Relaying the High Frequency Contents of Tactile Feedback to Robotic Prosthesis Users: Design, Filtering, Implementation and Validation

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***Abstract*—It is known that high frequency tactile information conveys useful cues to discriminate important contact properties for manipulation, such as first-contact and roughness. Despite this, no practical system, implementing a Modality Matching paradigm, has been developed so far to convey this information to users of upper-limb prostheses. The main obstacle to this implementation is the presence of unwanted vibrations generated by the artificial limb mechanics, which are not related to any haptic exploration task. In this work, we describe the design of a digital system which can record accelerations from the fingers of an artificial hand, and reproduce them on the user's skin through voice-coil actuators. Particular attention has been devoted to the design of the filter, needed to cancel all those vibrations measured by the sensors that do not convey information on meaningful contact events. The performance of the newly designed filter is also compared with the state of the art. Exploratory experiments with prosthesis users have identified some applications where this kind of feedback could lead to sensory-motor performance enhancement. Results show that the proposed system improves the perception of object-salient features such as first-contact events, roughness and shape.**

***Index Terms*—Haptics and Haptic Interfaces; Prosthetics and Exoskeletons; Wearable Robots**

I. Introduction

OVER the years, robotics-enabled myo-electric hand prostheses have been proposed to restore motor functionalities [1], e.g. through the development of devices capable to perform intelligent grasps of shapes and endowed with automatic slip response [2]. Although there is still room for improving device embodiment and intuitiveness [3], the adoption of these systems in users' every-day life is slowly increasing. However, the sole substitution of motor function lacks in restoring the loss of the sensory function, which is still one of the top priorities felt by people with limb loss

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(a) (b)

Fig. 1. (a) Complete view of the vibrotactile system applied to the SoftHand Pro and (b) the device worn by the subject. In (a) it is possible to note the: actuators (1), Control Board (2), Prosthetic device (3), IMUs (4) and Battery (5). In (b) the two actuators are visible, the one in the foreground is the actuator connected to the little finger. The two wires coming out from the hand are the battery connection and the connections from the accelerometers to the haptic device control board.

[4], [5]. While still far to be exhaustively achieved, it is an aspect studied since more than 20 years. Indeed, none of the actual commercial prostheses include tactile feedback, with the exception of one recent example of upper limb prosthetic device that provides vibrotactile feedback on the grasping force of the upper limb[1]. Vibrotactile stimulation is, indeed, one of the most studied non-invasive sensory substitution techniques: the first usage dates back to 1953 [6], and it has attracted an increasing attention ever since thanks to its simplicity. In literature, there are many examples where this type of stimulation has been used to deliver contact information [7], [8], force feedback [9], or proprioceptive cues [10], where the amplitude and/or frequency of vibration are controlled to be proportionally related to the physical haptic property to be communicated.

However, none of the prosthetic applications present in literature ever explored vibrotactile feedback within a Modality Matching (MM) paradigm. According to MM, a cue delivered for sensory substitution should be mediated by a stimulus sharing the same sensory modality as the one that would be felt naturally. This stimulation paradigm was proven to be effective to deliver touch-based information to prosthesis users [11], since it could likely favor the re-learning process of the novel inputs, through minor neural adaptation of the central nervous system [12]. Under this regard, vibrations could be

[1]Vincent Evolution 2. 2016. http://vincentsystems.de/

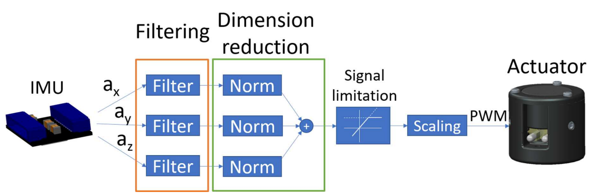

Fig. 2. Information processing scheme. The signals read from the IMU go throught the signal elaboration process (filtering, dimensional reduction and other minor elaboration steps), and are finally sent to the actuation unit coded through a PWM signal.

naturally associated to high-frequency physical information of the surface, such as texture [13], and first-contact cue. A first attempt towards this direction is described in [14]. In [14], more specifically, an analog system, inspired by the architecture in [13], acquires signals from accelerometers placed on the back of artificial hand nails, analogically filters them and then drives eccentric mass vibrational motors, through current amplification. This kind of feedback was proven to be effective in increasing grasping performance in able-bodied subjects. To bring these results to an effective usage by prosthesis users is not a trivial task. Indeed, vibrations generated by the motors actuating the prosthetic device can interfere with the accelerometers of the vibrator feedback system and severly affect performance. This problem was not accounted for in [14], where, during haptic exploration, the hand was not actively moved to grasp. An effective way to tackle this issue could be through digital filtering, as this offers a wide range of possibilities for signal elaboration, that would be hard to achieve by relying on an analog architecture only. Furthermore, for the sake of embodiment and intuitiveness [15], the implementation of digital solutions deserves specific attention to guarantee a reduced delay between the sensed information and its artificial replica.

