Artificial redirection of sensation from prosthetic fingers to the phantom hand map on transradial amputees: vibrotactile versus mechanotactile sensory feedback

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Abstract[1]— This work assesses the ability by transradial amputees to discriminate multi-site tactile stimuli in sensory discrimination tasks. It compares different sensory feedback modalities using an artificial hand prosthesis in: (i) a modality matched paradigm where pressure recorded on the five fingertips of the hand was fed back as pressure stimulation on five target points on the residual limb; and (ii) a modality mismatched paradigm where the pressures were transformed into mechanical vibrations and fed back. Eight transradial amputees took part in the study and were divided in two groups based on the integrity of their phantom map; group A had a complete phantom map in the residual limb whereas group B had an incomplete or non-existent map. The ability in localizing stimuli was compared with that of ten healthy subjects using the vibration feedback and eleven healthy subjects using the pressure feedback (in a previous study), on their forearms, in similar experiments. Results demonstrate that pressure stimulation surpassed vibrotactile stimulation in multi-site sensory feedback discrimination. Furthermore, we demonstrate that subjects with a detailed phantom map had the best discrimination performance and even surpassed healthy participants for both feedback paradigms whereas group B had the worst performance overall. Finally, we show that placement of feedback devices on a complete phantom map improves multi-site sensory feedback discrimination, independently of the feedback modality.

Index Terms— Prosthetic hand, sensory feedback, transradial amputee.

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I. INTRODUCTION

TACTILE sensory feedback stems from the stimulation and activation of mechanoreceptors in the skin and is crucial for motor control. In humans the interaction between sensory and motor functions is particularly evident within the hand: even simple manipulation tasks, such as a power grasp, require sophisticated control engaging large areas of the brain [1]. Humans need almost a decade of daily practice before they master this apparently simple sensorimotor task; indeed the coordinated lifting patterns observed in adults are not achieved in humans until 8-10 years of age [2], [3]. Sensory feedback is also fundamental in eliciting self-attribution of a body part, due to multi-sensory integration mechanisms taking place in the premotor cortex, [4]. The lack of sensory feedback from a body part can even lead to effects where it is no longer perceived as part of the body [5].

For amputees the situation is different; a person who has lost a limb suffers loss of both motor and sensory function and it is the replacement of this sensory function that is the focus of this work. In modern myoelectric prostheses, although a certain level of dexterity is restored by means of motorized components (e.g. hand, wrist, elbow) and close-to-natural control [6], no somatic sensory feedback is intentionally provided to the amputee. Users mostly rely on visual feedback when operating the prosthesis, and the lack of extended tactile feedback is frequently invoked as one of the reasons for their rejection [7].

Having force sensors in the fingertips of the prosthesis and providing physiologically- and timely- relevant feedback stimuli through a suitable man-machine interface could regain complete functionality of the hand, and hence could reduce the abandonment ratio. Nevertheless, providing such feedback is challenging because of the lack of connections from the artificial hand to the neural / physiological channels that served the missing hand. In theory, there are two ways to replace the afferent pathway in amputees: (i) invasively, by interfacing directly to neural structures normally involved in

the control (like the peripheral nerves [8]) or (ii) non-invasively, by providing feedback to intact sensory systems normally not involved in the task (e.g., tactile stimuli on the residual limb). In both cases the subject should be trained to associate stimuli to events occurring to the artificial hand and fingertips.

Among the non-invasive methods, the most investigated stimulation techniques have been electrotactile, vibrotactile or mechanotactile. Electrotactile feedback (also termed electrocutaneous) is induced by a current that flows through the skin [9]; this principle was pioneered by Beeker et al. [10], Rohland [11], Shannon [12]. Recently it was exploited in the Yokoi Hand [13] to deliver grip force feedback on a single skin-site, and by Geng et al. [14] to investigate the effects of different patterns on the perception threshold. Conversely, vibrotactile stimulation is evoked by a mechanical vibration of the skin, typically at frequencies in the range of 10–500 Hz [9]. Afferent biofeedback based on this principle, has been investigated for the last decades because of its non-invasive nature that promises higher acceptability compared to electrotactile stimulation [9], [15]. Recent examples include, robotic prostheses [16], [17] or robotic interfaces [18] that were connected and tested with single-site vibrotactile systems representing the grip force, in order to investigate and assess parameters of vibrotactile stimulation during object grasping. Among these, Saunders and Vijayakumar [19] used a multi-site vibrotactile array where the grip force of a prosthetic hand was translated into a stimulation location. In broad terms, haptic devices are man-machine interfaces able to reproduce tactile parameters, such as e.g. touch, pressure, vibration, temperature etc. The main advantage of these, when properly designed, is that they can deliver modality matched sensory feedback. Mechanotactile displays are a particular class of haptic devices that can display pressure on body sites as a representation of pressure sensed on the prosthesis. In the recent years, small sized, haptic devices have been developed and successfully tested on transradial amputees [20], and on shoulder disarticulation amputees that underwent the targeted muscle reinnervation procedure [21], [22].

