, subjective opinions have been collected by means of an interview. In order to appraise the benefits of the vibrotactile feedback, the training duration, and the three control strategies, a list of 18 statements has been prepared as follows:

- The vibrotactile feedback system is useful.
- The vibrotactile feedback system physically disturbs.
- The training duration is long.
- Control strategy $\mathrm{M}x$ is difficult to control (where $x = 1, 2, 3$).
- Control strategy $\mathrm{M}x$ requires attention.
- Control strategy $\mathrm{M}x$ causes physical fatigue.
- The interface of control strategy $\mathrm{M}x$ is complex.
- Control strategy $\mathrm{M}x$ is overall satisfying.

Fourteen subjects were asked to respond to the 18 statements based on the Likert scale (i.e., $1 =$ strongly disagree, $2 =$ disagree, $3 =$ neither agree nor disagree, $4 =$ agree, $5 =$ strongly agree) [44].

VII. RESULTS

The three control strategies M1–M3, both with and without the vibrotactile feedback system, have been tested by 14 able-bodied subjects. Each volunteer has performed 136 grasps, for a full amount of 1904 grasps. Objective and subjective results are presented.

A. Objective Results

Grasp success percentage, in the first and second trials of each experiment, is presented in Fig. 14. The highest percentage has been obtained in the second trial of experiments EM3 V and EM2 V (90%), whereas the lowest one is in the first trial of EM1 (81%). Experiment EM2 V (82% first trial, 90% second trial) results in higher percentages than experiment EM2 (81% first trial, 87% second trial). Statistical differences were found among the eight trials; however, comparing the first trials of the four experiments, no differences were found, and the same was observed on comparing the second trials.

During the experiment EM3 V, only few subjects exploited the enhanced capabilities of M3 control strategy, i.e., the possibility of finely moving the thumb to obtain good preshaping of the prosthetic hand. Most of the subjects were satisfied by roughly moving the thumb until it reached its mechanical stops, for performing lateral or cylindrical grasps [Fig. 12(A) and (C)].

All second trials present higher success percentage than the first trials; this trend is partially confirmed by the ANOVA analysis: the p value calculated for comparing the two trials of EM1 is 0.10; it is 0.06 for EM2, 0.01 for EM2 V, and 0.04 for EM3 V. Statistical differences are found only between the first and the second trial of experiments EM2 V and EM3 V.

Success percentages related to the second trial of all experiments are presented for each object in Table IV.

The objects P1, P3, P4, and S1 have been grasped with high success percentages (from 93% to 100%) in all the experi-

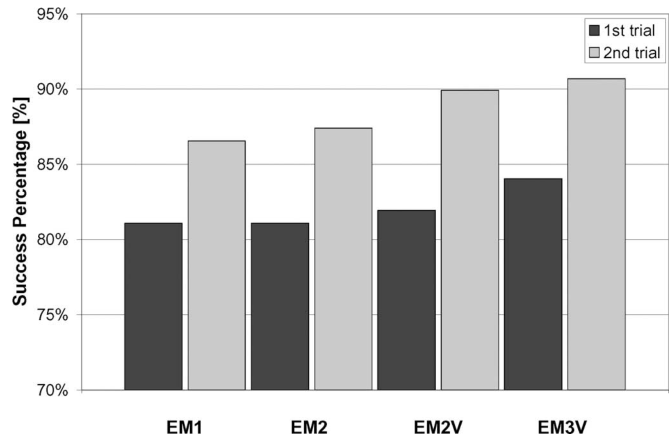


Fig. 14. Success percentage graph in the four experiments. Grasps were considered successful when the objects were correctly lifted off without slippage. Success percentage is calculated based on 238 grasping tasks (14 subjects $\times$ 17 objects).