To the best of our knowledge, this paper represents the first work to propose a digital architecture for the control of a wearable device. This device is thought to render online high frequency contact information, recording it from a prosthetic device and conveying it to a prosthesis user in MM, using vibrotactile stimuli (see Fig. 1). We propose a digital implementation of the system in [14], with a careful design of the filtering stage. This allows to cope with the previously mentioned noise transfer problem, still guaranteeing the fulfillment of online constraints for rendering. The latter aspect is fundamental to guarantee the immersiveness and naturalness of the haptic interaction [16]. The need for the digitalization is motivated by the wider range of elaboration and filtering options it enables and the ease of integration with modern digitally-controlled prosthetic devices. Another unique contribution of the work, in addition to the digital implementation of the rendering techniques used in [14], is the application and pilot testing of the feedback system with prosthesis users performing different tasks.

The feedback system consists of accelerometers placed on the fingernails of an underactuated soft hand prosthesis, the prosthetic version of the Pisa/IIT SoftHand [17], hereinafter SoftHand Pro; a control board to perform all the required computations; voice coil actuators, which were chosen to correctly elicit touch-related perception in users (see Fig. 2).

A series of exploratory experiments to understand for which tasks this kind of feedback could lead to sensory-motor performance improvement was performed with three prosthesis users. Although the limited number of users that took part to the pilot experiments, this work provides insights on the real usability of the system, useful to plan the next design iterations.

For the sake of simplicity, hereinafter we will refer to the system presented in this work using the general name of Vibro-Tactile device.

II. System Design

The Vibro-Tactile device is composed of three main building blocks: (i) the sensing unit, (ii) the control component and (iii) the actuation system, as shown in Fig. 2. The electronic board used to acquire sensory signals and control the whole system was custom-built to match the design measurements.

A. Sensing Unit

Two Inertial Measurement Units (IMUs) MPU-9250 Motion Tracking devices (by InvenSens, Inc, San Jose, CA, USA) were used as sensing units to record acceleration signals arising from the surface interaction. They are mounted on PCBs (8×6 mm) placed on the SoftHand Pro fingernails.

The MPU-9250 is a 9-axis Motion Tracking digital device containing 3-axis accelerometer. Outputs are digitized with 16-bit analog-to-digital converters (ADCs). For our application, we only used acceleration information within the range of $\pm 2g$, the same used in [14]. The choice of this IMU was driven by the reduced layout dimensions ($3 \times 3 \times 1mm$) and by the required operating voltage (2.4V to 3.6V).

B. Control Board

A custom electronic board (based on Cypress Programmable System on Chip-PSoC, with RS485 communication protocol) was used for our implementation. The board is composed of two electrically isolated subcircuits: a logic circuit and the power circuit. The logic circuit is used to read the sensors and to elaborate the signals, the power circuit is instead used to drive the motors. A set of opto-coupling components enables the microcontroller to operate the motor driver, while keeping the two circuits isolated. The board can be powered from 5V up to 24V; all external logic ports are 3.3V. The power output can be adapted to the requested power input of the actuator via firmware, regardless of the power source actually applied to the board. More information can be freely downloaded from Natural Machine Motion Initiative[2] [18].

C. Actuation Unit

A correct choice of the actuation units is mandatory to enable a good rendering of the haptic information. In [19] the authors analyzed different types of actuators, focusing the analysis on vibrotactile applications. They show that linear

[2] www.naturalmachinemotioninitiative.com/

voice-coil actuators without bushings and rotational DC motors are preferable among all the other solutions, for their control simplicity and for the possibility to modulate both the amplitude and the frequency of the generated vibrations. However, voice-coils actuators without bushings need an external structure to keep the system aligned and bring the moving mass back to the rest position. Compared to DC motors, voice coil actuators have the advantage of a smaller size. Furthermore, they directly generate a linear movement, which can be easily transformed in a stimulation of the skin along the normal to the surface. This can ultimately favor the integration with the prosthesis socket. On the contrary, rotational DC motors require an ad-hoc structure to generate vibrations along the normal to the skin surface from the rotational movement, making the actuation solution cumbersome and not suitable for our goal. We did not consider actuation unit as the one used in [14] because of their reduced versatility, as they are optimized for working only at their resonant frequency.

For the aforementioned reasons, we decided to not use rotational DC motors. Through a preliminary experiment the linear voice-coil NCC01-04-001-1X (by H2W Technologies, CA, USA) was chosen.