Comparison studies among sensory feedback approaches were conducted by Shannon [15] who investigated the differences between the vibrotactile and electrotactile methods, and by Patterson and Katz [23] that compared vibrotactile stimulation against a haptic pressure cuff able to display pressure on the arm. The latter study showed that the combination of vision-pressure yielded to better results with respect to the combination of vision-vibration (although this result was not statistically assessed). Both the aforementioned studies were not carried out with the potential target users (i.e. amputees) but on able-bodied subjects; additionally, the sensory feedback systems used displayed compound afferent information (the grip force) on a single body-site. As multi-digit hands are becoming the reality [24]-[26], a multi-site approach in which force from each artificial finger is redirected to physiological channels that served the missing

hand, represents a natural way of providing intuitive sensory feedback to the user.

Many transradial amputees experience tactile phantom sensations when their residual limb is touched. Imaging studies by Vilayanur Ramachandran showed that these sensations are due to rearrangement of cortical circuits occurring in the first hours after amputation [27]. Ramachandran has called this *remapping of referred sensations* (also known as *referred phantom sensations*) [28]. In these cases, by transferring the information from sensors in the fingers of a prosthetic hand to specific locations on the skin, fingers of the phantom hand can be stimulated. The objective underlying such a method is to provide a physiological and natural feedback and thus to make the prosthesis being felt as a part of the body scheme, as proposed by Ehrsson et al. [29].

In this work we investigated the spatial perception by eight transradial amputees to stimuli delivered by a multi-site vibrotactile (VT) or a multi-site mechanotactile (MT) display applied on specific spots on their residual limb. The MT display used a modality matched paradigm where pressures on the fingertips of the prosthesis were delivered as pressure on the skin, whereas the VT display translated the pressures on the fingertips into vibration cues (sensory substitution). Three of the amputees had distinct referred phantom sensations from all five phantom fingers: for these subjects, the VT or MT actuators were directly applied onto the phantom finger mapping sites. The other five participants had no or only partial sensations from at most two phantom fingers: in such cases the VT and MT actuators were placed upon the phantom map to the extent possible. A robotic hand prosthesis was worn by the amputees' on their residual limb (in an anatomically correct setup) using a customized socket and sensation from the robot hand was redirected to the phantom fingers/residual limb sites using the tactile displays. Hence this work addressed -for the first time- the accuracy in multi-site, spatial discrimination with regard to VT and MT stimuli, delivered on the residual limb of transradial amputees watching and wearing a prosthesis equipped with pressure sensors.

Sensing of vibration is affected by a number of factors, the most important being contact pressure and mechanical impedance of the skin, that makes the vibration propagate to nearby regions. Considering such issues, and that the points identified on the residual limbs could range from a part with very little muscle tissue to a part that was dominantly muscle tissue, we hypothesized that multi-site feedback provided on the residual limb by the VT display would be harder to discriminate than that by the MT display. We also hypothesized that due to the cortical reorganization yielding referred phantom sensations, and to the experimental setup with the physical hand, subjects with a complete phantom map would demonstrate significant ability in discriminating multi-site stimuli with both displays, and greater than the subjects with limited or inexistent map. In order to further assess such hypothesis, i.e. remarkable discrimination ability by subjects with a complete map, a comparison with healthy individuals

TABLE I
DEMOGRAPHIC DATA OF PARTICIPANTS

Participant ID	Cause	Time since amputation (years)	Amputated side (residual limb length)	Phantom mapping of fingers (group)	Prosthesis used
P1 (m, 25)	Tumor	3	Right (17 cm)	I-V (A)	Myoelectric hook
P2 (f, 36)	Trauma	7	Right (15 cm)	V (B)	Myoelectric hand
P3 (f, 36)	Trauma	3	Right (18 cm)	I,V (B)	Myoelectric hand
P4 (m, 40)	Trauma	25	Left (11 cm)	I-V (A)	Myoelectric hand
P5 (m, 50)	Trauma	13	Right (21 cm)	I (B)	Cosmetic hand
P6 (m, 56)	Bacteria	9	Bilateral (28 cm)	- (B)	Myoelectric hand
P7 (m, 38)	Trauma	25	Right (12 cm)	I-V (A)	Cosmetic hand
P8 (f, 25)	Congenital	-	Left (11 cm)	- (-)	Myoelectric hand

was undertaken, performing similar experiments.

II. METHODS

A. Participants

Eight volunteers (P1..P8, cf. Table 1) took part in this study (5 males and 3 females; aged between 25 and 56 years). They were healthy with the sole exception being that they all had one upper limb amputated at transradial level (see clinical data in Table 1). Five had had their right arm amputated, two their left one, and one had a bilateral amputation. Five had their amputation after a traumatic accident, whereas two had undergone surgery to remove tumors or treat a bacterial infection; one participant had a congenital failure of formation.

The participants were recruited by phone, from a list of upper-limb amputees at Skåne University Hospital, mostly residing in the southern part of Sweden. The other inclusion criteria were not taking any medication, and that they were using a prosthesis (any kind) at least 4–8 h daily for 5–7 days per week. As this was a relatively unselected group of amputees, the time after amputation, referred phantom sensations, and daily prosthetic usage were factors that all varied greatly in the group.

