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# Vibrotactile Sensory Substitution in Multi-fingered Hand Prostheses: Evaluation Studies

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*Abstract*— **This paper presents a vibrotactile sensory substitution system that could be used to deliver sensory feedback to transradial amputees wearing a myoelectric hand prosthesis. The novelty is an architecture that allows simultaneous variation of both amplitude and frequency using low-cost components and traditional techniques. The small dimension of the system allows to place it on different target points of the residual limb of an amputee (e.g. corresponding to phantom fingers). Experiments to evaluate the human capability to discriminate differently modulated stimulations and stimulation sites were carried out on healthy volunteers. Subjects were able to properly discriminate the different force amplitudes exerted by the device at different fixed frequencies. The effect of amplitude on the frequency discrimination was also studied and for most subjects it was easier to discriminate a lower frequency when its amplitude was lower than the amplitude of the reference signal. The distance of the stimulation sites for an optimal discrimination was also identified.**

***Keywords: vibrotactile feedback; upper limb prostheses; haptic perception.***

## I. INTRODUCTION

The amputation of an upper limb causes in subjects severe impairments in the ability of carrying out activities of daily living (ADL) and in sensing the surrounding environment through the physiologic sense of touch. In modern myoelectric prostheses, while a certain level of dexterity is restored by means of motorized components (e.g. hand, writs, elbow) and electromyographic (EMG) control [1], afferent sensory biofeedback is not yet purposely provided. Myoelectric prosthesis users often employ the sound and vibration of the motor(s) to control their artificial limb, albeit surveys report they would like to get enhanced feedback from it [2,3]. The lack of sensory feedback is a drawback in the system and probably one of the main reasons for rejection of a prosthesis [4]. In such case, a system that provides artificial feedback can be used.

There are several ways to convey afferent information like through electrocutaneous [5,6], vibrotactile stimulation [5], or pressure sensory feedback systems [7-9]. Besides systems able to display a unique kind of stimulation, Kim at al. developed a multi-function haptic device able to display touch, pressure, vibration and shear force [10]. Such device was recently successfully investigated on transhumeral amputees that underwent targeted muscle reinnervation procedure [11], but are complex and would turn out cumbersome if they were to be applied to the forearm of trans-radial amputees.

Vibrotactile stimulation is evoked by a mechanical vibration of the skin, typically at frequencies of 10–500 Hz [5]. Afferent biofeedback based on this principle, has been investigated and debated for the last decades, and the non-invasive nature of such an approach promises high acceptability compared to e.g. electrocutaneous feedback [5,7]. In addition, vibrotactile systems are small and unobtrusive allowing easier integration with respect to force feedback systems [7,8]. Many aspects of vibrotactile perception have been studied in great detail. The vibrotactile amplitude detection threshold (i.e., the lowest perceivable difference in amplitude) is known for the hairy skin of human to be approximately an order higher than for glabrous skin [12], such detection threshold depends on the initial amplitude reference stimulus [13] and changes with the frequency in particular for the hairy skin decrease with increasing the frequency [14]. Also, the ability to discriminate changes in frequency depends on the given stimulation frequency [14, 15], and best results are obtained at frequency above 200 Hz. Previous studies also reveal that the frequency discriminative performance are similar in hairy and glabrous skin, especially for high frequency (> 50 Hz) [14]. Some studies relative to the effect of amplitude of vibrotactile stimulation on the frequency perception were also carried out [16]. Vibrotactile systems using small electric motors have been used on the Otto Bock Electric Hand [17], the CyberHand [18], MANUS hand [19] and the FluidHand [20].

This paper presents a flexible vibrotactile system composed of vibratory elements (hereafter named as vibels) that could be used in conjunction with multi-fingered anthropomorphic prostheses endowed with current sensors as those nowadays available like Touch Bionics i-Limb [21] and RSL Steeper Bebionic hands [22]. Vibels are composed of three identical miniature vibration motors having same vibration amplitude. Therefore for each vibel it is possible to vary both its vibration frequency (varying the strength of the driving current) and to some extent its vibration amplitude (varying the combination of active motors). Compared to the state of the art two are the novelties of the present system: first, the architecture allows simultaneous variation of both amplitude and frequency using low-cost components and traditional techniques; secondly the

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small size elements allows to easily integrate the system within a prosthetic socket. Hence, such system is intended to be easily integrated inside a prosthetic socket, and to convey modulated mechanical vibration on sensory target sites in the stump, in a very flexible way. Every time the finger of the prosthesis touches an object a tactile stimulation would be instantaneously delivered to the stump, thereby tricking the brain into experiencing the sensation of touch from the artificial finger [23]. In addition, this system could exploit the reorganization in sensory brain cortex that occurs in the first hours after amputation [24], causing transradial amputees to experience sensations in their phantom hand when their stump is touched [25]. Specific locations on the skin corresponding to the fingers of this phantom hand can indeed be stimulated by miniature vibrators, using corresponding sensors of the hand prosthesis. The underlying objective is to provide acceptable and physiological feedback and thus to make the prosthesis being felt as a part of the body scheme. This paper presents the architecture and basic principles of operation of this sensory substitution system. Then, the implementation and evaluation on a working prototype, and results from a preliminary experimentation on healthy subjects are presented.