To support the actuators, we designed and built suitable frames to keep the moving mass of each actuator aligned with the coil (see Fig. 3(d) for more details). An elastic fabric band (3) keeps the moving mass in place avoiding it to exit from the coil shaft, without obstructing the transmission of vibration to the user. The user's skin, together with the fabric acts as an elastic component to bring the moving mass back to the rest position. In the final setup, the actuator was positioned on the user's arm with the axis of the coil normal to the skin. This allows the transmission of stimuli normal to the skin. The choice of normal, rather than tangential stimuli (as done e.g. in [14]), was guided by the need of reducing the size of the system and maintaining the MM paradigm. This choice has been demonstrated equally efficient in reference [20]. The coil is driven with a Pulse Width Modulation (PWM) signal by the electronics. To avoid the introduction of unwanted high frequency noise from the PWM, the PWM fundamental frequency (6.7 kHz) was set higher than the mechanical cut-off frequency of the actuator (17.90 Hz). This configuration results in a 90 dB Signal-to-Noise Ratio (SNR).

III. Filter Design

The acceleration measurements are digitized by the IMU, then all information is processed digitally. The clock frequency of the microprocessor is enough to maintain reduced delays between information sensing and rendering, to fulfill transparency requirements.

The implemented signal processing consists of two parts: signal filtering and dimensional reduction (see Fig. 2).

A. Signal Filtering

The filtering of the measures obtained from the accelerometers aims at removing unwanted artifacts due to: accelerometer readings during free-hand motion, and vibrations coming from the prosthesis actuation system. Furthermore, filtering removes

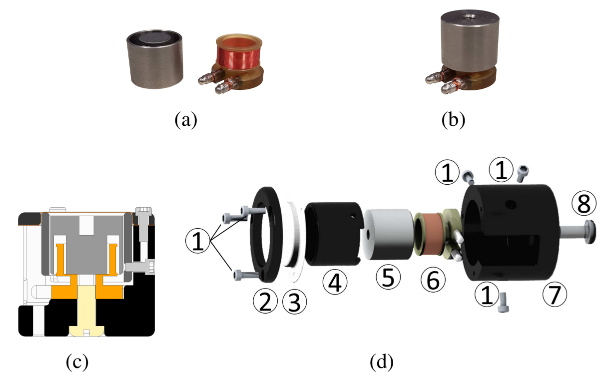

Fig. 3. NCC01-04-001-1X Voice Coil Actuator (H2W Technologies, CA, USA) in its two components, the moving magnet and the coil (a), and in working configuration (b). In (c) the section of the actuation unit. In (d), the exploded view of the actuation system with all the case components is shown: 1) screws, 2) closing ring, 3) fabric, 4) inner cylinder, 5) actuator moving mass, 6) actuator coil, 7) main case, 8) plastic screw.

TABLE I
List of actions performed to tune the filter and expected system output. SF refers to the Sensorized Finger, NSF to one of the Non-Sensorized Fingers.

Action	Expected Feedback Output
Fast Closing Movement	No Feedback
Slow Closing Movement	No Feedback
Fast Opening Movement	No Feedback
Slow Opening Movement	No Feedback
Hand Still on the Table	No Feedback
Free Hand Movement in the Space (no hit)	No Feedback
Sliding of a NSF on Rough Surface	No Feedback
Sliding of a NSF on Smooth Surface	No Feedback
Hit of a NSF on Rigid Object	No Feedback
Hit of a NSF on Rigid Object	No Feedback
Free Hand Movement in the Space - NSF Hit	No Feedback
Sliding of the SF on Rough Surface	Proportional to the Roughness
Sliding of the SF on Smooth Surface	Initial Hit followed by No Fb
Hit of the SF on a Rigid Object	Impulsive Hit
Hit of the SF on a Soft Object	Impulsive Hit
Free Hand Movement in the Space - SF Hit	Silence followed by Imp. Hit
Hand Closing on a Rigid Cylindrical Object	Silence followed by Imp. Hit
Hand Closing on a Soft Cylindrical Object	Silence followed by Imp. Hit

not only low-frequencies (free-hand motion) but also high-frequency noise, keeping only the frequency range that specifically elicits human mechanoreceptors involved during tactile exploration of high-frequency contact-related information: i.e. Fast adapting type I (FA-I) and Pacinian corpuscles (PC) (see [19]). The frequencies sensed by these receptors range from 4 to 400 Hz, with a minimum threshold below 64 Hz for the FA-I, and between 128 and 400 Hz for the PC [21] (Data from healthy subjects with age between 20 and 40 years). A simple band-pass filter between 50 and 300 Hz (referred to as Classical Filter, given its wide use for similar analyses in literature [22], Figure 5) is the baseline approach to compare our approach with.

