HyVE: Hybrid Vibro-Electrotactile Stimulation for Sensory Feedback and Substitution in Rehabilitation

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HyVE: Hybrid Vibro-Electrotactile Stimulation for Sensory Feedback and Substitution in Rehabilitation

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***Abstract*— Electro- or vibro-tactile stimulations were used in the past to provide sensory information in many different applications ranging from human manual control to prosthetics. The two modalities were used separately in the past, and we hypothesized that a hybrid *vibro-electrotactile* (HyVE) stimulation could provide two afferent streams that are independently perceived by a subject, although delivered in parallel and through the same skin location. We conducted psychophysical experiments where healthy subjects were asked to recognize the intensities of electro- and vibro-tactile stimuli during hybrid and single modality stimulations. The results demonstrated that the subjects were able to discriminate the features of the two modalities within the hybrid stimulus, and that the cross-modality interaction was limited enough to allow better transmission of discrete information (messages) using hybrid versus single modality coding. The percentages of successful recognitions (mean ± standard deviation) for 9 messages were 56±11% and 72±8% for two hybrid coding schemes, compared to 29±7% for vibrotactile and 44±4% for electrotactile coding. The HyVE can be therefore an attractive solution in numerous application for providing sensory feedback in prostheses and rehabilitation, and it could be used to increase the resolution of a single variable or to simultaneously feedback two different variables.**

***Index Terms*— sensory substitution, vibrotactile, electrotactile, electrocutaneous, hybrid stimulation, sensory feedback, prosthetics.**

I. Introduction

STIMULATION of the tactile sense was used in the past for many different applications. Tactile stimulation was investigated as a mean to provide an alternative or additional feedback channel for the human manual control of different dynamic systems [1], [2]. This was used to decrease the demand on the visual or auditory senses which in general provide better control performance but can be overloaded in the case of a complex control task. In rehabilitation, tactile stimulation can be applied during a therapeutic exercise to augment the feedback provided naturally through the contact with the environment or rehabilitation device (e.g., robotic exoskeleton) [3] or to communicate the desired or erroneous activations and/or movements [4], [5]. It was demonstrated that the provision of an augmented haptic feedback can facilitate the motor learning [6]. Finally, in the context of prosthetics, the stimulation of the skin was used to implement sensory substitution, which is a method for restoring lost or diminished sensory functions by stimulating alternative, still intact sensory receptors [7]. For example, the lost vision, hearing, or kinesthetic senses can be restored to a limited extent by capturing the information of interest (e.g., sound, position status or image) and delivering it to the skin through an array of stimulators in the form of intensity or spatially modulated stimulation patterns. One specific case that lately receives an increasing attention of the scientific community is a challenge to close the loop in a sensorized hand prosthesis by providing artificial proprioceptive and grasping force feedback [8].

Tactile sensations can be elicited in two ways: mechanically, by physically displacing the skin, or electrically, by passing an electrical current through the skin [7], [9].

Vibrotactile stimulation is a common method for direct mechanical activation of the tactile receptors and it can be provided in different ways: linear and rotary electromagnetic motors and several non-electromagnetic actuators (e.g., ceramic piezoelectric materials, electroactive polymers, shape memory alloys, or pneumatic and hydraulic systems). The former are still much more common and convenient for practical application [10], [11]. Depending on the frequency, the generated vibrations can be perceived as slow kinesthetic motion (< 3Hz), flutter (10-70 Hz), or smooth vibration (100-300 Hz) [10]. Qualitative aspects of generated vibrations are thoroughly investigated in [12] by using adjective rating along multiple dimensions. Linear electromagnetic motors employ electrically energized coils to move a piece of ferromagnetic material (solenoids) or a permanent magnet (voice coils) along

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the coil axis, producing vibrations that are perpendicular to the skin. In some models, such as C2-tactor (EAI engineering acoustics, inc.), a miniature moving element (contactor) locally indents the skin, while the surrounding skin area is shielded by a passive housing, providing well localized, point like sensations. Rotary electromagnetic actuators are electric motors with an eccentric mass attached to the rotor shaft, and they can produce mechanical vibrations of different amplitudes and frequencies. They are nowadays available as very low-cost, low power and miniaturized components due to the advances in mobile phones over the last decade and hence the use of these vibrators seems the simplest approach to provide vibrotactile stimulation. They are built in a flat fashion (pancake) which is convenient for laying them onto the skin. The generated vibrations are tangential to the skin and propagate around the stimulated site.

In *electrotactile* stimulation, low level current pulses are delivered to the tissue using electrodes placed on the skin. Usually, concentric electrodes with an active inner field (cathode) and an outer ground ring (anode) are used [9]. The electrical current therefore travels locally and superficially. This prevents the stimulation of deeper sensory-motor structures (e.g., motor nerves and muscles). Typically, this focused stimulation produces a well localized tactile sensation through the activation of surface cutaneous afferents. In some cases, the current can reach a sensory nerve deeper into the tissue, hence eliciting a sensation that is spread to a wider and/or more distant area (so called referred sensations [7], [13], [14]). Electrotactile stimulation can produce a wide range of possible sensations (i.e., vibrations, tingling, pressure, itching, pricking etc. [7], [13]- [14] [15]) and the sensation quality can be modulated by adjusting the electrical features of the applied waveform (i.e., frequency, current amplitude and pulse width) [16]- [19]. Typically, electrotactile devices consume less power and respond faster than vibrotactile systems as there are no moving mechanical parts. However, in general, electrical stimulation can be considered as a more invasive approach with respect to mechanical vibration since, if the parameters are not carefully adjusted, it can cause discomfort and pain [7], [20].

Both electro- and vibro-tactile stimulation are convenient for practical applications (as the devices are compact, low cost and low power) and hence they represent attractive candidates for providing the tactile information. In the current work, we hypothesized that the two modalities (electrical and vibratory stimulus) could be combined into a hybrid *vibro-electrotactile* stimulation (hereafter called HyVE) and applied simultaneously and to the same target site on the skin. Such an interface could be advantageous with respect to the conventional single modality implementations. Specifically, the HyVE could be used to provide two simultaneous afferent information streams that are independently perceived by a subject, although they are being delivered in parallel and through the same physical location. The psychophysical basis for this hypothesis is that the sensations elicited by the vibro- and electro-tactile stimulations can have different qualities (e.g., vibration vs. constant pressure) and the neurophysiological foundation is that the two stimulation modalities engage different mechanisms to activate the tactile sense. Vibratory stimuli act directly on the mechanoreceptors sensitive to vibration (i.e., Pacinian or Meissner's corpuscles) [7], [21], while the electrical stimuli are less specific, activating skin afferents and thereby potentially many different receptor types [7], [9], [22].