TABLE IV
SUCCESS PERCENTAGE FOR EACH OBJECT IN EACH EXPERIMENT IS CALCULATED BASED ON THE SECOND TRIALS

Object Id	Experiment EM1	Experiment EM2	Experiment EM2V	Experiment EM3V
P1	100%	100%	93%	100%
P2	71%	100%	100%	100%
P3	100%	100%	100%	93%
P4	100%	93%	93%	93%
P5	100%	79%	100%	100%
S1	100%	100%	100%	100%
S2	86%	79%	79%	64%
T1	57%	86%	71%	100%
T2	71%	71%	86%	79%
T3	86%	86%	93%	100%
T4	29%	43%	50%	71%
T5	100%	71%	86%	93%
T6	79%	100%	93%	93%
L1	93%	100%	100%	100%
L2	100%	93%	93%	71%
L3	100%	86%	100%	93%
L4	100%	100%	93%	93%

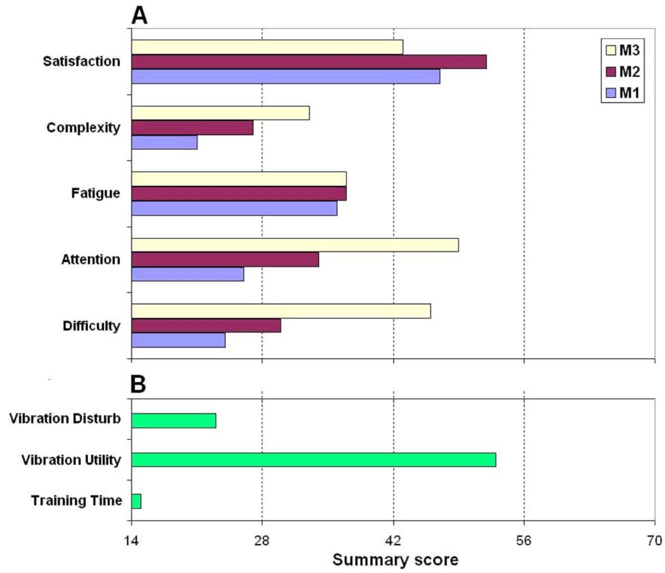


Fig. 15. Bar graph of subjective summary scores. (a) Subjective comparison among the three grasping strategies M1–M3. (b) Summary score graph on the vibrotactile feedback system and on the duration of the training time.

ments. In contrast, the object P2 (the 1.0-kg bottle) has been successfully grasped during experiment EM1 in 71% of the trials and the object P5 in 79% during EM2. Moreover, the percentage of S2 is much lower (from 64% to 86%) than the other objects and varies depending on the particular experiment. The rate of successful tip/tripod grasps changes varying the experiment and the object. All Tx objects (with $x = 1 - 6$), except T5 (the mobile phone), have been grasped with lower success in EM1 than in the other experiments. Moreover, the felt-tip pen (T4) presents quite a low percentage in the first three experiments (from 29% to 50%), while a better percentage is found in EM3 V (71%). For tip/tripod grasps, on the whole, higher success has been obtained during the last experiment (from 71% for T4, to 100% for T1 and T3). Lateral grasps have been obtained with high success percentages in all the experiments (from 86% to 100%), except for L2 (the key) in EM3 V. Finally, some objects such as P4, T5, and L2 are grasped with 100% of success only in experiment EM1 and with lower success in the other experiments. ANOVA analyses comparing the objects' success percentage in the four experiments, shows that statistical differences are found only for P2, P5, and T1; the other objects are statistically grasped with equal percentage in all the four experiments.

B. Subjective Results

At the end of the experiments (after 136 grasps), the 14 subjects were asked to compare the three control strategies M1–M3, by giving a score based on a Likert scale to statements regarding the following issues: control difficulty, required attention, physical fatigue, interface complexity, and overall satisfaction. Fig. 15(a) shows the bar graph of the resulting summary score: the horizontal axis shows the score from 14 (strongly disagree) to 70 (strongly agree); note that 42 is the value referring to the "neither agree nor disagree" answer; the vertical axis refers to the statements defined in Section VI-D.