To allow a meaningful information delivery, a frequency analysis of all the vibrations (wanted and unwanted) was performed, to distinguish the frequency distribution of the different signals, with the goal of fine tuning the filter to increase the SNR (see Fig. 4(b)). For this analysis, a series of acceleration recordings, listed in Table I, was performed, decoupling desired accelerations (arising from surface exploration) from unwanted ones. This analysis shows that most

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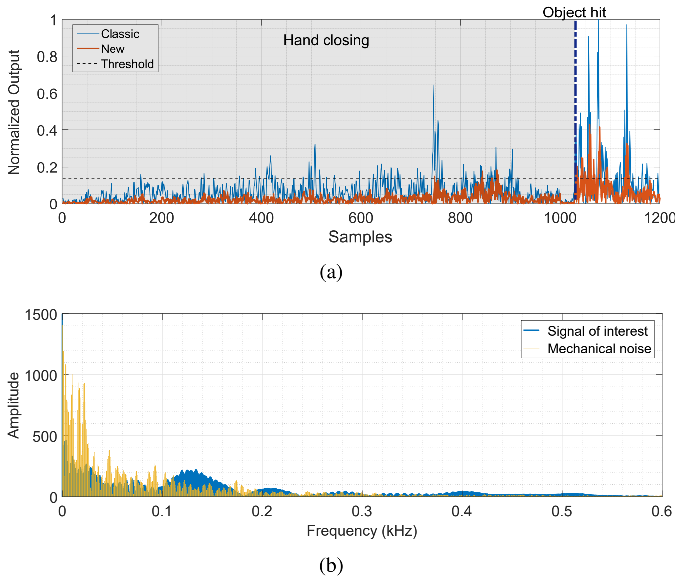

Fig. 4. (a) Difference between the output of the system using the Classic Filtering and the one we implemented in this work, sampling frequency 1.2 kHz. In grey, the part of the plot relative to the free hand closure; a vertical line is placed in correspondence with the object hit. During the reported experiment the hand closes until touching a rigid (ABS plastic) cylindrical object. (b) Power spectrum of the wanted and unwanted signals.

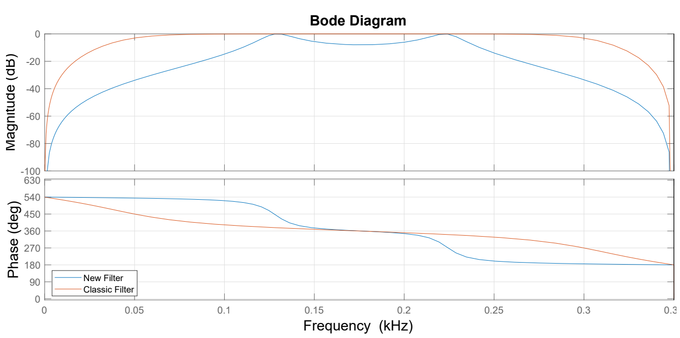

Fig. 5. Bode plot for the filter developed in this paper compared with the old one.

of the vibrations generated by the SoftHand Pro mechanical parts during opening and closing movements share much of the frequency band of interest, so they are difficult to isolate from the desired signals. We observe also that the signals of interest remain always below the 300 Hz threshold. After this analysis, we chose a fourth order Chebyshev Type I band pass filter (Figure 5). The selected filter has a bandwidth optimized between 120 Hz and 230 Hz, with a reduction of the signal in the band 140 Hz to 210 HZ (-8dB), where most part of the energy of the noise signals is concentrated. This filter, which we will refer to as New Filter, removes most disturbances, at the price of slightly reducing the amplitude of the signals of interest. The results of the two filter applications to the Hand Closing on a Rigid Object movement is reported in Figure 4(a).

B. Dimensionality Reduction

It is known that human skin response to vibration is independent from acceleration direction [23]. Because of this, our device stimulates the user skin along one direction, orthogonal to the skin surface. Since acceleration is measured as a 3 component vector, it has to be reduced to one scalar value to be used to drive the actuators. Various solutions to this problem are presented in [24], all of them with the goal of maintaining the largest amount of information as possible from the source values. In particular, in [24], a technique based on Discrete Fourier Transform (DFT) is suggested as favorable. Unfortunately, compatibility, power and space constraints due to wearability, drove us to choose a very low power micro-controller, not offering sufficient computational power for DFT. This compelled us to chose a different solution. We chose a modified version of the Sum of Components from [24] computed as

$$a = |a_x| + |a_y| + |a_z| \quad (1)$$

where a is the output value, used to drive the coil, and a_x, a_y and a_z are the three acceleration components measured by the accelerometer. The proposed solution satisfies the real-time constraint and avoids destructive interference between different components of acceleration. Moreover, this choice meets another characteristic of our system, that is the fact that our voice-coil is uni-directional and has to be operated by positive voltages only. To evaluate the quality of our choice we assessed the time-domain correlation between SoC321 from [24] and the output of (1) using the Pearson coefficient (PeC), obtaining a 0.65 value, and computing the Mmt coefficient (see [24]), obtaining 0.30 for (1) and 0.21 for the SoC321. A PeC equal to 1 indicates a perfect statistical correlation - this implies that our result is acceptable; Mmt reveals a low correspondence between the input signals and the output for (1) (1 for the perfect match), but comparable with the SoC321 method. We also performed Spectral Coherence analysis between (1) and SoC321 obtaining an average result in the band of interest (120 Hz, 230 Hz) of 0.90 (1.0 represents a complete correspondence between the two signals). Finally the signal is scaled down and fed to PWM for actuators control.