The HyVE interface could be built in a very compact fashion, since the two information channels share the same target site, and it would allow the delivery of sophisticated stimulation patterns exploiting the two parallel information streams. It could be used as a general purpose haptic interface in numerous applications and body sites to convey multidimensional, multimodal information in a compact fashion. As we demonstrate in this work, the HyVE could be exploited either to increase the dynamic range (i.e., more discernible classes for one feedback variable) or to provide two parallel streams of information (i.e., simultaneously conveying two feedback variables). Importantly, this could be accomplished without the concomitant increase in the area of the skin occupied by the stimulators.

We are especially interested in the potential application of the HyVE for sensory substitution in prosthetics. In the recent years, vibrotactile systems have been used in research to implement experiments with robotic hands in closed-loop control [23]- [26] aiming at evaluating the role and importance of providing the feedback. The main finding of these experiments was that the use of vibrotactile feedback improves user performance by lowering the number of errors in task execution due to, for example, a better control of grip force [24], [25] and/or joint position during reaching and matching tasks [27]. There are several studies in which electrical stimulation was used to implement a closed loop control of transradial prostheses, and they reported positive results [28]- [33]. In some of them [28]- [30], the presented evidence for the effectiveness and acceptance of feedback has mainly an anecdotal character, but there are also studies in which the closed loop system was actually quantitatively evaluated. Those studies have reported an increased performance in grasping tasks [17], [31], better control of grasping force [16], and more accurate discrimination of object sizes [32], [33]. Although all of these studies focused on vibrotactile or electrotactile systems [23]- [33] and others compared the two modalities [7], [20], [34], [35], none considered combining them into a unique device that would deliver a hybrid vibro-electrotactile stimulation.

The HyVE could be a promising option for this particular application since there is a limited area available to place the stimulators (e.g., prosthetic socket over the residual limb), and the HyVE saves the space by physically overlapping the two stimulation channels. The two parallel afferent streams, electrical and vibrotactile, could simultaneously deliver any combination of continuous or discrete information streams, for example: 1) discrete information about two different grasp parameters, such as, grasp type (palmar, lateral, pinch) and size (small, medium, large), 2) continuous information about interaction forces and finger status/position values (e.g., while

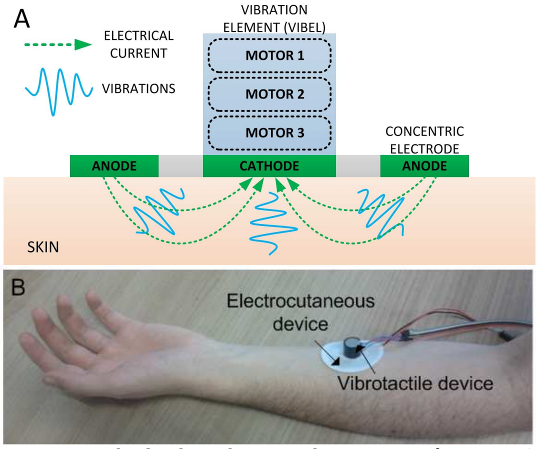

Fig. 1. HyVE: *Hybrid Vibro-Electrotactile* system configuration (A) and placement on the forearm of an able-bodied subject (B). The electrical and vibrational stimulation are delivered simultaneously and "through" the same location on the skin. The vibrotactile interface is a *vibel* (detailed in [36]) comprising three coin type vibration motors stacked together within a rigid plastic housing. Electrocutaneous stimulation is delivered using a concentric electrode. The vibel is placed over the inner contact (cathode) of the electrode.

grasping a compliant object), or 3) continuous information about interaction force (or finger position value) and discrete information about the status of the hand (e.g., current grasping force and grasp type performed by the hand).

In this paper we present the HyVE concept and its evaluation for the first time. The goal of this study was twofold. First, we tested the fundamental hypothesis about the perception of the hybrid stimulation. Namely, we performed psychophysical tests in healthy subjects in order to assess if they were able to recognize electro- or vibro-tactile features from the hybrid stimulation, or put differently, if they were able to perceive concurrently the two parallel afferent information streams. As control conditions we assessed how well they perceived the features of the same electro- or vibro-tactile stimuli when they were delivered in a conventional, single modality manner. Outcomes and comparisons between experimental and control conditions confirmed the hypothesis and provided evidence that it is possible to discriminate different modalities within the hybrid stimuli, and that the cross-modality interaction and resulting effect on the subject perception is limited.

Next, the goal was to evaluate if the interaction between different modalities is limited enough to allow more effective transmission of information to the subject through a given area of the skin using hybrid versus single modality stimulation. We conducted an experiment in which the task for the subjects was to receive (recognize) a set of discrete information (messages) communicated through the same skin area using intensity coding with hybrid or single modality stimulations. The experiment demonstrated that the HyVE interface was superior to both electro- and vibro-tactile stimulation in terms of the number of successfully received messages.

The list of abbreviations used in the manuscript is given in Table AI in Appendix.

II. Methods

A. HyVE interface

The HyVE physical interface developed for our experiments consisted of a vibration element placed on the top of a self-adhesive concentric electrode connected to an electrical stimulator delivering current pulses (Fig. 1A). The vibrator was aligned with the inner (active) contact of the electrode. The vibrotactile stimulator used in the present work was a real-time controllable device called *vibel* (detailed in [36]). The vibel comprises three coin-type vibration motors stacked together within a rigid plastic housing and is able to produce mechanical vibrations with selectable amplitudes and frequencies. The electrotactile interface was a fully programmable, eight channel stimulator (TremUNA, UNA Systems, Serbia) and disposable, self-adhesive concentric electrodes (CoDe 501500, Spes Medica, IT). The diameters of the inner, active field and the outer, ground ring were 16, and 42 mm, respectively, with 5 mm of separation between the two. The electrodes were thin (conductive field: 1 mm thickness, adhesive material: 0.5 mm thickness) and they thus had a marginal effect on the mechanical vibration. Only one stimulation channel was used in the present experiments. The stimulation was current-controlled and biphasic with a square pulse to depolarize the fibers and an exponential relaxation phase to remove the injected charge from the tissue. The vibrotactile and electrotactile stimulators were connected to a host (laptop) and were controlled in real time by sending simple commands over a USB connection. The software implementing experimental protocols and controlling the HyVE was programmed in *LabView 7.1*.