Before the experiments started, participants were interviewed to establish the referred phantom sensation on the residual limb. The patients were asked if they felt that their fingers were being touched when different parts of the residual limb was touched. Each patient was then asked to touch their residual limb and define the referred phantom fingers (divided into digits I–V). Thereafter, custom prosthetic sockets molded on the residual limb of each participant with holes for accessing the phantom finger sites were manufactured. Three participants (P1, P4, P7) had distinct phantom sensations from all five phantom fingers (hereafter referred as participants in group A). Four remaining participants (P2, P3, P5, P6, hereafter group B) had no referred phantom sensations or only partial sensations from at most two phantom fingers. The only participant with congenital failure of formation (P8) had no phantom sensations; since her body representation had never included the missing hand she was not included into the previous groups. For participants in group B and subject P8, the accessing holes in the socket were placed on the existent phantom fingers, or on distal residual limb regions allowed by the technical setup if no phantom-finger sensations were felt.

B. Multi-site mechanotactile display (MT)

The mechanotactile display (MT) consisted of five actuators (as the number of fingers on a hand) to be placed on the amputee's residual limb (cf. Fig. 1 A) and controlled by an electronic board, providing tactile/pressure sensory feedback. The actuators were digital servo motors (Graupner DS281, Germany, shown in Fig. 1 C) with 12 mm diameter plastic buttons affixed at the end of their 15 mm long motor shaft levers. The plastic button was always parallel to the skin, and as the motor rotated, it caused a displacement of the skin by pressing against it. In this study, although the actuators were capable of providing different force levels, only *on/off* stimulations were used to provide the same and repeatable level of stimulation for each site and trial. The *off* condition consisted in a light touch (contact) of the actuator on the skin-site where it was placed, whereas the *on* condition consisted in a contact force in the range of 2 N (button pressure: 17 mN/mm^2). This force/pressure value was selected as it is above the touch threshold [30], and it was found to be easily perceivable on the forearm in preliminary tests [20], [31]. The time required to reach the target of 2N was around 130 ms (cf. Fig. 2). A detailed description of the MT display can be found in [31].

C. Multi-site vibrotactile display (VT)

Vibrotactile feedback was selected as the mismatched modality feedback due to higher acceptability compared to electrotactile stimulation, ease of use, and safety issues [9]. The VT display [32] consisted of five miniaturized vibrators (Precision Microdrives, UK) (8 mm diameter, 3.4 mm height, 0.7 g weight, shown in Fig. 1B) for which vibration frequency was modulated and controlled by an electronic board, that was in turn connected to a PC and to the artificial hand. Like the MT display this system provided a digital output: either no vibration (off condition) or a 0.36 N amplitude vibration at 165 Hz, as shown in Fig. 2. This stimulation amplitude is so large (much greater than the discrimination amplitude threshold in humans at each given frequency [9]) that is clearly and easily perceivable when applied on sensory-functional body sites. The time required to the vibration to reach its steady state was around 300 ms. A detailed description of the vibrotactile display can be found in [32].
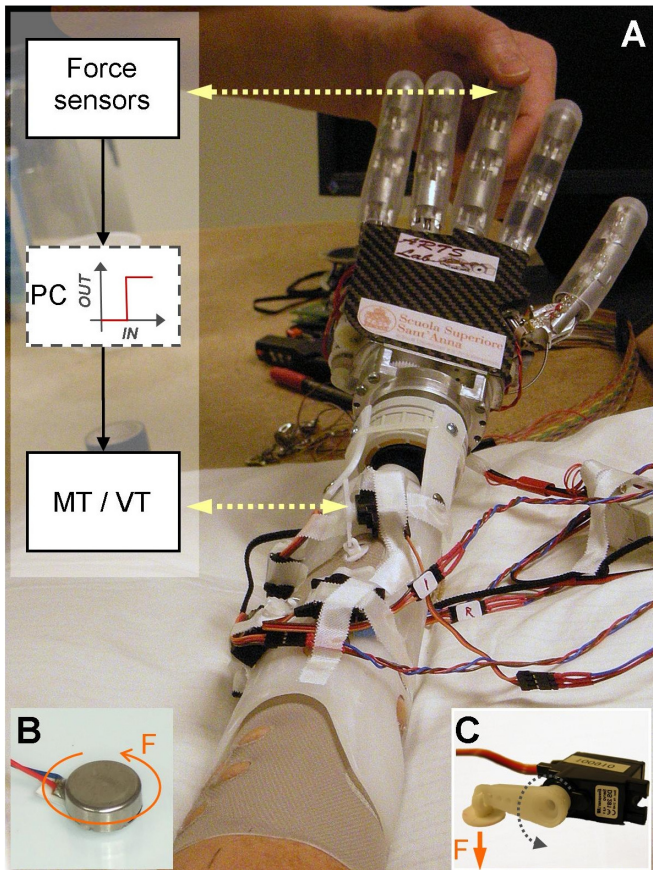
Fig. 1. Technical setup. A) The picture –showing the experimental setup during the mechanotactile experiments - is taken from next to the right shoulder; it shows that the hand was in full view and in anatomically correct position from the participant's perspective. The blocks on the left present the simple architecture: force sensors from the fingers are connected to the Personal Computer (PC, not shown in the picture) that implements a simple threshold technique and in turn controls the MT or the VT. B) Vibrotactile stimulator; the arrow shows the rotation of the vibrator shaft, hence the shear plane on which force F is produced. C) Mechanotactile stimulator: the rotation of the lever shaft (dotted circular arrow) produces a normal force F onto the skin.