IV. Experimental Setup

Results obtained with the filtering stage seemed promising: improvement in the SNR from 2.86 dB to 36.85 dB for the movement on a rough surface, and from 7.91 dB up to 31.08 dB for the closing on an object movement (see Figure 4). For that reason, we decided to perform a pilot study with three prosthesis users, to preliminarily assess the validity of the system. The main objective of this pilot study was to verify if the system still maintains sufficient information after the filtering stage implementation and how this information is evaluated by prosthesis users. A second goal was to identify for which tasks the system can play a positive role for successful action execution.

A. Integration With the SoftHand Pro

The Vibro-Tactile device is integrated with the SoftHand Pro [17], as shown in Figure 1(a).

Our goal is to convey the acceleration recorded from prosthetic device fingers, related to contact and surface texture, to the user: for this reason, we need to apply the accelerometers as close as possible to the fingertips of the device. We place

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them on the nail side of the fingers as in [14], to avoid damages to the sensors.

We chose to use only two IMUs to reduce the complexity of the solution and the cognitive burden on the users. The accelerometers were placed on the little finger and index finger nails (Fig. 3). This choice was driven by the fact that these two fingers, together, span enough workspace for object size discrimination, and by the fact that the index is the most used finger to explore surface textures. This choice was also motivated by the outcomes reported in [14], where two MM vibrotactile conditions were considered: (i) all the accelerations from the fingers of the artificial hand were delivered to the users; (ii) only the accelerations from two fingers were rendered on the user's side. Results of [14] showed no difference in grasp and haptic exploration performance for conditions (i) and (ii).

The two accelerometers were connected to the control board through custom wirings. The board was connected to the two actuators worn on the user arm (Fig. 1(a)). For the system to function correctly, after the dimensional reduction, the obtained signal was scaled to stay in the amplitude range of the coil input.

All the system (including the artificial hand) is powered by a single 12V battery, as shown in Fig. 1(a).

B. Participants

Three prosthesis users took part in the experiments (2 female). All of them use the prosthesis on the left forearm. Subject 1 (S1), 37 years old, was affected by limb agenesis and is used to wear a cosmetic prosthesis even if having experience with myoelectric hands. Subject 2 (S2), 44 years old, was amputated seven years ago and uses both a myoelectric hand and a body powered hook on a daily basis. Subject 3 (S3), 24 years old, was amputated 22 years ago and occasionally uses myoelectric hands. The participants did not suffer from any cognitive impairment that could have affected their ability to follow the instructions of the study. All of them gave their informed consent to participate to the experiments. All the procedures were approved by the Ethical Committee of the University of Pisa.

C. Method

The experiment consisted in five tasks the participants were asked to perform. Each task focused on a particular action our device could help by delivering informative cues. The tasks were studied to place the participants in front of different conditions, such as actions where the movement of the prosthetic device was required and actions where no movement of the subject was required. Thanks to the use of the MM paradigm, only a 5 min training period was needed for the participants to correctly interpret the provided stimuli.

At the end of the tests, a 7-point Likert-scale questionnaire was presented to participants, to collect opinions on the device effectiveness and usability.

The five tasks were: (i) roughness discrimination, (ii) finger contact discrimination, (iii) object grasping, (iv) object slippage detection, and (v) integration of shape and roughness information.

During all tests, participants were insulated from external visual and auditory inputs by wearing blackout goggles and headphones with pink noise, in order to obstruct the view of the objects and the hearing of the noise from the actuators. All tasks are performed in three conditions, without feedback (NF), with feedback using the Classical Filter (BP) and with feedback using our filtering techniques (Ch).

In all the experiments the subject was seated on a chair in front of the working desk (with the exception of the RD task, in which the subject was standing). Objects needed for the current task were placed on the desk. The subjects' arm laid down relaxed on the table with the prosthetic hand palm facing up or down, depending on the task.

The subject wore the feedback system during all the tasks. During the trials without feedback (NF), the system was kept turned off. The two actuators were placed on the upper arm, the one corresponding to the little finger sensing was placed on the back of the upper arm, in correspondence with the vertical line starting from the little finger. The one corresponding to the index finger was applied on the front, following the same procedure (see Fig. 1(b)).

1) Roughness Discrimination (RD): the subject was asked to sort in order of increasing roughness three sheets of sand paper (40, 80, and 400-grit). For this task, a comparison of the magnitudes of roughness of the three sand papers was required. The three sheets were presented to the subject, one at a time, in a randomized order. The subject was asked to actively touch each of them with the fingers of the prosthetic hand and order them from the roughest to the smoothest. The experimenter, after placing and fixing the test sample in front of the subject, moves the subject's arm to place the fingers of the prosthetic hand in correspondence with the top of the sample. Once the positioning was completed, the experimenter started the trial by touching the subject. The movement the subject was asked to perform is to slide the fingers from the top to the bottom of each sample (See Fig. 6(b)). The subject was free to choose if and how much to close the hand before and during the task. The exploration is not time-constrained, the subject chose when to pass to the next sample. Three trials were performed for each condition.