B. Experiments to determine the parameters of electrical stimulation

Four healthy subjects (2 males and 2 females, age 28±3 years) participated in pilot tests aimed at preliminarily assessing the perception of stimuli when the HyVE was applied to the glabrous skin of the forearm and roughly identifying the ranges of stimulation parameters that could be correctly perceived. From the subject reports during the pilot tests, we discovered that low pulse-rate electrical stimulation (e.g., < 50 Hz approximately) feels like tapping or vibration, in which the intensity of the tap depends on the intensity of stimulation and frequency is equal to the pulse rate. At higher rates (e.g., > 50 Hz approximately) the subjects no longer perceive pulses individually. The individual sensations *fuse* together and the sensation resembles a constant pressure. Importantly, the transition from the individual pulses to the continuous sensation is not abrupt, and it was not possible to pinpoint a single, well-defined border frequency. The change is rather gradual and subjective, and the above indicated ranges should be therefore considered only as the rough estimates. The mechanical vibration produced by our stimulator (range: 0.49-2.11 N) was always well above the vibration perception threshold and evoked sensations of higher intensity compared to the electrotactile system. Based on these

TABLE I
SUMMARY OF PERFORMED EXPERIMENTS

Name	Description	Electrotactile levels	Vibrotactile levels	Subjects (no.)
HyVE9	Hybrid stimulation with nine classes	LE, ME, HE	LV, MV, HV	Group A (10)
HyVE9Z	Hybrid stimulation with nine classes and zero level for vibratory modality	LE, ME, HE	ZV, LV, HV	Group B (10)
ELE3	Single modality with three classes	LE, ME, HE	-	Group A (10)
VIB3	Single modality with three classes	-	LV, MV, HV	Group A (10)
ELE9	Single modality with nine classes	9 equidistant steps from LE to HE	-	Group C (5)
VIB9	Single modality with nine classes	-	9 levels of intensity from LV to HV	Group D (5)

empirical considerations, we expected that vibratory stimulation could "mask" the electrical one, especially when the latter was delivered at low pulse-rate, i.e., when the electrical stimulation elicited a "vibratory-like" sensation. We aimed to test this hypothesis in order to optimally choose the electrical stimulation frequency for the hybrid modality.

To test the hypothesis, we performed experiments using a *two alternatives forced choice* paradigm [37]. Subjects were exposed to trials comprising a sequence of two 1-s long hybrid stimuli. The vibratory stimulus was always the same (i.e., at the highest intensity, corresponding to 2.11 N of tangential force and vibration frequency of 160 Hz) whereas the electrical stimulus could be one of the following: reference stimulus (RE), a low-intensity comparison stimulus or a high-intensity comparison stimulus. The stimulation parameters for these electrical stimuli were determined for each subject individually before the experiment. We first tested the Sensation Threshold (ST) using the method of limits [37] by varying the pulse width (PW) of the stimulus: the PW was increased in equidistant steps (50 μs) while the subject verbally indicated when he/she felt a slight sensation. We chose to vary the PW of the waveform instead of the current intensity since the former usually provides more accurate control of the elicited sensation. The RE stimulus was set to 1.2*ST. Next, we determined the Just Noticeable Difference (JND) from the RE by using the *staircase method* [37]. The low-intensity and high-intensity comparison stimuli were set to RE+JND and RE+2*JND, respectively. In each trial of the two alternatives forced choice test, the RE and one of the two comparison stimuli were presented in a random order. The subject was asked to focus on the electrical stimulation during the delivery of the hybrid stimulus and to report which electrical stimulus (first or second) was perceived as the strongest. We performed these tests at two pulse-rates of the electrical stimulus (25 Hz and 100 Hz) and, as a control condition, the same tests were repeated with the vibrations turned off (single modality stimulation).

The results of these pilot tests confirmed our hypothesis. When the hybrid stimulation was delivered at a pulse rate of 25 Hz, the recognition rate (mean ± standard deviation) of the human subjects for the low and high comparison stimuli was equal to 50±17% and 54±14%, respectively, i.e., at the chance level, compared to 83±10% and 88±10% if the vibration was not present (single modality). However, when the pulse rate was set to 100 Hz in hybrid stimulation, the subjects were able to recognize the low and high comparison stimuli with the rates of 69±12% and 85±4%, respectively. The control conditions in single modality at 100 Hz yielded recognition rates of 89±10% and 94±4% for low and high comparison stimulus, respectively. Based on these outcomes we chose the rate of 100 Hz for the electrical stimulus during hybrid stimulation.

C. *Experimental protocol*

The experimental paradigm in the core tests was similar to that used for single modality stimulation in [13], [26], [36], [38], [39]. The subjects were asked to recognize the intensities of electro and vibrotactile stimuli delivered during hybrid and single modality stimulations. The stimulus intensity was randomly drawn from a predefined set of discrete levels. The HyVE was placed on the anterior side of the right forearm, approximately at mid-forearm (Fig. 1B). Prior to the experiments, the sensation (ST) and pain thresholds (PT) for the electrical stimulation were determined for each subject using the *methods of limits* by varying the PW [37]. The pulse rate and intensity were set to 100 Hz and 3 mA, respectively. This test was repeated three times and the mean values were adopted as the ST and PT for each subject. The mean ST calculated for all subjects was equal to 140±50 μs. The value of PT was more variable among the subjects, with the overall mean of 620±320 μs. While testing the thresholds, we were also checking for the signs of possible motor response (e.g., finger movement, muscle contraction), but this was not registered or reported by any of the subjects.

Six experiments, randomized among the subjects, were then performed: two with hybrid stimuli, aimed at evaluating the subjects' perception of the two parallel streams of afferent information, and four with single modality stimuli, serving as the control conditions for the first two.

All experiments had the same structure that comprised three phases: *learning* with visual feedback, *reinforced learning* without vision, and *validation*, also without vision. In the first phase (learning), the participants received a visual feedback on a computer screen indicating the level of electro and vibrotactile stimulation that was being delivered. The participants were instructed to focus on the stimulation and to associate it to the visual description on the screen (i.e. a three-level or nine-level intensity scale for each modality). In the reinforced learning phase, the participant was blindfolded.

TABLE II
VIBRATION FORCE AMPLITUDES EMPLOYED IN VIB9 EXPERIMENTS

Message	1	2	3	4	5	6	7	8	9
Force amplitude [N]	0.49	0.61	0.88	1.05	1.18	1.38	1.57	1.85	2.11
Active motors	1	1	2	2	2	2	2	3	3
Duty cycle [%]*	53	67	53	63	77	87	100	83	100

* Duty cycle can be set in the range from 50 to 100 %.

After the presentation of each stimulus, he/she verbally indicated the stimulation levels and the experimenter stated the correct answer. During the final validation phase, the participant verbally indicated the stimulation levels and no feedback was given. This latter session was used to validate the results of the learning and reinforced learning sessions. Each stimulus was presented to the subject 14 times during the first two sessions and 7 times during the validation phase. There was a break of 30 s between the successive stimulus presentations in order to minimize the influence of the previous stimulus on the recognition of the next one. Throughout all the experiments the vibro- and/or electro-tactile levels were randomly selected and delivered for one second. White noise was played during the stimulation through the speakers in order to cover the noise generated by the vibration motors that could affect the recognition. The six experiments are described hereafter and summarized in Table I. All experiments were approved by the local ethic committee.