D. The artificial hand

The SmartHand research-prosthesis was used in this study [24]. The hand had five anthropomorphic fingers designed to accurately replicate both the appearance (shape and size) and the dynamics of the natural hand as reported by Cipriani et al. [24]. Although the hand was actuated by 4 electrical motors that allowed several degrees of freedom, in this study the fingers were kept in fixed position and only passively manipulated by the experiment leader, in order to produce a force feedback cue. In particular, the force sensors within the fingers were used to generate the feedback signals through the haptic displays. A simple threshold technique on the force sensor signals was applied to generate the afferent cue (trigger) each time one of the five artificial fingers was extended (pushed) by the experiment leader (approximate force around 2 N) (cf. Fig. 1 and Fig. 2 C). The hand and each display at a time were connected to the host PC through a standard RS232 serial cable. A detailed description of the SmartHand can be found in [24].
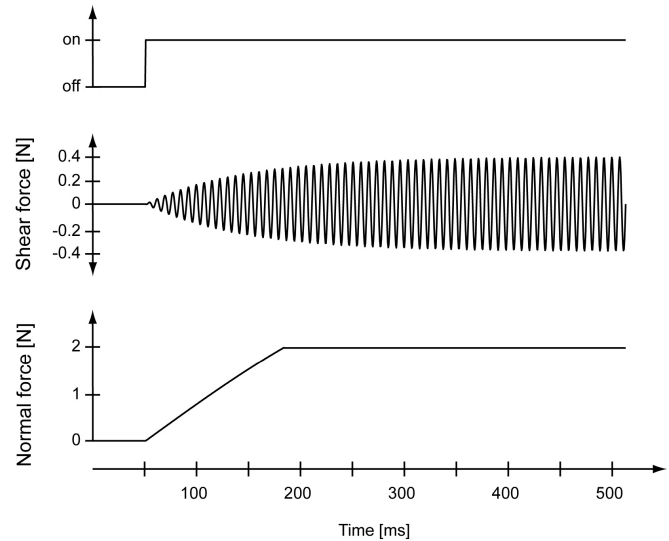

Fig. 2. Shear force amplitude generated in the "on" condition by each vibrator of the vibrotactile display and normal force created by each stimulator of the mechanotactile display used in this study.

III. EXPERIMENTAL SETUP AND PROCEDURE

The comparison between the two stimulation modalities was made with regard to localization discrimination, that is, the ability to selectively perceive which part of the residual limb is stimulated.

The experiment was divided in two parts: one using the MT display and one using the VT display. Half of the group started the tests with the VT display and the other half with the MT display, to avoid any learning bias in the results that would potentially arise from using one of the systems before the other. Each of the sensory feedback systems was placed upon the phantom map of the participants to the extent possible, through the holes in the socket (cf. Fig. 3 A-C). Each of the five stimulators was virtually wired to the corresponding force sensor of one of the five finger force sensors of the hand, and therefore redirected force information from the artificial hand to the phantom fingers (for group A) or target sites on the residual limb (group B).

The hand and the sensory feedback systems were embedded in the prosthetic socket worn by the participants; throughout the experiment, they were sitting on a chair with their artificial arm in a supine position placed on a cushion (as shown in Fig. 3 C). Hence, with this setup from the perspective of the participant the hand looked like a part of their own body, and was likely to generate a strong "feeling of body ownership" of the prosthesis itself, as previously demonstrated [33]. Because we had only a right-hand prosthesis we had to use a mirror to create a reflection of it on the left side for the two left-hand amputees. A mirror was therefore placed obliquely in front of the subject so that the right-hand prosthesis was reflected and visually superimposed as close as possible to the residual limb.