2) Finger Contact Discrimination (FCD): the subject was asked to recognize which finger was touched by the experimenter. The answer could be either of the four long fingers (although only index and little fingers are sensorized). The experimenter touched on one of the four long fingers in a randomized order, touching each finger twice, paying attention to touch only the finger of interest. Two experimental conditions were considered: palm facing up and palm facing down. In these conditions, the experimenter touched the pulps or the nails of the prosthetic hand respectively (see Fig. 6(c) and Fig. 6(d)).

3) Active Object Contact Detection (AOCD): the subject was asked to detect object presence in the palm of the prosthetic hand, with the palm facing up, during a closure movement. The participant was also asked to stop the closing motion as soon as the contact was perceived. To avoid unwanted movements during the task, the hand was placed on the table, being sure it laid on the flat surface of the dorsum.

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Eight trials were performed in two conditions: four without any object, four with random wooden spheres from a set of three (diameters 50, 60 and 80mm). In the trials with the objects, the experimenter placed one of the spheres on the palm of the hand in proximity of the fingers, and held it during the closing movement, to avoid the sphere falling out of the palm, paying attention to not be touched by the fingers of the hand. In the trials without objects, the experimenter performed exactly the same procedure but without placing any object on the subjects' prosthesis hand. In Fig. 6(e) it is possible to see a trial with the wooden sphere.

4) Object Slipping (OS): the participant was asked to detect whenever an object, grasped with the prosthetic hand, was slipping from the grasp. To avoid unwanted movements during the task, the hand was placed on the table being sure it laid on the flat surface of the dorsum. For this task, the experimenter kept the wrist of the prosthesis fixed, to reduce force transmission from the hand to the patient (see Fig. 6(f)). This test was performed grasping two different objects, a half-full 1 l water bottle and a rigid 3D printed ABS cylinder (diameter 60mm). Four trials were performed for each object, two with slipping and two with no slipping. The object was kept in the palm of the prosthetic hand, with the prosthetic hand closed on it with the minimum closure needed to lift the object, i.e. to compensate for the object weight. The experimenter pushed the object, by exerting a force on the surface of the object itself (preliminary trials were used to define the hand closure position and the amount of force the experimenter needed to perform to trigger slipping). In the trials without slipping, the force was still exerted but was immediately below the slippage threshold.

5) Shape and Roughness Integration (SRI): participants were asked to recognize one out of 4 different objects. Objects differed in shape and surface roughness: a rough cone (A, Fig. 6(g)), a smooth cone (B, Fig. 6(h)), a rough pyramid (C, Fig. 6(i)), and a smooth pyramid (D, Fig. 6(j)). All the objects, smooth or rough, were covered with sand paper, 150 grit for the rough and 400 grit for the smooth. A total of 40 repetitions for each subject was performed. The objects were presented in randomized order in front of the subject. At the end of each trial, the subject was asked to move the prosthetic hand back to the rest position (see Fig. 6(k)). A 5 min rest pause was performed after 20 trials. There were no restrictions in the actions the participant can perform, but the subject was asked to contact the object only with the fingers of the prosthetic device. A Velcro band was attached to a wooden tablet placed on top of the experimental surface to keep the objects fixed during the exploration. The object to be tested was randomly selected and placed on the Velcro stripe. For a better view of the setup, see Fig. 6(k). Because of the duration of the experiment, for this experiment, condition BP was not tested.

V. Results and Discussion

Tables from II to VIII report the experimental results. Because of the small size of the subjects batch, a statistical analysis of the significance of the results could not be performed. Nevertheless, data suggest a possible trend that we would like to verify in future investigations.