1) Hybrid and single modality stimulation experiments

Experiment HyVE9. Three vibrotactile stimuli and three electrotactile stimuli were combined for a total of 9 different, hybrid stimuli. The stimulation parameters were chosen in order to maximize the differences in the intensities of the stimuli. The features (tangential force, frequency) of the low (LV), medium (MV) and high (HV) vibrotactile stimuli were: LV = (0.49 N, 120 Hz), MV = (1.20N, 140 Hz), and HV (2.11 N, 160 Hz). The PWs for the low (LE), medium (ME) and high (HE) electrotactile stimuli were: LE = 1.2*ST, ME = LE+0.3*(HE-LE) and HE = 0.8*PT, respectively. The increment for the medium level was set to 30% of the full range since the sensation–intensity characteristic is logarithmic [7], [22]. The vibrotactile stimuli were obtained by adjusting the inputs for the three vibration motors within a vibel. Due to a motor construction, the amplitude and frequency of vibrations of a single motor are coupled and both depend on the duty cycle of the applied pulse-width modulated voltage signal. For each stimulus, we selected the number of active motors and their duty cycles so that the distance between the intensities of the generated stimuli was maximized. Ten subjects (6 men and 4 women, age 31±4 years) took part in this experiment (Group A).

Experiment HyVE9Z. The three electrical stimuli and the low and high vibrotactile levels were identical to the ones used in the HyVE9 experiment. However, the third level of vibrotactile stimulus was *no stimulation* or *zero level* (ZV). Ten subjects (6 men and 4 women, age 30±3 years) volunteered in this experiment (Group B).

Control experiments: ELE3 and VIB3. The same three levels of electro and vibrotactile stimulation that were used in HyVE9 to produce a hybrid sensation were tested in experiments involving only a single modality, i.e., either vibrotactile (VIB3) or electrotactile (ELE3). The same group of subjects that participated in HyVE9 performed the ELE3 and VIB3 experiments as well (Group A).

Control experiments: ELE9 and VIB9. The electro- or vibro-tactile stimulations were tested in single modality experiments with 9 intensity levels. The PW levels for the electrical stimulation were obtained by dividing the range from LE to HE in 9 equidistant steps. The vibrotactile stimuli were constructed, as explained previously, so that the intensity was monotonically increasing from 0.49 N at 120 Hz to 2.11 N at 160 Hz (see Table II). Two groups composed of five subjects took part in these experiments: Group C (4 males and 1 female, 31±2 years) for ELE9 and Group D (3 males and 2 females, 30±3 years) for VIB9.

2) Comparison of the results and hypotheses testing

Two information streams discrimination. The results of HyVE9 were compared to the results of the control conditions ELE3 and VIB3. The HyVE9 experiment was used to assess how well the subjects perceived the electro- and vibro-tactile stimuli when they were delivered simultaneously. In ELE3 and VIB3, we determine the subjects' ability to recognize exactly the same stimuli but when the conditions were ideal (i.e., no interference from the other modality). This was used to test the fundamental hypothesis of this work, i.e., the eventual interaction between the modalities during the hybrid stimulation. If this interaction is not substantial, then the HyVE can be used to implement two independent afferent information streams flowing simultaneously through the same area of the skin.

Transmission of discrete information (messages). The results of HyVE9 and HyVE9Z were compared to the results of the control experiments ELE9 and VIB9 in order to assess the performance in transmitting a set of discrete information (messages) through the same area of the skin using hybrid versus single modality stimulations. In this test, we started from a hypothetical task: conveying nine different messages to the subject through a tactile display using intensity coding. In an actual application, this could be, for example, information about the current grasp type (palmar, lateral, pinch) and size (small, medium and large). In this case the message is received only if both pieces of information are correctly conveyed to the subject. This communication context is similar to the notion of "tactons" or "haptic icons" introduced, for example, in [42]. With the single modality interfaces, the messages were coded using 9 intensity levels separated as much as possible within the dynamic range of the stimulation (e.g., level 1 = palmar small, level 2 = palmar medium and so on). With the hybrid interface, three levels were used in each modality (i.e., 3 grasps transmitted electrically x 3 sizes through vibrations). The difference between HyVE9 and

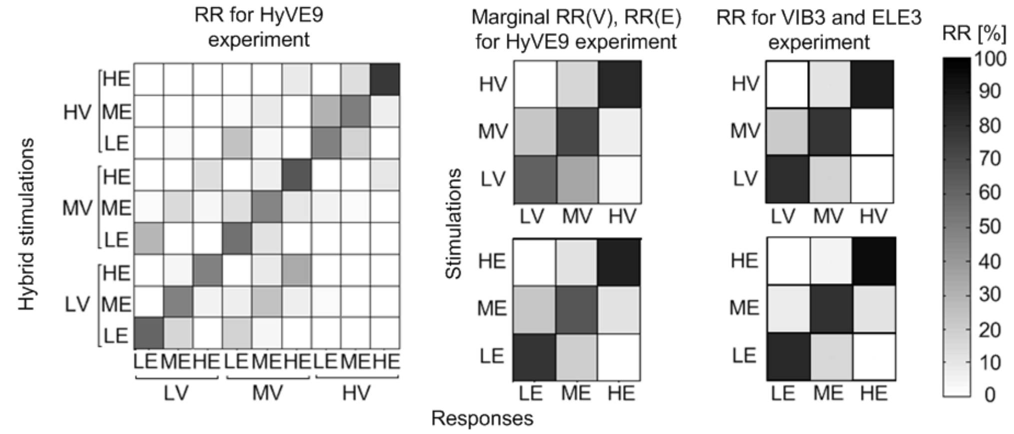

Fig. 2. Confusion matrices for the overall and marginal RR in HyVE9 (left and central panels) and overall RR in ELE3 and VIB3 experiments (right). The results demonstrate a good recognition of 9 classes in hybrid stimulation (well-focused diagonal line). Marginal RR is very similar to the RR of single modality experiments implying that the subjects were able to independently recognize the single modalities within the hybrid stimuli.

HyVE9Z lies in a slightly different coding. Namely, in HyVE9Z one modality (vibrotactile) is allowed to go into a zero state. This could be regarded simply as a different way to code the information, but it also relates to the practical application in which it is to be expected that one of the feedback variables can go to zero (e.g., the prosthesis opens and the grasping force goes to zero). The main purpose of HyVE9Z was therefore to evaluate the effect of an alternative hybrid coding method on the information transfer. We expected that, in this particular case, the performance in receiving the transmitted messages would increase since the absence of vibro-tactile stimulation was easy to detect, and the removal of the ML made it easier to discriminate between the LV and HV.

D. Data analysis

The recognition rate (RR), i.e., the percent of correctly recognized stimuli, was the performance metric for all of the experiments. With the hybrid stimulation, the recognition was deemed successful if the intensities of both modalities were correctly recognized by the subject. Similarly, for the single modality experiments the recognition was successful if the intensity of electrical (ELE3 and ELE9) or vibrotactile (VIB3 and VIB9) stimulus was correctly recognized. The RR was calculated for each class/message individually and globally for the whole trial. Results were presented in the form of confusion matrices so that we could evaluate the overall performance and identify prevalent mistakes. In the hybrid case, the RR for a class (xE,yV), where x and y belong to L, H, M, or Z, whereas E and V refer to electrical or vibratory, is an estimate for the probability RR(xE,yV) of successfully recognizing a particular combination of the intensities of the two modalities. From the RR in the hybrid stimulation experiments, it is also possible to calculate: 1) the marginal RR(E) or RR(V), i.e., the overall RR for one modality regardless of the intensity of the other, and 2) the conditional RR(E|yV) and RR(V|xE), i.e. the overall RR for one modality when the other had a certain intensity (i.e., yV or xE). The marginal and conditional RR were calculated for HyVE9 and HyVE9Z to obtain insights into the potential interaction between the two modalities within a hybrid stimulus.