The experimental task was to discriminate the location of the stimulus across the five fingers spots (I..V). The experiment consisted of three phases. In the first phase the participants got acquainted with the system: the experiment
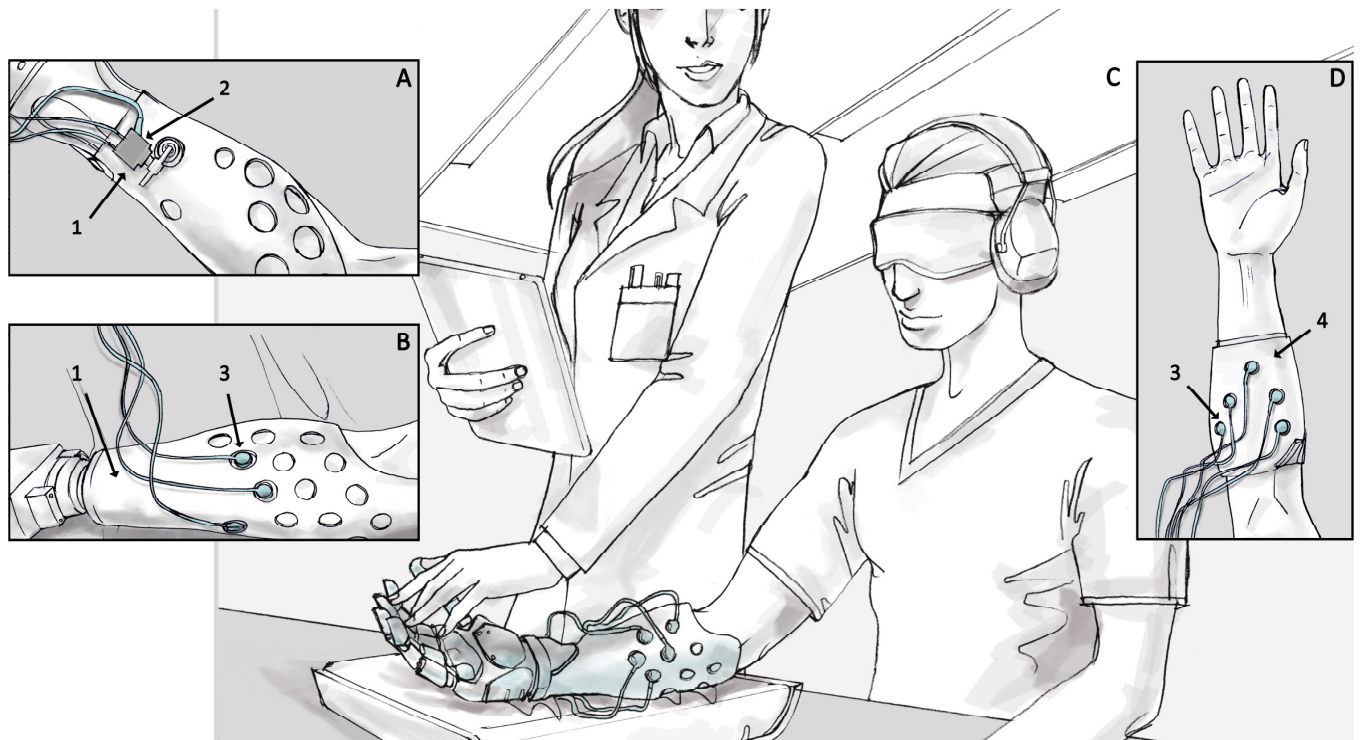
Fig. 3. A) Representative placement on amputee's residual limb of one of the mechanotactile stimulators (2) in the holes of the customized socket (1). B) Representative placement of a vibrotactile stimulator (3) in the holes of the customized socket (1). C) Experimental setup while subject was wearing earmuffs and blindfolded (during the reinforced learning and evaluation sessions). The feedback systems were held on the socket by means of an elastic bandage (not shown); during the whole experiment the subject kept his/her residual limb in a supine position on the table. D) Representative placement on healthy subject's forearm of vibrotactile stimulators (3) within the holes of the rigid mask that mimicked the socket (4). This setup was evaluated with non-amputees.

leader pushed on a finger of the hand and the corresponding site on the phantom map got stimulated (duration of the stimulation: 2 s). The second phase was a reinforced learning session in which participants were blindfolded: after the presentation of each stimulus, the participant verbally indicated the stimulation site, and then, the experiment leader stated the correct answer, hence reinforcing the learning. In the first two phases, 50 stimulations, randomized across the fingers, were delivered. The third and final phase was identical to the second phase, albeit without any verbal feedback and with just 25 randomized stimulations (evaluation session). Overall the three phases lasted approximately 30 minutes for either kinds of display. The experimental setup during the reinforced learning and evaluation session is depicted in Fig. 3 C.

All participants gave their consent and the experiments were conducted in accordance with the Helsinki declaration. The local ethic committee of Lund University approved the study.

A. Experiments with healthy subjects

To better understand the localization perception of vibrotactile stimuli, we performed equivalent experiments with a control group composed of ten non-amputees (7 men, 3 women, mean age 29±4 years, hereafter group C). For each of the participants, the VT display was placed in the same way using a rigid plastic mask, with the 5 vibrators of the display forming a U-shape, roughly reflecting the position of the fingers of an open hand (cf. Fig. 3 D). Vibrators were placed with an inter-distance of approximately 4 cm, corresponding to the two-point discrimination thresholds of the forearm [34]. The plastic mask, which was firmly placed on the right forearm, was used to mimic the pressure conditions of the prosthetic socket worn by amputees, i.e. to block the propagation of the vibration through the surface of the skin. Group C participants were seated at a table in front of a computer screen running a PC application, with their tested arm on the table resting comfortably in a supine position. The PC application controlled the VT display and was used by the experiment leader to generate the stimuli. The computer screen displayed a virtual hand showing which of the five fingers was stimulated synchronously: the experimental procedure was the same as for the group of amputees: 50 randomized stimulations in the learning session (participant watching the screen), 50 randomized stimulations during the reinforced learning session (participant blindfolded), and 25 randomized stimulations in the evaluation session (participant blindfolded).