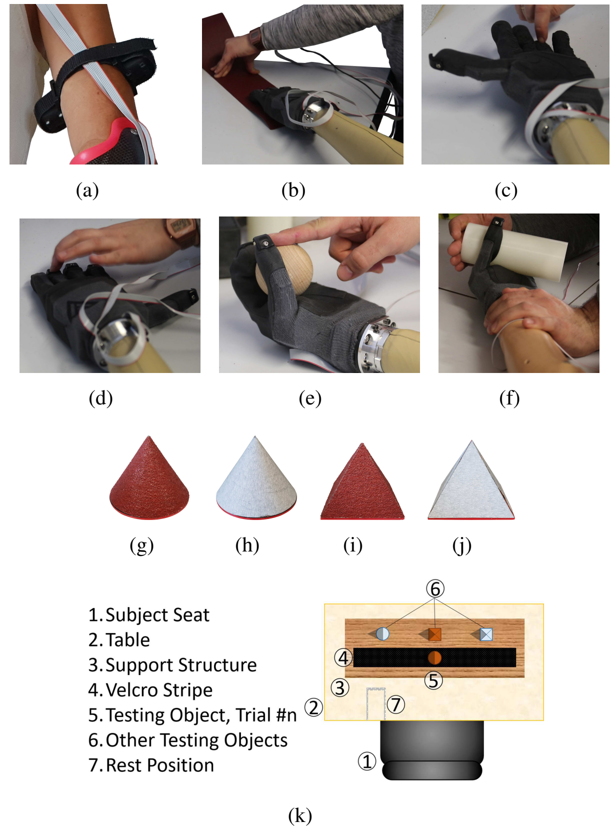

Fig. 6. Detail of the actuators on the subject's arm (a) and the experimental setups: (b) **RD Task Setup**. (c-d) **FCD Task Setup**: View of the task in palm up configuration (c) and in palm down configuration (d). (e) **AOCD Task Setup**: View of the experimental setup during the grasp of a wooden sphere. (f) **OS Task Setup**: View of the experimental setup with the rigid 3D printed ABS Cylinder. (g-k) **SRI Task Setup**: Objects to be identified in the Shape and Roughness Integration Task (g-j) and (k) the top view of the experimental setup.

Observing the general outcomes of the experiments, we can conclude that, for some of the tasks, the presence of feedback does not seem to improve success. This is visible e.g. for the RD (Table II) and the SRI tasks (Table VIII). In Table III, it is even possible to observe that in the RD task, errors are less in the condition without haptic feedback. This may be due to the reduced number of participants or to other mechanical aspects, i.e. participants could feel the vibrations through the socket. This is consistent with [25], where it is shown, with experiments on healthy subject, that humans are able to discriminate between touched objects, also by using information coming from accelerations transmitted through their body.

Table IV shows that, in the FCD task, the improvement due to the different filtering is not so strong, but the improvement related to the use of the feedback device is visible, especially in Table V. This last Table shows the confusion matrices of the results: it is possible to observe how errors are more concentrated between close fingers for the trials with the feedback, and more distributed between all the fingers in the trials without feedback. This can be due to the ability of the New Filter to remove the vibrations generated by a farther source. The explanation for the comparable results obtained using the New Filtering and the Classic one, in this task, can

TABLE II
RD RESULTS: NUM OF ERROR OVER A TOTAL OF 9 TRIALS.

	Ch	BP	NF
S1	7	5	6
S2	1	2	2
S3	2	3	0

TABLE III
RD RESULTS: CONFUSION MATRICES FOR THE THREE CONDITIONS FOR ALL THE SUBJECTS - ROUGH (R), MEDIUM (M), SMOOTH (S).

	New Filter			Classic			No Feedback		
	R	M	S	R	M	S	R	M	S
R	5	0	4	6	2	1	6	3	0
M	2	6	1	1	5	3	2	5	2
S	2	1	6	2	1	6	0	1	8

be due to the fact that the New Filtering helps in reducing the vibrations connected to the prosthetic hand movements. Indeed in this test, the prosthetic hand is kept still, and so the information transmitted by the two filters has, at most, the same information content.

The AOCD task, together with OS, are those in which the use of the Vibro-Tactile with the New Filter generates the highest performance improvement. Regarding the AOCD task, in Table VI it is possible to observe that the error rate when the Classical Filtering was used was always larger than the one with the New Filter. This can be explained by the fact that, when using the Classic Filter, all the vibrations of the hand closing are transmitted to the user, who is not able to isolate the sensations enough. It can be observed, also for the OS task (Table VII), that the use of the Vibro-Tactile yields an almost perfect recognition of the slipping of the object. This effect is greater with the rigid object, for which no error was performed in the New Filter configuration. In the task with the water bottle, the improvement is still present, but less significant. This difference between the rigid cylinder and the water bottle can be due to the fact that during the slippage, the plastic water bottle deforms, generating more vibrations, directly transmitted on the finger.

Finally, the scores of the Likert questionnaire suggest that participants did not feel hampered by the device and that the use of it (i) increased the feeling of a better sensory-motor performance and (ii) allowed to discriminate contact and roughness. Moreover, those results show that the participants were very confident on the usefulness of the feedback for roughness discrimination, even though it appeared to not dramatically lead to performance increase. Positive reception of the feedback could be due to the novelty of the feedback, as the participants never tried this kind of feedback before and were naive in experiencing roughness-related cues on the missing limb. On the other hand, reduced performance could be due on the fact that the final perception generating the results depends both on the given feedback and the mechanical vibrations transmitted through the socket. This can degrade the perceptual outcomes even if the subjects felt a stimulus. Neverthless, all the subjects agreed on the intuitiveness of the feedback, but also on the fact that an integration of the device inside the socket would improve usability. This possibility is already under investigation.

TABLE IV
FCD RESULTS: NUM OF ERROR OVER A TOTAL OF EIGHT TRIALS.