A one-way ANOVA and (when required) a post-hoc test for multiple groups' comparison (Tukey's honestly significant difference criterion) was applied in order to compare the results from HyVE9, HyVE9Z, VIB9 and ELE9. A paired two-tailed t-test was used to compare the marginal RR from HyVE9 to ELE3 and VIB3, since the same group of subjects participated in both tests, and also to compare the RR across learning and evaluation phases.

III. Results

Each of the 9 class/messages experiments lasted approximately half an hour, whereas the 3 classes experiment took approximately 10 min. A complete experimental session (setup and tests) lasted from 1 to 2 hours on the basis of subject's group. If not indicated differently, the results reported in this section refer to the validation phase of the experiments, and are given in the form of mean ± standard deviation in text and figures.

The confusion matrices reported in Fig. 2 describe the overall (left panel) and marginal RR (center panel) obtained in HyVE9 and the overall RR from the control experiments ELE3 and VIB3 (right panel). The RR for HyVE9 experiment was 56±11% which is approximately 5 times higher than the chance level (i.e., 1 out of 9 or 11%). The confusion matrix for HyVE9 demonstrates a clearly visible diagonal line standing for a correct class recognition and typical errors due to the misjudgments of the intensity of the vibratory stimulus (see parallel diagonals above and below the main diagonal) and less frequently of the electrical stimulus (see 2x2 squares along the main diagonal) for one level up or down from the actually presented (correct) intensity.

The distribution of the errors in confusion matrices for the marginal RR (Fig. 2, central panel) is similar to the ones obtained for ELE3 and VIB3 (Fig. 2, right panel). The marginal RR was RR(V) = 72±13% (vibro) and RR(E) = 77±13% (electro) while the overall RR in the single modality experiments was 83±11% for VIB3 and 86±12% for ELE3. A statistically significant difference was found only between RR(V) and RR in VIB3 ($p < 0.001$) but not between RR(E) and RR in ELE3 ($p = 0.13$).

Fig. 3 shows the conditional RR for the electrical [RR(E|yV)] and vibratory [RR(V|xE)] stimulation in HyVE9.

For the vibratory modality the conditional RR did not vary with the intensity of electrical stimulation. In the case of electrical stimulation there was a drop in performance only when the vibratory stimulation was at the highest level. Nevertheless, the difference was not statistically significant in either case ($F(2,27) = 0.6$, $p = 0.56$; $F(2,27) = 0.1$, $p = 0.91$ in conditional RR for electrical and vibratory stimulation, respectively). Therefore, the ability of judging the features of one of the two simultaneously delivered stimuli was not significantly influenced by the intensity level of the other modality.

The confusion matrices characterizing the transmission of 9 messages using hybrid (HyVE9 and HyVE9Z) and single modality coding (ELE9 and VIB9) are given in Fig. 4. The matrices for the hybrid stimulation exhibited high diagonal values (especially for HyVE9Z) compared to the blurred,

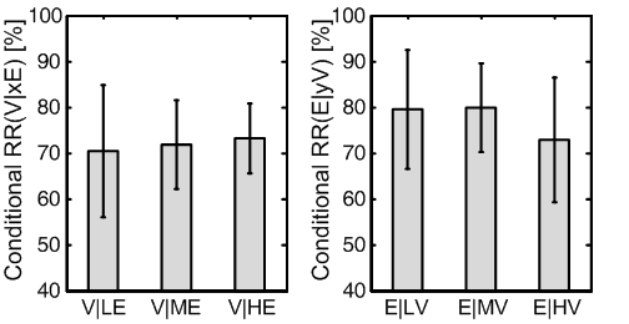

Fig. 3. Conditional RR (mean ± standard deviation) for the vibrotactile [RR(V|xE)] and electrotactile [RR(E|yV)] stimuli during hybrid stimulation (HyVE9 experiment). The conditional RR for one modality was not significantly affected by the intensity of the other modality.

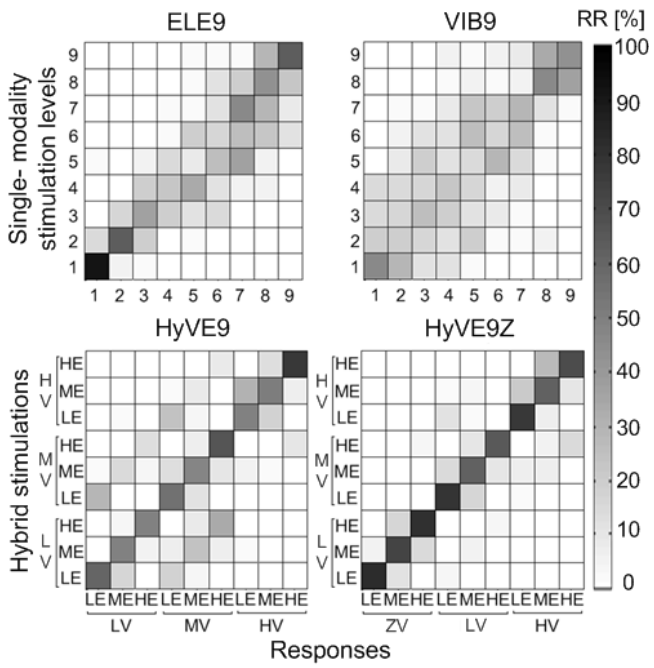

Fig. 4. Matrices for the RR of 9 classes in the validation phases of hybrid (HyVE9 and HyVE9Z) and single modality (VIB9 and ELE9) experiments. The confusion matrix for HyVE9 is identical to the one in Fig. 2 and is repeated here for convenience. The matrices demonstrate the superior performance in recognizing the hybrid stimulation. HyVE9Z (hybrid stimulation with zero level of vibration) resulted in the best performance.

relatively wide diagonal areas in ELE9 and VIB9. The RR for both conditions with hybrid stimulation (HyVE9 and HyVE9Z) was greater than the RR for the single modality conditions and the difference was statistically significant ($F(3,26) = 33.3$, $p < 0.001$): HyVE9 vs. VIB9 ($p < 0.001$), HyVE9 vs. ELE9 ($p < 0.05$) and HyVE9Z vs. ELE9 and VIB9 ($p < 0.001$). This demonstrates that the performance in communicating discrete information to the user was better when using hybrid than single modality coding of 9 messages.