The subjective outcomes of the strategy comparison, underline several aspects. First, regarding the difficulty in control: M1 is felt as the easiest control strategy, whereas M3 as the most difficult. M2 is more difficult to control than M1, but is still regarded as being easy, while M3 is regarded as difficult. About the required attention with reference to the prostheses: the score grows progressively passing from M1 to M2 to M3. In particular, the level of attention is low and similar for M1 and M2, while it becomes higher for M3. A similar outcome can be found on the interface complexity, subjects find M1 very low complex and M2 and M3 a bit harder, but still not complex. Moreover, the subjects do not suffer particular tiredness (fatigue) by performing the experiments, and, regarding this issue, do not feel differences among the three control strategies. The subjective overall satisfaction bar shows that M2 is finally believed to be the best control strategy for grasping tasks. The Kruskal–Wallis test shows statistical differences in the answers on the three control strategies for the questions regarding difficulty in control and required attention; a p level close to the significant value is found for overall satisfaction ($p = 0.10$) and interface complexity ($p = 0.12$), while no statistical differences are found among the subjects' answer on the physical fatigue ($p = 0.9$).

Subjective opinions have also been collected regarding the vibrotactile feedback system; the question referred to the system benefits during the selection of the force closure and about the discomfort caused by its wearing. The opinion on the vibrotactile feedback system is summarized in Fig. 15(b). According to all the subjects, the vibrotactile system does not disturb at all and is helpful during the grasp tasks. The analysis of training duration is also shown in Fig. 15(b): subjects feel that a very short training time is required in order to correctly use the prosthesis.

VIII. Discussion

The proposed experiments are aimed to assess user acceptability and satisfaction using an anthropomorphic prosthetic hand with different shared control hierarchical control strategies. The first goal of our research is to find an equilibrium point between good grasping capabilities of the device (strongly related to the complexity of the control interface) and low required attention for the user to complete grasping tasks. The second goal is to determine whether a vibrotactile feedback system is subjectively or objectively useful and how this system changes users' performance.

In order to compare expert performance, this discussion will be focused on the experimental results of the second trial only, i.e., when the user should be better trained. This assumption appears to be evident by looking at the graph in Fig. 14: the second trial of each experiment shows higher success than the first one. Also, statistical differences between the first trial and the second trial, partially prove subjects' learning: differences can be found in experiment EM2 V and EM3 V; while the other values are close to the significant level of 0.05. Users' learning capabilities are finally confirmed by subjective impressions on the training time to correctly use the device: according to all the subjects, the learning duration is very short [Fig. 15(B)]. This learning trend is clear (three experiments out of four show a

p value much close to 0.05); however, the focus of this paper is not to prove such learning. Nevertheless, in order to obtain more robust results, new experiments should be carried out with a greater sample.

The performed experiments are in agreement with the theoretical grasping capabilities described in Section VI; the best performances with equal success percentage (around 90%) have been obtained during experiments EM3 V and EM2 V; performances become lightly worse in experiments EM2 and EM1 (Fig. 14). However, no statistical differences are found among the four experiments. The reason for the lack of difference between EM2 and EM2 V can be explained: despite the fact that in the first experiment only visual feedback is used, and, in the second, also vibrotactile, in both, the exploited control strategy is identical: $\mathrm{M2}$. The reason why the EM1 grasping success outcome is statistically equal to EM2 (and EM2 V) can be explained by the limitations of the experimental conditions and protocols. The objects that have been chosen are limited in weight (1-kg maximum, big bottle P2) to avoid grasps with high-level force closure that could possibly damage the system (actuation transmission rather than tendon sensors). Because of this, the selected force closure levels in the grasping algorithm of $\mathrm{M1}$ (either for power or light cylindrical grasp) are maximized for the available objects. This explains how some of these (P4, T5, and L2) are always correctly grasped only in experiment EM1 and why its grasping success is so good (and statistically equal to the other experiments). Further experiments extending the objects set with daily used objects will be carried out in future research; these will inevitably decrease the $\mathrm{M1}$ grasping success.