Finally, for a comprehensive comparison with healthy subjects, we report in this paper results from equivalent experiments carried out by our group and published elsewhere [35]. The latter focused on the localization discrimination by young healthy subjects (11 participants, 8 men, 3 women, mean age 30±4 years, hereafter *group D*), of stimuli delivered by the present MT display on their forearms. The experimental procedure was identical except for the numbers of stimulations: 75 in the learning and reinforced learning sessions, and 50 during the evaluation session.

IV. RESULTS

This section will principally report the five-site discrimination results by different groups of amputees and the results achieved by the unimpaired in the equivalent experiments, for the sake of comparison.

The graph in Fig. 4 shows the performance (correct discrimination) by each of the amputees during reinforced learning (R), and evaluation (E) sessions, employing the mechanotactile (MT) or vibrotactile (VT) system. The graph reveals four main results:

1. There was no statistically significant difference between the reinforced learning and evaluation sessions within each system at the individual level (Wilcoxon signed-rank test for each subject using each system: p-value > 0.05). For this reason, the following description and discussion is based on the results achieved during the evaluation sessions (i.e. the most significant).

2. There was no statistically significant difference between the MT and the VT display at the individual level (Wilcoxon signed-rank test between evaluation session results, for each subject: p-value > 0.05). In other words, for each subject, if the performance was good using the mechanotactile display, it was also good using the vibrotactile display.

3. As hypothesized, the spatial discrimination accuracy achieved with the MT system, always outperformed the VT setup.

4. As hypothesized, the performance was related to the participants' group; in particular, subjects belonging to *group A* (P1, P4, and P7) achieved 100% accuracy employing the MT system and 91% using the VT system; conversely participants in *group B* achieved average accuracies below 61% (MT) and 49% (VT). Subject P8 demonstrated a great ability in both the MT (average 98%) and the VT (average 81%) systems.

A. Group Analysis

Although the groups were very small (3 or 4 amputees), and a statistical analysis of the results would not be relevant, it is interesting to observe the raw-data at group level: the graph in Fig. 5 shows the mean (± stand. dev.) discrimination accuracies. As hypothesized, there were considerable differences between the accuracies with both the mechanotactile (*group A* 100% vs. *group B* 61%) and the vibrotactile system (*group A* 91% vs. *group B* 49%). Conversely, small differences were found within each group across the two systems. These results show that all subjects, either belonging to *group A* or *group B*, achieved similar results regardless of the feedback system being used. Importantly, placement of feedback devices on a complete phantom map improves multi-site sensory feedback discrimination, independently of the feedback modality. The performance of *P8*, the participant with congenital failure of formation is closer to *group A* than to *group B*.

The graph in Fig. 5 also shows the results from healthy subjects (group C and group D [39]). These demonstrate that there was no statistical difference in five-site discrimination between MT or VT stimuli, in healthy subjects (Wilcoxon signed-rank test p value = 0.158). It is worth noting that compared to amputees with phantom finger mapping (group A) the ability of the unimpaired is (around 20%) reduced using both systems.

The confusion matrices in Fig. 6 (indicating using a grey colored scale which site/phantom finger site was confused with which) show the results from the amputees during the evaluation sessions. When misclassified, sites were primarily confused with adjacent ones with both systems. The vibrotactile stimuli were, on average, harder to localize than mechanotactile ones (more diffused misclassification). This was especially true for group B, for which judgment errors were greater than group A (and than the patient with congenital failure of formation), and greater (and more distributed) with the VT compared to the MT display.
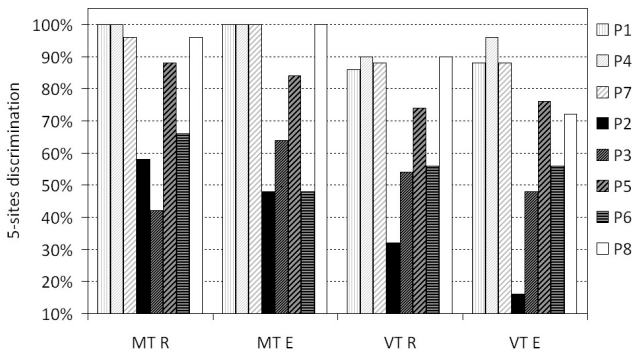

Fig. 4. Five-sites discrimination accuracy for each subject and experimental session (R: reinforced learning; E: evaluation) with the mechanotactile (MT) and vibrotactile (VT) system. The dark and light coloration of the bars highlights subjects belonging to different groups.
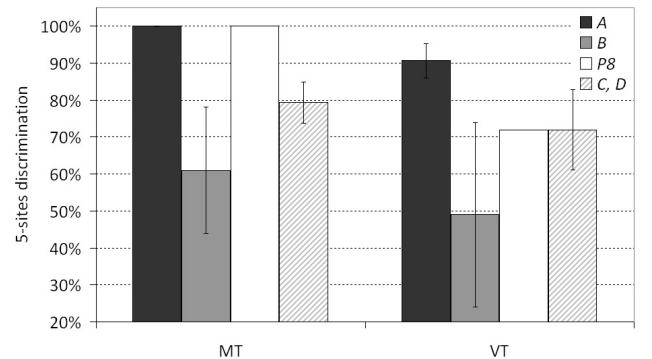