The introduction of the vibratory zero level in the hybrid stimulation increased the RR from 56±11% (HyVE9) to 72±8% (HyVE9Z) (HyVE9 vs. HyVE9Z: $p < 0.01$) and this was much higher than the RR achieved in VIB9 (29±7%) or ELE9 (44±4%) (HyVE9Z vs. ELE9 and VIB9: $p < 0.001$). The parallel lines that appeared in the confusion matrix of HyVE9, denoting the misclassification of vibration levels, had lower values for HyVE9Z, while on the other side the main diagonals had very similar structure in both matrices. This means that it was easier to recognize the vibratory stimulation in HyVE9Z, since there were only two levels plus zero (but there was no change for the electrical stimulation). This was confirmed by the marginal RR in HyVE9Z that was 91±2% for the vibrotactile stimulation and 79±7% for the electrotactile. The RR(V) in HyVE9Z, as we hypothesized, was higher than RR(V) in HyVE9 ($p < 0.001$) and this boosted the overall performance. On the contrary, in case of RR(E) the difference between HyVE9Z and HyVE9 experiments was not significant ($p = 0.82$).

The mean RR for each message in the hybrid [RR(xE,yV)] and single modality [RR(En) and RR(Vn), n = 1,2, …9] experiments is presented in Fig. 5. In the single modality conditions, the RR for individual messages ranged from 14±13% to 46±6% in VIB9 and from 9±8% to 91±8% in ELE9. Note the characteristic concave shape of the envelope connecting the tip of the bars. Certain messages were therefore very hard to successfully recognize, especially those coded by the middle part of the intensity range, while some others were quite obvious, namely the ones coded by the intensity values at the extreme ends, particularly in the electrotactile condition. The RRs for the messages within one modality were significantly different ($F(4,36) = 2.5$, $p < 0.05$; $F(4,36) = 10.5$, $p < 0.001$ for VIB9 and ELE9, respectively). For the hybrid conditions (HyVE9 and HyVE9Z), the RR ranged from 47±27% to 77±18% in HyVE9 and from 61±12% to 81±18% in HyVE9Z. The minimum value of RR for the messages transmitted using the hybrid coding was higher than for the single modality experiments, and the range from minimum to maximum was narrower compared to the single-modality outcomes. Contrary to ELE9 and VIB9, no statistically significant differences were highlighted by ANOVA between the RRs of the individual messages in HyVE9 and HyVE9Z ($F(8,81) = 1.5$, $p = 0.18$; $F(8,81) = 1.71$, $p = 0.10$ for HyVE9 and HyVE9Z experiments, respectively). The performance in receiving different messages was therefore more consistent in hybrid vs. single modality experiments.

Fig. 6 shows the mean RR obtained in the reinforced learning phase compared to the one in the validation phase for

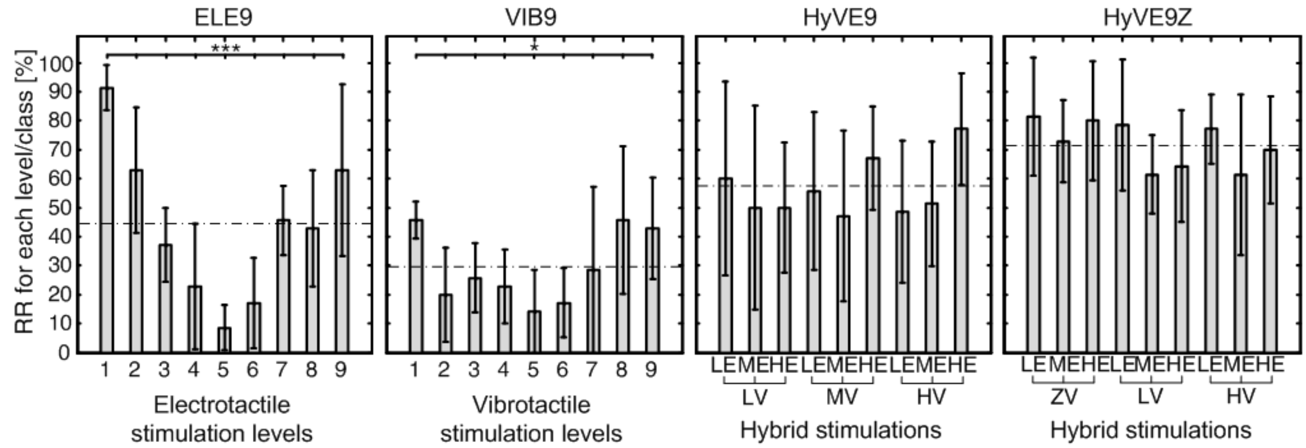

Fig. 5. Individual class RRs (mean ± standard deviation) obtained for the validation phases of hybrid [RR(xE, yV) in HyVE9 and HyVE9Z] and single modality [RR(Vn) in VIB9 and RR(En) in ELE9, n = 1, 2,…9] experiments with nine classes. The horizontal broken lines depict the mean RR calculated over the experiment. The performance for different classes in the hybrid experiments was less variable. Asterisk legend: * $p < 0.05$, *** $p < 0.001$.

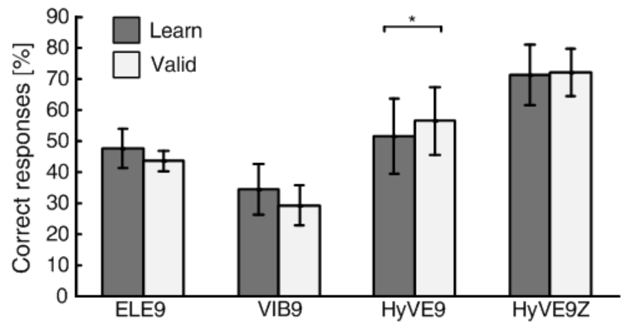

Fig. 6. Mean RRs (mean ± standard deviation) obtained in learning and validation phase for 9 message transmission experiments. Asterisk legend: * $p < 0.05$

TABLE III
SUMMARY RESULTS (MEAN ± STAND. DEV.) OF EXPERIMENTS

Test	Overall RR [%]	RR(E) [%]	RR(V)[%]
HyVE9	56±11	77±13	72±13
HyVE9Z	72±8	79±7	91±2
VIB3	83±11	-	-
ELE3	86±12	-	-
VIB9	29±7	-	-
ELE9	44±4	-	-

each of the message transmission experiments. The RR during the validation phase increased with respect to the reinforced learning phase only in the case of HyVE9 ($p < 0.05$). Therefore, the training did not significantly improve the performance in the case of HyVE9Z ($p = 0.75$), ELE9 ($p = 0.15$) or VIB9 ($p = 0.16$). In fact, in the experiments with the single modality coding, there was a drop in the mean RR in the validation with respect to the training phase. The overall and marginal RRs from all the tests are summarized in Table III.