The real unexpected outcome is the lack of differences between control strategies $\mathrm{M2}$ and $\mathrm{M3}$. The obtained results show equal success percentage (90%) between EM3 V and EM2 V (and statistically also with EM2); this could be explained by subjective reasons. Even if most users consider the $\mathrm{M3}$ interface to be not significantly more complex than $\mathrm{M2}$, they prefer $\mathrm{M2}$ and $\mathrm{M1}$ because of the significantly higher level of attention required by $\mathrm{M3}$ [Fig. 15(A)]. Furthermore, subjects found $\mathrm{M3}$ difficult to use [Fig. 15(A)]: the experiment EM3 V evidenced that only few subjects put into effect the enhanced capabilities of the $\mathrm{M3}$ control strategy, i.e., the possibility to finely move the thumb to obtain good preshaping of the prosthetic hand. Most of the subjects were satisfied by roughly moving the thumb until it reached its mechanical stops, to perform lateral or cylindrical grasps [Fig. 12(A) and (C)], and, for this reason, they were more satisfied by simply using $\mathrm{M2}$, requiring less effort [Fig. 15(A)]. As a consequence, although the $\mathrm{M3}$ control strategy theoretically permits achieving the highest performance, most of the subjects just used it as if it was $\mathrm{M2}$, i.e., with fixed thumb preshaping. This explains the equal success percentage outcome by using $\mathrm{M2}$ or $\mathrm{M3}$.

The previously described experiment limits also affect the statistical differences among objects in the four experiments, so that further experiments should be performed to validate these preliminary results. For this reason, statistical differences are found only for P2, P5, and T1; while the other objects are statistically grasped with equal percentage in all the four experiments. However, some further explanation can be provided. EM1 success percentage for object P2 (the 1.0-kg bottle) may be lower than the others, due to the EMG classifier success ratio (refer to Section III-A); in order to be stably grasped, the object required a power force closure level (refer to Section VI-A), and, sometimes, the user did not contract the muscle as needed or the classifier failed. Object T1 (the smallest sphere) presents different success percentages, probably because of its dimensions; it is well graspable using modality $\mathrm{M2}$ and $\mathrm{M3}$ due to the user-dependent force closure, while it is hardly graspable with $\mathrm{M1}$ due to the fixed value.

A second experimental limitation should be underlined; since the order of execution of the experiments was fixed (from the easiest to the hardest control strategy), there is a learning effect in the data and in the observed performance changes. In the authors' opinion, however, this effect is not significant; thanks to the simplicity of the EMG classifier, as a matter of fact, after the first 5–10 min of practice, all subjects were able to generate voluntary commands with high success ratio. Therefore, before starting the experiments, subjects already had a good knowledge of the EMG classifier. The performance changes between different experiments are, thus, mainly caused by the difference in complexity among the three modalities; the learning effect in the data is a minor effect.

Regarding the importance of the vibrotactile feedback system, the lack of statistical differences between EM2 and EM2 V previously introduced, appears to cancel out its objective effectiveness. The identical control strategy ($\mathrm{M2}$), used with or without vibrotactile feedback, brings about statistically equal success percentages. Two reasons could explain this result. First, during the performed experiments, the subjects did not bother selecting the minimum force required; they roughly stopped the closure after the fingers had reached the object: to do this, visual feedback was enough.

Second, during the grasping of all objects, the fingers were always under visual control, so that the enhanced proprioception provided by the vibrotactile system was not used by the subjects. However, the overall subjective opinion declares the importance of the vibrotactile system. According to all volunteers, the feedback system does not physically disturb the wearer ($\mathrm{score} = 15$). Moreover, most of them think that it is useful during grasp tasks [$\mathrm{score} = 53$ cf. Fig. 15(b)]. However, the validity of previous assumptions should be assessed by further experiments in which visual feedback is not sufficient (i.e., experiments in the dark, big objects that hide fingers).

IX. Conclusion

An anthropomorphic underactuated prosthetic hand, endowed with position and force sensors and controlled by means of myoelectric commands, has been used in order to perform experiments of shared control between the HLC depending on the user intentions and the embedded prostheses LLC. Three hierarchical control strategies, with different ratios of the shared control, have been developed and tested by able-bodied subjects by achieving grasping tasks used in ADLs. In order to compare grasping success percentages, experiments have been performed both using visual feedback and visual plus vibrotactile feedback. Force feedback is delivered to the subjects by means of a developed vibrotactile system applied on biceps, where the frequency varies from 0 to 250 Hz proportionally to the force closure applied by the hand on the objects.