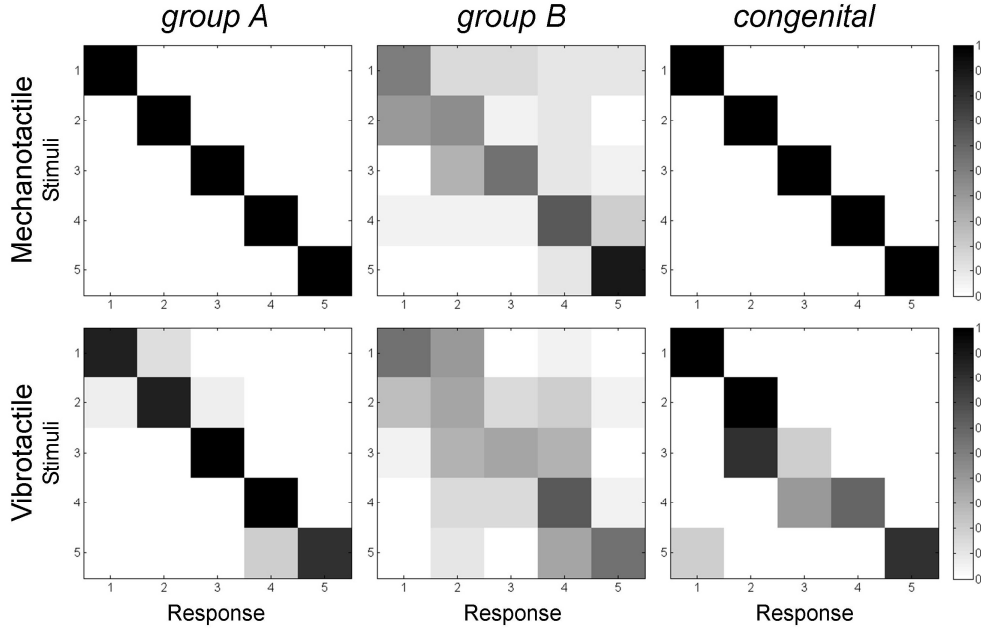Fig. 5. Mean five-site discrimination percentage for each group (amputees: A, B; non-amputees: C, D) and P8.

Fig. 6. Confusion matrices describing the results from tactile and vibrotactile systems for each group (A and B) and the congenital amputee.

B. Residual limb site analysis

Table 2 shows the detailed performance from each amputee comparing the two systems during the evaluation phases. The table indicates, using a 6-grade grey colored scale, how well the subject perceived the stimuli on the five spots identified on the residual limb (white 0 %; black 100%). We recall that for participants belonging to group A these spots corresponded to the referred phantom digits I..V (referred phantom fingers are marked with an "x" in the first row). The second row denotes the accuracies with the MT system, whereas the third row denotes those with the VT system. The table highlights, also at the spot-level, a clear separation between the groups: the coloration for P2, P3, P5 and P6 –group B– is lighter than that of P1, P4, and P7 –group A–. In general (as a consequence of the overall subjective results described above), the accuracy is worse when using the vibrotactile system (the coloration of VT row is lighter than the MT one). Additionally, the table demonstrates great variability in digit-accuracy within subjects in group B: e.g. although subject P5 correctly discriminated among the five sites (tactile: 84 %; vibrotactile: 76 %), he poorly perceived stimuli on spot no. III (i.e. tactile: 60 %; vibrotactile: 20 %). As an opposite example, P6 poorly perceived stimuli on all spots except for no. V. The spots that corresponded to the referred phantom fingers of group B (i.e. P2-V; P3-I,V; P5-I) were on the average worse perceived

compared to those of group A with both stimuli. The numbers involved in the analysis at site level prevent the computation of meaningful statistics. Nevertheless, it is interesting to note that especially for group A the differences in discriminating MT or VT stimuli were very small. In other words, the results suggest that if a residual limb-spot on the phantom finger map (group A) is able to convey perceivable artificial tactile stimuli (like touch and pressure), it is likely to convey perceivable vibration stimuli as well, although with reduced performance.

V. DISCUSSION

The results of this study support similar works on multi-site discrimination (e.g. [31], [32]), and the hypothesis that using (i) perceivable values for the stimuli (above the threshold: 17 mN/mm2 pressure, or 0.36 N amplitude vibration at 165 Hz), and (ii) distances greater than the two-point detection threshold, VT stimulation is harder to discriminate than MT stimulation, when delivered on the hairy skin of the forearm. This is shown with amputees experiencing well-defined referred phantom sensations, with amputees not experiencing phantom fingers, in our single amputee with congenital failure of formation, and with healthy subjects. Pacinian corpuscles (the mechanoreceptors mainly firing in the frequency range of the VT stimulator, i.e. around 165 Hz) have large receptive fields with spatial acuity coarser than that of Merkel's disks

TABLE II
ACCURACY IN THE EVALUATION SESSION FOR EACH SUBJECT FOR THE TACTILE (MT) OR VIBROTACTILE (VT) DISPLAY. THE SIGN "X" INDICATES PHANTOM FINGERS.