IV. DISCUSSION

This paper introduces a novel concept of a hybrid vibro-electrotactile stimulation interface providing two different modalities of stimulation simultaneously and through the same target location on the skin. Based on the concept that vibratory and electrical stimulation can activate different receptors and elicit qualitatively different sensations, we hypothesized that a human subject would be able to recognize and independently analyze the features of the two modalities within a hybrid stimulus. This would mean that the two independent afferent information channels could coexist in the same space and time. In addition, we also wanted to compare the novel hybrid and "classical" single modality stimulations in a more concrete context, i.e., when the task was to convey a set of discrete messages to the subject by using hybrid and single modality interfaces for message coding and transmission. We hypothesized that the hybrid coding would lead to a better performance. We exposed healthy subjects to hybrid and single modality stimulations in 6 psychophysical experiments and the results confirmed our hypotheses (Table III). In order to evaluate the results from the test of the fundamental hypothesis (HyVE9 vs. ELE3 and VIB3), the following considerations have to be taken into account. ELE3 and VIB3 were very simple and fast experiments lasting less than 10 min, with a single stimulus and only 3 classes to recognize. On the other side, the marginal RR in HyVE9 was obtained from an experiment that lasted 3 times longer and with a more difficult task to accomplish (recognizing two simultaneous stimuli, 9 combinations in total). Therefore, we expected that the marginal RR in the HyVE9 experiment would be lower than the overall RR obtained during the single modality stimulations, and the results confirmed the assumption (Fig. 2). However, the difference in performance between the marginal RR in the hybrid and the overall RR in the single modality experiment was just ~ 11% and 9% for the vibro- and electro-tactile stimulation, respectively, and this difference was statistically significant only between the marginal RR(V) and RR for VIB3 experiment. Therefore, the "perceptual" interaction of the stimuli during the hybrid stimulation seems to be very limited.

Furthermore, the other results supported this conclusion as well. The conditional RR in HyVE9 and the difference in the overall and marginal RR between HyVE9 and HyVE9Z also demonstrate that the two parallel afferent information streams are essentially independent, i.e., there is no significant interaction between the channels. Changing the intensity of one modality does not influence the conditional RR of the other (Fig. 3). The vibratory stimulation levels in HyVE9Z were different than in HyVE9 (i.e., ZL in HyVE9Z instead of ML in HyVE9). This improved the marginal RR for the vibratory stimulation while the marginal RR for the electrotactile modality was largely unaffected (Table III). Strictly speaking, in HyVE9Z the task of the subject was not to discriminate between the three levels of vibrational stimulation, but between off and on state, and in the latter case between low and high. Therefore, the fact that RR(V) has improved with respect to HyVE9 is not very surprising, but the important conclusion is that changing the properties (i.e., stimulation levels) of one modality (V) had a "local" effect only within that specific modality (different RR(V) values, similar RR(E) values). Finally, in hybrid experiment, the following expression approximately held: RR(E,V) = RR(E)*RR(V), i.e. the overall RR is equal to the product of the marginal RRs, which correspond to the property of two independent variables whose joint probability is the product of the marginals. This means that knowing the result of recognition (correct/incorrect) of one modality does not provide information about the success in recognizing the other. Note that this would not hold if, for example, we had a case that one modality was often masking the other. All in all, taking into account the aforementioned results from different tests, we can conclude that even if there is an interaction between different modalities during hybrid stimulation, this interaction is not substantial.

More specifically, we demonstrated that the interaction is limited enough to allow the HyVE interface to achieve more effective transmission of a set of discrete information (messages) compared to the single modality interfaces. Indeed, the RRs, which in this context represent a percent of successfully received messages, achieved for HyVE9 and especially HyVE9Z were high, taking into account that the task of receiving 9 discrete messages was quite challenging. The outcomes from the control conditions (ELE9 and VIB9) demonstrated that, with the single modality stimulations, a person cannot reach such a performance. Importantly, the performance gained with the hybrid interface was obtained by the multimodal coding scheme, while the physical channel (i.e., the area of the skin) through which the messages were transmitted was the same as in the single modality cases. The performance in recognizing the intensity levels of single modality stimulation drops fast when increasing the number of levels, as highlighted for electrotactile stimulation [13] and for pressure levels [38], [39]. The advantage of hybrid stimulation coding is the decrement of the number of levels that the subject needs to recognize per modality but, as disadvantage, the subject has also to discriminate between the two stimuli of different modalities delivered simultaneously and to the same skin location. However, since there is only a limited interaction between the electro- and vibro-tactile stimulations, as demonstrated by the experiments, the overall performance of the hybrid coding is significantly higher. As a future step, it would be interesting to investigate further the characteristics of within- and cross-modality discriminations. For example, a systematic evaluation using tasks with different number of messages could be used to determine the conditions in which the single and hybrid coding result with a similar performance (e.g., coding Y messages using a hybrid interface is equivalent as coding X messages using single modality stimulation). This test would also allow to determine how the performance changes with a removal (as in HyVE9Z) or addition of more intensity levels in one or both modalities within the hybrid stimulus.

The performance during the training also supported the advantage of the hybrid interface. The RR in the reinforced learning phase was not statistically different from the RR in the validation phases of ELE9, VIB9 and HyVE9Z, meaning that the training failed to improve the performance in these three cases. We hypothesize that the reasons for this are very different for the hybrid and single modality conditions. In ELE9 and VIB9 the RR was low, which means that the task was too difficult for the provided (short) training to improve the performance significantly. In HyVE9Z on the other side, the RR was high, implying that the task was easily grasped by the subjects, resulting in a high performance from the beginning, so that the training was not truly needed. Overall, the aforementioned results demonstrated the potential practical utility of the HyVE interface: namely, the stimulation modalities can be combined to obtain a higher success rate in message transmission that could not be reached if the modalities were applied individually (at least not without an extensive training). Importantly this improvement in communication can be obtained without the concomitant increase in physical space, since the stimulators are placed over the same location. In the current experiment, the training was relatively short in order to limit the total duration of the experiment. An important future step is to assess through a longitudinal study how the performance depends on the amount of training the subjects receive, especially if the number of messages to transmit is further increased (e.g., 4x4 = 16 messages).

The performance of the HyVE interface can be tuned in different ways. One method was presented in this study by introducing a zero level for the vibratory modality (HyVE9Z experiment). With the two different modalities comprising a hybrid stimulus, there are more schemes available for information coding compared to a single modality interface. The HyVE9Z demonstrated how this flexibility of the hybrid stimulation can be exploited to improve the transfer of discrete messages through a given area of the skin. Adding a zero level for the electrical stimulation or using mechanical vibrations with a larger dynamic range might increase the RR even above the levels achieved in HyVE9Z. Furthermore, the integration of electrical stimulation with the other types of vibrotactile stimulators (e.g., linear electromagnetic motors such as C2-tactor) could be tested.

From the technical point of view the integration of electrical and vibratory interfaces is feasible. In our experiments, we used two separate real time systems, one for the control of electrical and one for the vibratory stimulation. However, the control electronics is in fact very similar in both cases (e.g., a microcontroller based embedded system) and these devices could be therefore integrated into a single real time system with two output stages. At the same time the concentric electrode and vibration motor could be merged into a single composite element for delivering the hybrid stimulation: a concentric electrode could be implemented at the bottom of a coin type vibration motor. Such integration would facilitate the mounting of a hybrid stimulator into a prosthetic socket.