The first goal of this research is to find a tradeoff between good grasping capabilities of the device (strongly related to the complexity of the control interface) and low subject effort into completing grasping tasks, without addressing advanced algorithm for EMG signal processing. The second goal is to determine whether a vibrotactile feedback system is subjectively or objectively useful, and how this system changes user performance.

The three control strategies, both with and without the vibrotactile feedback system, have been tested by 14 able-bodied subjects, aged 23–38 years. Each user has performed 136 grasps, for a full amount of 1904 grasps. Objective results have been based on success percentage, whereas subjective results have been collected by an interview.

The experiments show that users are able to correctly operate the device in the three different control strategies with high success percentages, and that the grasp success increases with more interactive control strategies. Although a high interactive control strategy permits to theoretically achieve better performances, practice has proven that when too much effort is required in controlling the device, subjects do not do their best, preferring instead a less-interactive control strategy. *Acceptability is more dependent on the required attention than on the success in grasping*. About the importance of the vibrotactile feedback system, the experiments show that when a grasping task is carried out *under visual control*, the enhanced proprioception of the hand offered by the system is not exploited. Nevertheless, in subjective opinion, the vibrotactile system seems to be quite important.

In conclusion, in the authors' opinion, research on prosthetic hands should move toward the development of control strategies that are able to improve the interaction of the amputee with its device without substantially increasing effort in its control. A solution to the problem could be the development of neural interfaces that are also able to provide proprioceptive and exteroceptive feedback to the patients.