## II. SYSTEM ARCHITECTURE

The vibration element (vibel) is composed of 3 identical miniature vibration motors free to vibrate and connected coaxially together within a rigid package. The picture in Fig. 1 shows its conceptual scheme and how the vibel vibratory movement may be –in first approximation- modelled. Each vibration motor consists of a miniaturized DC motor (Precision Microdrives, UK) (12 mm diameter, 3.4 mm heigth, 1.7 g weight) having an eccentric mass on the shaft.

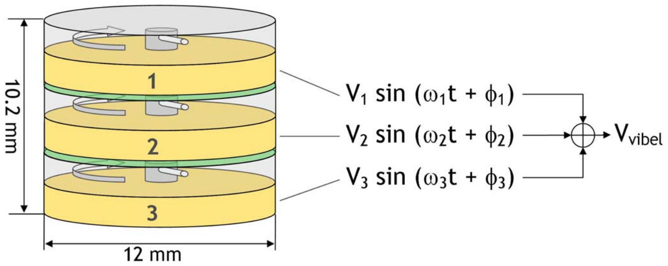

Figure 1. Vibel conceptual architecture and first approximation vibratory combination.

The rotation of the unbalanced shaft, induced by the flow of electrical current causes a forced vibration of the motor it-self, having a frequency equal to the rotor revolution period, and vibration force amplitude proportional to the weight of the eccentric mass, to its eccentricity and to the square of angular speed. As a result each micro-vibrator oscillates in a sinusoidal waveform, generically modeled as a pure tone:

$$V = V_i \sin(\omega_i t + \phi_i) \qquad (1)$$

and -neglecting second order interferences- the mechanical output waveform is the sum:

$$Vvibel = \sum_{i=1}^{3} V_i \sin(\omega_i t + \phi_i) \qquad (2)$$

where $V_i$ is the vibration amplitude (in Newton), $\omega_i$ the angular speed (radiant/sec) and $\phi_i$ the phase shift (radiant). Therefore, generically speaking the output is a complex three-tones oscillation easily described through frequency (spectral) representation but with unintuitive temporal interpretation. A simpler two-tones combination problem may be more easily illustrated in a time framework, under certain restricted hypotheses, as follows. With constant amplitude $V$, through the prosthaphaeresis formulas and neglecting phase shifts we have:

$$\sin(\omega_1 t) + \sin(\omega_2 t) = 2\cos\left(\frac{\omega_1 - \omega_2}{2} t\right) \sin\left(\frac{\omega_1 + \omega_2}{2} t\right) =$$

$$= 2\cos(\omega_{LF} t) \sin(\omega_M t) \qquad (3)$$

with $\omega_{LF}$ (lower frequency tone) half the difference between $\omega_1$ and $\omega_2$, and $\omega_M$ (higher frequency tone) the mean angular speed value. In other words we obtain interference between the two tones, turning out into a modulation of the mean frequency sinusoid $\omega_M$ at the lower frequency rate $\omega_{LF}$. If the tones have slightly different frequencies this interference is called *beat*. If the amplitude $V$, and angular speed $\omega$ are fixed we have, again through prosthaphaeresis formulas:

$$\sin(\omega t) + \sin(\omega t + \phi) = 2\cos\left(\phi/2\right) \sin\left(\omega t + \phi/2\right) \qquad (4)$$

i.e. a delayed ($\phi/2$) and attenuated (by a $2\cos(\phi/2)$ factor) waveform compared to the original one. If the phase shift $\phi \approx 0$, the delay can be neglected and the waveform has about double amplitude with respect to the original one. In the case of combination of three mechanical vibrations, the time-domain mathematical description becomes significantly heavy, and basically all frequency combinations modulate the output waveform. However, if the amplitude $V$, and angular speed $\omega$ are fixed and the phase shift of the motors are similar among them ($\phi_1 \approx \phi_2 \approx \phi_3 \approx \phi$), the combination of vibrations generates a waveform with same angular speed of original signals and with a force amplitude equal to $\approx 3V$.

Fig. 2 shows the forces exerted by a vibel measured by means of 6 axis load cell (nano43, ATI, NC, USA). The graphs show the force recorded by varying the numbers of active motors (1, 2, or 3) with same angular speed for different frequencies. Coherently with the equations described above the amplitude of the force increases with the number of active motors, whereas the frequency is maintained.