	P1					P4					P7					P2					P3					P5					P6					P8				
	I	II	III	IV	V	I	II	III	IV	V	I	II	III	IV	V	I	II	III	IV	V	I	II	III	IV	V	I	II	III	IV	V	I	II	III	IV	V	I	II	III	IV	V
	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X					X	X				X	X														
MT	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	0,0	0,0	0,8	0,6	1,0	0,8	0,8	0,4	0,4	0,8	0,8	0,8	0,6	1,0	1,0	0,4	0,2	0,4	0,6	0,8	1,0	1,0	1,0	1,0	1,0
VT	0,8	0,8	1,0	1,0	0,8	1,0	0,8	1,0	1,0	1,0	0,8	1,0	1,0	1,0	0,6	0,2	0,0	0,4	0,2	0,0	0,4	0,4	0,4	0,8	0,4	1,0	0,8	0,2	0,8	1,0	0,6	0,2	0,4	0,8	0,8	1,0	1,0	0,2	0,6	0,8

(i.e. those responding to pressure stimulation, i.e. to the MT display) [36], [37]; this probably explains the differences between the two methods. Patterson and Katz [23] suggested that modality matched feedback reduces errors in the grip-force control of a robotic hand with respect to vibrotactile feedback; our study extends theirs and demonstrates that the modality matched paradigm surpasses the modality mismatched paradigm for multi-site sensory feedback discrimination.

This study also confirms the hypothesis for group A: the capability of recognition for this group was radically better with respect to group B and to the healthy subjects. This was true not only for the MT system (that stimulated receptors with focused receptive fields), but also for the VT system (targeting receptors with large receptive fields). Since subjects in group A have a well-defined phantom hand in the residual limb when a phantom finger is stimulated, no matter if the stimulus is vibration or pressure, information reaches cortical tissue that used to process information from the missing hand. The results show how the cortical reorganization yielding referred phantom sensations is pervasive and stable: although the perception of vibrotactile stimuli depends on a number of factors including fat/muscle tissues, and –importantly– density of mechanoreceptors and spatial acuity, referred phantom digits elicited vibration sensations that were clearly distinguishable (discrimination performance by group A: 91%). It should be noted that receptor density (hence accuracy of localization and spatial resolution) in the forearm is far reduced compared to the hand/fingertips [30].

The results achieved by subjects of *group A* in discriminating vibrotactile stimuli, suggest that the sensory system present within the hairy skin of the forearm is naturally capable of discriminating spatially distributed tactile stimuli to a degree of accuracy significantly higher than normal/sound limbs. The tactile discrimination capacity shows up in the cases where referred phantom sensations occur after the amputation. In fact, it is unlikely that new mechanoreceptors develop or get innervated after the surgery, and hence, one possible explanation for the ability by amputees (*group A*) might be due to brain plasticity, long term integration into the body scheme, of already present (available) mechanoreceptors. This hypothesis is in agreement with the work by Cholewiak et al. [38] that showed that mechanoreceptors in the forearm decrease with age, but the ability to discriminate vibrotactile stimuli is maintained. Both studies highlight that higher order brain processes are of importance to compensate for the reduction of mechanoreceptors, or for the loss of a hand [26], [29].

Group B gained a lower recognition ratio with respect to group A but also with respect to the healthy subjects (groups C and D). While the difference in performance between group A and group B seems clear (i.e. the latter had reduced or no referred phantom sensation), the differences between group B and groups C-D (for which the experiments were not more than a forearm-stimulation learning task) can only be hypothesized. A possible explanation for the poor performance of group B might be related to the trauma in the residual limb that caused a generally limited perception of touch [39]. The congenital amputee with no phantom map and no injured residual limb gained a recognition performance similar to that of healthy subjects.

The results of this study have important implications for the prosthetics field; they highlight the importance of mechanotactile sensory feedback in future prostheses, and they provide a demonstration of a high capability of spatial localization of a stimuli in amputees with a complete phantom hand map, independent of the modality of stimulation. For a partial or absent phantom hand map the perception of tactile information is more difficult. However, by selecting sensitive areas in the residual limb and by training these patients to perceive the stimulus as coming from the prosthesis, it might be possible to obtain an acceptable discrimination level. In future studies it would be of interest to evaluate combinations of both intensity and spatial information while using the prosthesis in activities of daily living. In addition, the results show the possibility of incorporating sensory feedback in an artificial limb using small tactile actuators embedded in the prosthetic socket and placed on referred phantom fingers. Since transradial sockets are usually suspended on condyles and hence display a firm fit, positioning shifts of the feedback devices with regard to the targeted sites, should be negligible. Finally, it is interesting to observe that such feedback has a potential to induce a sensation of body-ownership of the prosthesis by the amputee.

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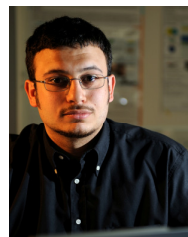
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