We did not test for the eventual change of electrode-skin impedance during the experiment. However, the electrodes were made from a light and breathable material. The experiment comprised of several tests of limited duration, and in between the tests the stimulation interface was taken off (i.e., rest periods for the skin). Therefore, the sweating was very limited. Furthermore, we have used a current-controlled stimulator, which means that the quantity of charge injected and thereby the activated cutaneous fibers did not depend on the current impedance of the interface. Also, the stimulation intensity was regulated by using a pulse width modulation, which is claimed to elicit more consistent and stable sensations [41]. Finally, to minimize the influence of this and other uncontrollable and unforeseen factors, we have randomized the order of the tests and also the order to the stimulus presentations.

When transmitting stimulations in a sequence, a previous stimulation could affect the reception of the next one and this likely depends on the time between the stimulations. The goal of this work was to evaluate the quality of transmission of isolated messages using single and dual-modality coding. However, the influence of the inter-stimulation time interval on the HyVE performance should be carefully investigated in the future work, since this parameter can impose an upper limit to the overall speed of communication (messages/s).

After the experiments, our subjects reported that there were qualitative differences in the sensations that were generated by vibrotactile and electrotactile stimulations. Importantly, we did not systematically record nor evaluate the subjective quality of the elicited sensations in the current experiment, since that was outside the scope of the current work. The following observations therefore have an anecdotal character. Vibrotactile stimulation was felt over a broad area and also deeper into the forearm. Low level electrotactile stimulation evoked a sensation, similar to a pressure, which was felt by most of the subjects as being localized on the very surface of the skin, whereas for higher stimulation levels the evoked sensation seemed spreading to a larger area and was felt as a deeper sensation. For several subjects, a referred tingling sensation at the wrist was evoked at the higher electrical stimulation levels (i.e., ME and HE). This is likely due to the different receptors that are activated by the electro- and vibro-tactile stimulations, as indicated in the Introduction: Pacinian corpuscles sensitive to vibrations are deep into the skin and have a large receptive field. The electrical stimulation first activates superficial cutaneous afferents. With increasing intensity, an increasing number of superficial and also some deeper fibers are recruited. In several cases, the electrical current pulses reached and activated a sensory nerve eliciting the referred sensations. In our experience from the experiments, the appearance, extent and quality of the referred sensations depend on the current intensity and individual anatomy. A further analysis of the impact of electrode positioning and referred sensations on the discrimination of the modalities within the hybrid stimulus could be used to fine-tune the placement of the HyVE in order to maximize its effectiveness.

For the current tests, we have used a single frequency of electrical stimulation which was identified as a reasonably good choice through the relatively brief pilot experiments. One of the future steps is to systematically investigate the effect of stimulation frequency on HyVE performance relevant for practical application (i.e., two information streams discrimination and discrete message transmission). In addition, from the point of view of basic neurophysiology but also for the further understanding of hybrid stimulation and its fine tuning, it would be interesting to explore how the stimulation parameters and modalities determine the receptors that are actually activated using the hybrid interface.

The results of this work are very promising, suggesting that healthy subjects are able to perceive simultaneous dual-modality information through the same physical location. Furthermore, in a difficult task with many messages to communicate to the user, the HyVE resulted with much better performance compared to the conventional, single modality stimulation. This study focused on the transfer of discrete information through a hybrid interface. The next step will be to test if subjects can receive continuously changing signals and also to which extent they can use these signals to control a dynamical system. This scenario could be of particular interest for the application of the HyVE within the context of human manual control [42], in which the task of the human operator is to steer a dynamical system (e.g., simulation, robot, vehicle) while the feedback about the system state is provided via the tactile stimulation [43].

In a hand prosthesis, dual modality stimulation could be useful for providing both touch and slip information; this could be an especially convenient context for the application of the hybrid interface since the information coming from the same location of the hand (touch and slip occurring on the same finger) would be delivered to the same target site on the skin of the residual limb. In addition, the HyVE could be also employed to deliver two unrelated information (e.g. touch/force from two different fingers) through the same location on the skin, thus saving space on the residual limb and socket. To test the assumption about the applicability of the HyVE for sensory feedback in upper limb prosthetics, the next step is to implement the HyVE with a real hand prosthesis and conduct a study evaluating the closed loop system during a functional task. This development is currently in progress.

As described in Introduction, electro- and vibro-tactile devices were tested in the past for providing sensory feedback in hand/arm prostheses. Different solutions and single/multi-channel configurations were proposed but none have been widely adopted (e.g., commercial applications). This might be due to many different reasons; it could be related to the subjective experience of the users (e.g., acceptance and preferences), or technological and implementation constraints. As an integration of the two existing interfaces, the HyVE could face the same obstacles as the previous single modality implementations considering that it does not represent a radically different technological solution. However, the HyVE combines the two interfaces in a specific way (shared time and space) and this improves the compactness and information transfer rate.

The main finding of this paper, i.e., the advantage of hybrid with respect to single modality stimulation, has a rather general extent and applicability. A multimodal interface with a small form factor such as the HyVE could be useful for many portable systems providing haptic feedback, for example, rehabilitation systems, navigation guidance for blind people, video game controllers etc. At the even more basic level, the integration of the mechanical and electrical stimulation is itself a general idea that could be exploited in many ways. Different forms of electrical stimulation (e.g., pulses, interferential currents) could be combined with mechanical stimulation methods (e.g., indentation, rotation, stretching) to elicit simultaneous in time and space multimodal tactile stimulation, which could have advantages with respect to applying the modalities individually. Some advantages were demonstrated in this initial work and the others are yet to be investigated, such as the possibility to use different modalities to target particular receptors and thereby elicit specific sensory experiences. All in all, there are many promising hybrid combinations yet to be explored and the initial findings in this paper could stimulate the further research into this topic.

APPENDIX

TABLE AI
LIST OF ACRONYMS

Acronym	Meaning
RR	Recognition rate
RE	Reference stimulus
JND	Just noticeable difference, i.e., a minimal difference in PW with respect to the RE that can be perceived by a subject
PW	Pulse width of electrical stimulation
ST	Sensation threshold, i.e., the lowest PW of an electrical stimuli that can be perceived by a subject
PT	Pain threshold, i.e., the lowest PW of an electrical stimuli that elicits a painful sensation
LE	Low electrical stimulation
ME	Medium electrical stimulation
HE	High electrical stimulation
ZV	Zero vibration (no vibration)
LV	Low vibrotactile stimulation
MV	Medium vibrotactile stimulation
HV	High vibrotactile stimulation

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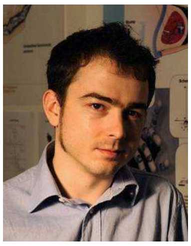

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