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REFERENCES

[1] Otto Bock Healthcare, Minneapolis, MN [Online]. Available: http://www.ottobockus.com, 2008.
[2] Touch EMAS Ltd, Edinburgh, U.K. [Online]. Available: http://www.touchbionics.com
[3] P. J. Kyberd, O. E. Holland, P. H. Chappel, S. Smith, R. Tregdigo, P. J. Bagwell, and M. Snaith, "Marcus: A two degree of freedom hand prosthesis with hierarchical grip control," *IEEE Trans. Rehabil. Eng.*, vol. 3, no. 1, pp. 70–76, Mar. 1995.
[4] P. A. O'Neill, E. L. Morin, and R. N. Scott, "Myoelectric signal characteristics from muscles in residual upper limbs," *IEEE Trans. Rehabil. Eng.*, vol. 2, no. 4, pp. 266–270, Dec. 1994.
[5] F. Q. Xiong and E. Shwedyk, "Some aspects of nonstationary myoelectric signal processing," *IEEE Trans. Biomed. Eng.*, vol. BME-34, no. 2, pp. 166–172, Feb. 1987.
[6] M. Zecca, S. Micera, M. C. Carrozza, and P. Dario, "On the control of multifunctional prosthetic hands by processing the electromyographic signal," *Crit. Rev. Biomed. Eng.*, vol. 30, no. 04–06, pp. 459–485, 2002.
[7] D. J. Atkins, D. C. Y. Heard, and W. H. Donovan, "Epidemiologic overview of individuals with upper limb loss and their reported research priorities," *J. Prosthet. Orthot.*, vol. 8, no. 1, p. 2, 1996.
[8] D. H. Silcox, M. D. Rooks, R. R. Vogel, and L. L. Fleming, "Myoelectric prostheses. A long-term follow-up and a study of the use of alternate prostheses," *J. Bone Joint Surg.*, vol. 75, no. 12, pp. 1781–1789, 1993.
[9] M. C. Carrozza, B. Massa, S. Micera, R. Lazzarini, M. Zecca, and P. Dario, "The development of a novel prosthetic hand—ongoing research and preliminary results," *IEEE/ASME Trans. Mechatronics*, vol. 7, no. 2, pp. 108–114, Jun. 2002.
[10] P. J. Kyberd, D. Gow, H. Scott, M. Griffiths, L. Sperling, L. Sandsjo, C. Almstrom, C. Wartenberg and S. Jonsson, "A comparison of upper limb prostheses users in Europe," *Myoelectr. Controls Symp. Fredericton*, NB, Canada, 1999.
[11] G. Lundborg and B. Rosén, "Sensory substitution in prosthetics," *Hand Clin.*, vol. 3, pp. 481–488, 2001.
[12] R. A. Roeschlein and E. Domholdt, "Factors related to successful upper extremity prosthetic use," *Prosthet. Orthot. Int.*, vol. 13, no. 1, pp. 14–18, 1989.
[13] C. Pylatiuk, S. Mounier, A. Kargov, S. Schulz, and G. Bretthauer, "Progress in the development of a multifunctional hand prosthesis," in *Proc. 2004 IEEE EMBS Int. Conf.*, San Francisco, CA, vol. 2, pp. 4262–4263.
[14] K. A. Kaczmarek, J. G. Webster, P. Bach-y-Rita, and W. J. Tompkins, "Electrotactile and vibrotactile displays for sensory substitution systems," *IEEE Trans. Biomed. Eng.*, vol. 38, no. 1, pp. 1–6, Jan. 1991.
[15] R. R. Riso, A. R. Ignagni, and M. W. Keith, "Cognitive feedback for use with FES upper extremity neuroprostheses," *IEEE Trans. Biomed. Eng.*, vol. 38, no. 1, pp. 29–38, Jan. 1991.
[16] Y. Sasaki, Y. Nakayama, and M. Yoshida, "Sensory feedback system using interferential current for EMG prosthetic hand," in *Proc. 2002 2nd Joint Eng. Med. Biol. Soc. Int. Conf.*, Houston, TX, vol. 3, pp. 2402–2403.
[17] K. B. Englehart and B. Hudgins, "A robust, real-time control scheme for multifunction myoelectric control," *IEEE Trans. Biomed. Eng.*, vol. 50, no. 7, pp. 848–854, Jul. 2003.
[18] Y. Huang, K. B. Englehart, B. Hudgins, and A. D. C. Chan, "A Gaussian mixture model based classification scheme for myoelectric control of powered upper limb prostheses," *IEEE Trans. Biomed. Eng.*, vol. 52, no. 11, pp. 1801–1811, Nov. 2005.
[19] The CYBERHAND Project (Development of a Cybernetic Hand, ISTFET Project #2001—35094) [Online]. Available: www.cyberhand.org
[20] P. Dario, P. Garzella, M. Toro, S. Micera, M. Alavi, J.-U. Meyer, E. Valderrama, L. Sebastiani, B. Ghelarducci, and P. Pastacaldi, "A microfabricated interface for neural recording and stimulation," *J. Micromech. Microeng.*, vol. 7, pp. 233–236, 1997.
[21] X. Navarro, T. B. Krueger, N. Lago, S. Micera, P. Dario, and T. Stieglitz, "A critical review of interfaces with the peripheral nervous system for the control of neuroprostheses and hybrid bionic systems," *J. Peripher. Nerv. Syst.*, vol. 10, no. 3, pp. 229–258, 2005.
[22] S. Micera, M. C. Carrozza, L. Beccai, F. Vecchi, and P. Dario, "Hybrid bionic systems for the replacement of hand function," *Proc. IEEE*, vol. 94, no. 9, pp. 1752–1762, Sep. 2006.
[23] G. S. Dhillon and K. W. Horch, "Direct neural sensory feedback and control of a prosthetic arm," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 13, no. 4, pp. 468–472, Dec. 2005.
[24] M. C. Carrozza, F. Vecchi, S. Roccella, M. Zecca, F. Sebastiani, and P. Dario, "The Cyberhand: On the design of a cybernetic prosthetic hand intended to be interfaced to the peripheral nervous system," in *Proc. 2003 IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Las Vegas, NV, vol. 3, no. 27–31, pp. 2642–2647.
[25] M. C. Carrozza, G. Cappiello, S. Micera, B. B. Edin, L. Beccai, and C. Cipriani, "Design of a cybernetic hand for perception and action," *Biol. Cybern.*, vol. 95, no. 6, Dec. 2006.
[26] L. Citi, J. Carpaneto, K. Yoshida, K. P. Hoffmann, K. P. Koch, P. Dario, and S. Micera, "Characterization of tfLIFE neural response for the control of a cybernetic hand," in *Proc. IEEE/RAS Eng. Med. Biol. Soc. Int. Conf. Biomed. Robot. Biomechatronics*, Pisa, Italy, 2006, pp. 477–482.