	Palm facing up				Palm facing down		
	Ch	BP	NF		Ch	BP	NF
S1	3	3	3	S1	0	2	6
S2	3	4	8	S2	2	1	8
S3	0	0	8	S3	0	0	8

TABLE V
FCD RESULTS: CONFUSION MATRICES FOR THE PALM FACING DOWN (D) AND UP (U) CONDITIONS FOR ALL THE SUBJECTS - SMALL (S), RING(R), MEDIUM (M), INDEX (I).

	New Filter D				Classic D				No Feedback D			
	S	R	M	I	S	R	M	I	S	R	M	I
S	6	0	0	0	6	0	0	0	0	4	2	0
R	2	4	0	0	1	5	0	0	2	2	1	1
M	0	0	6	0	0	0	5	1	1	1	1	3
I	0	0	0	6	0	0	1	5	1	1	3	1

	New Filter U				Classic U				No Feedback U			
	S	R	M	I	S	R	M	I	S	R	M	I
S	6	0	0	0	6	0	0	0	2	3	1	0
R	1	5	0	0	2	3	0	1	3	1	1	1
M	1	0	3	2	2	0	4	0	0	1	2	3
I	0	0	1	5	0	0	0	6	0	1	3	2

TABLE VI
AOCD RESULTS: NUM OF ERROR OVER A TOTAL OF EIGHT TRIALS PER CONDITION.

	Ch	BP	NF
S1	1	2	4
S2	2	5	8
S3	1	4	4

TABLE VII
OS RESULTS: NUM OF ERROR OVER A TOTAL OF FOUR TRIALS PER CONDITION.

	Rigid Cylinder				Water Bottle		
	Ch	BP	NF		Ch	BP	NF
S1	0	1	2	S1	0	1	1
S2	0	1	2	S2	1	2	2
S3	2	1	1	S3	0	1	2

TABLE VIII
SRI RESULTS: NUM OF ERROR FOR EACH CONDITION.

	Shape		Roughness		Total	
	NF	Ch	NF	Ch	NF	Ch
S1	14/40	14/40	16/40	16/40	30/40	30/40
S2	0/40	0/40	0/40	0/40	0/40	0/40
S3	16/40	11/40	11/40	8/40	27/40	19/40

TABLE IX
7-POINT LIKERT-SCALE TYPE QUESTIONNAIRE RESULTS FOR THE THREE SUBJECTS.

	Question	S1	S2	S3
Q1	I had feeling of performing better with feedback.	4	7	3
Q2	I felt hampered by the cutaneous device.	2	1	1
Q3	The stimulus from the cutaneous device was weird.	2	1	4
Q4	The given feedback can be useful in everyday life.	4	7	6
Q5	The design of haptic device must be changed.	5	7	7
Q6	This fb can be useful in the interaction with people.	6	4	1
Q7	I have to focus on the device instead of the task.	1	1	1
Q8	The given feedback can be useful during work.	4	7	6
Q9	The vibrations provided are confusing.	1	1	2
Q10	The vibrations provided are no disturbing.	6	7	7
Q11	The vt device allowed to distinguish roughness.	7	7	5
Q12	The vt device allowed to clearly detect the contact.	4	7	5

VI. Conclusion and Future Work

In this work, we described a haptic Vibro-Tactile feedback device used to convey high frequency information related to contact, shape, and texture of surfaces explored with a prosthetic hand. We reported the steps that led to the choice and the design of the system, including the filtering stage together with a pilot study with three prosthesis users.

Results suggest that in most cases the participants were able to use the feedback from the haptic device to improve the success rate in the proposed trials. In one out of five tasks, the information provided by the device was not used by the participants, resulting in no improvement in the task execution, but in the other four tasks, results seem to suggest that the system with the filtering stage developed here is in general more effective than the classic one. This is due to the fact that the New Filter selects the transmitted information, improving the quality of haptic perception.

Regarding the filter design, the obtained filter allows the system to almost completely remove the vibrations generated by the movements of the prosthetic device. This allows users to receive more clean, informative and intuitive stimuli.

The experimental trials performed in the pilot test presented in this work are only preliminary as they were performed only on a limited subjects pool. Nevertheless, the outcomes of this work, together with the positive feedback from the subjects, encourage us to perform new investigations.

Future works will be devoted to improve the system in terms of integration with the socket and to perform a more significant psychophysical characterization of the device. A larger number of conditions and pool of users will be considered. Finally, it is worth noticing that the results of this work can be applied not only to prosthetics but also to other fields of robotics, such as tele-operation, e.g. in exploration of remore environments, where a feedback apparatus as that described in this manuscript could be used to convey to the user, in a completely wearable manner, high-frequency information sensed on the slave side, thus increasing immersiveness [15]. Future works will be also devoted to further investigate the placement of the actuators, in order to maximize usability, system integration, users' comfort and perceptual response.

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