[27] Y. Ishikawa, W. Yu, H. Yokoi, and Y. Kakazu, "Development of robotic hands with an adjustable power transmitting mechanism," in *Intelligent Engineering Systems Through Neural Networks,* vol. 10, C. H. Dagli, *et al.*, Ed. New York: ASME, 2000, pp. 631–636.

[28] C. M. Light and P. H. Chappell, "Development of a lightweight and adaptable multiple-axis hand prosthesis," *Med. Eng. Phys.*, vol. 22, pp. 679–684, Feb. 2001.

[29] S. Schulz, C. Pylatiuk, and G. Bretthauer, "A new ultralight anthropomorphic hand," in *Proc. Int. Conf. Robot. Autom.*, Seoul, Korea, 2001, pp. 2347–2441.

[30] S. Schulz, C. Pylatiuk, M. Reischl, J. Martin, R. Mikut, and G. Bretthauer, "A hydraulically driven multifunctional prosthetic hand," *Robotica*, vol. 23, pp. 293–299, 2005.

[31] L. Rodriguez, A. Casals, A. Cuxar, and A. Parra, "Towards the definition of a functionality index for the quantitative evaluation of hand-prosthesis," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Aug. 2–6, 2005, pp. 541–546.

[32] C. Cipriani, F. Zaccone, G. Stellin, L. Beccai, G. Cappiello, M. C. Carrozza, and P. Dario, "Closed-loop controller for a bio-inspired multi-fingered underactuated prosthesis," in *Proc. 2006 IEEE Int. Conf. Robot. Autom.*, Orlando, FL, pp. 2111–2116.

[33] M. Kaneko, M. Wada, H. Maekawa, and K. Tanie, "A new consideration on tendon-tension control system of robot hands," in *Proc. 1991 IEEE Int. Conf. Robot. Autom.*, vol. 2, pp. 1028–1033.

[34] D. J. Magee, *Orthopedic Physical Assessment*. Philadelphia, PA: WB Saunders, 1997.

[35] C. M. Light, P. H. Chappell, and P. J. Kyberd, "Establishing a standardized clinical assessment tool of pathologic and prosthetic hand function: Normative data, reliability, and validity," *Arch. Phys. Med. Rehabil.*, vol. 83, pp. 776–783, Jun. 2002.

[36] M. R. Cutkosky, "On grasp choice, grasp models, and the design of hands for manufacturing tasks," *IEEE Trans. Robot. Autom.*, vol. 5, no. 3, pp. 269–279, Jun. 1989.

[37] J. Kerr and B. Roth, "Analysis of multifingered hands," *Int. J. Robot. Res.*, vol. 4, no. 4, pp. 3–17, 1986.

[38] M. T. Mason and J. K. Salisbury, *Robot Hands and the Mechanics of Manipulation*. Cambridge, MA: MIT Press, 1985.

[39] T. Iberall and M. A. Arbib, "Schemas for the control of hand movements: An essay on cortical localization," in *Vision and Action: The Control of Grasping*, M. A. Goodale, Ed. Norwood, NJ: Ablex, 1990, pp. 163–180.

[40] R. S. Johansson, "Sensory input and control of grip," in *Sensory Guidance of Movement*. Chichester, U.K.: Wiley (Novartis Foundation Symposium 218), 1998, pp. 45–63.

[41] E. Oztop and M. A. Arbib, "Schema design and implementation of the grasp-related mirror neuron system," *Biol. Cybern.*, vol. 87, pp. 116–140, 2002.

[42] R. S. Johansson, "Sensory and memory information in the control of dextrous manipulation," in *Neural Bases of Motor Behaviour*, F. Lacquaniti and P. Viviani, Eds. Dordrecht, The Netherlands: Kluwer Academic, 1996, pp. 205–260.

[43] J. R. Napier, "The prehensile movement of the human hand," *J. Bone Joint Surg.*, vol. 38B, pp. 902–913, 1956.

[44] R. Likert, "A technique for the measurement of attitudes," *Arch. Psychol.*, vol. 140, no. 55, pp. 5–53, 1932.

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