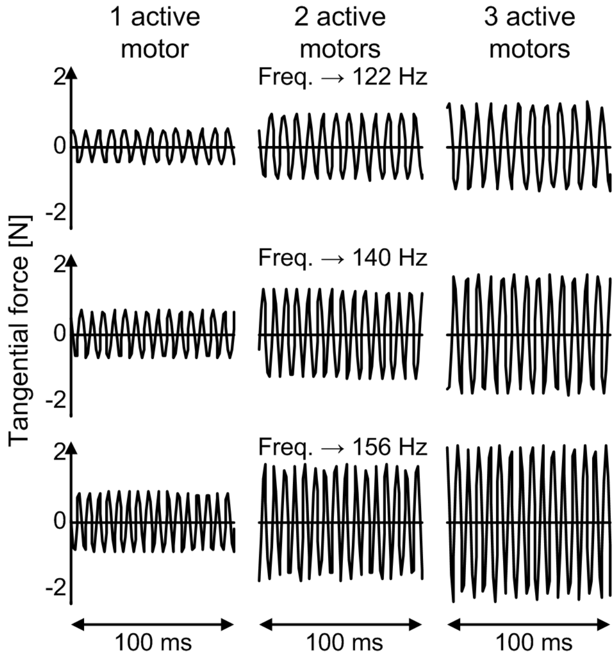

Figure 2. Vibratory combination for different frequencies

## III. EXPERIMENTAL PROTOCOLS

The discrimination capability of the humans was assessed by experimental sessions with able-bodied subjects, that volunteered to take part in the experiment, in order to evaluate the prototype. Vibels were positioned on the volar part of the forearm at a fixed distance from the proximal end of the radius (Fig. 3A), and held in place by an elastic sleeve. During the discrimination trials subjects sat with their dorsal part of forearm downward on bench top and white noise was delivered by headphones in order to eliminate any auditory stimulation associated with the mechanical sound of the motors. The experiments are described in details in sections III A-C.

### A. *Amplitude Discrimination*

The aim of this experiment was to evaluate the capability of the subject to discriminate among the 3 different vibration amplitudes allowed to the system. Nine healthy subjects were involved in this experiment. One vibel was positioned on the forearm. During each trial two trains of vibration consisting of mechanical vibrations with fixed frequency and different amplitude (1, 2 or 3 active motors in the vibel, cf. Fig. 2) were delivered in sequence. The duration of each stimulation was 2.6 s and the pause between two stimulations 1.3 s. Both orders of presentation (higher amplitude before the lower one and lower amplitude before the higher one) were tested. After the stimulation the subject stated which stimulation (first or second) was perceived with a higher intensity. During the experiment every combination of stimuli (1 vs. 2 motors, 1 vs. 3 motors, 2 vs. 3 motors) was tested 10 times for each frequency evaluated. The evaluated frequencies were two: 156 ± 2 (SE) Hz and 122 ± 1 Hz. During the experiment for each subject a total of 60 trials was randomized among them. The subjects were considered capable to discriminate when the percentages of correct response was above 75% of correct response (75% discrimination threshold).

### B. *Frequency Discrimination*

The aim of this experiment was to evaluate the capability of the subjects to discriminate different vibration frequencies, despite the amplitude variation correlated to it. Nine able-bodied subjects were involved in this experiment.

One vibel was positioned on the forearm. During each trial of the experiment two trains of vibration were delivered in sequence to forearm. The two trains of stimulation consisted of a standard stimulation that was the same for all trials and another stimulation with different frequency (and amplitude) of vibration. Durations of stimulations were those used in the amplitude discrimination experiment, and similarly both orders of presentation (standard vs. comparison stimuli and comparison vs. standard stimuli) were tested. After the stimulation, the subject stated which stimulation was perceived with a higher frequency. The subjects were also instructed to ignore, as far as it was possible, the intensity difference between standard and comparison stimuli, hence giving an answer based only on the frequency perception.

The standard stimulus had maximum frequency (156 ± 2 Hz) and the lowest amplitude (1 active motor). The comparison stimuli could have frequency equal to 140 ± 2 Hz (140 Hz comparison frequency) or 122 ± 1 Hz (122 Hz comparison frequency). These comparison frequencies were selected in order to test different conditions: one easier (with a difference between standard and comparison greater than 30 Hz) and one more difficult to discriminate (difference < 30 Hz). The vibration force amplitude changes with frequency (the centrifugal force increases with frequency, cf. Fig. 2) and with the number of active motors in the vibel (1, 2 or 3). Therefore, the total number of possible comparison stimuli was six. Each possible comparison stimuli was tested 10 times and during the experiment the 60 trials were randomized. A 75% discrimination threshold was used in order to evaluate the capability to discriminate of the subjects.

### C. *Discrimination of Stimulation Sites*

The aim of this experiment was to evaluate the capability of the subjects to discriminate two different sites of stimulation. Nine vibels were positioned on the forearm forming a cross shape: one was central, four were positioned along the proximal-distal direction and the other four perpendicular to such direction (radial-ulnar direction), the distance between the centers of nearby vibels was called *d*. The possible distances of the vibels from the central vibel were 2: equal to *d* and to 2*d* (see Fig. 3B). Two trains of vibration were delivered in sequence (durations as in the other experiments) to the forearm: one stimulation delivered only by the central vibel (standard), the other one delivered from either the central vibel or another one (comparison), in order to test the two different distances of stimulation and the different directions. After the stimulation, the subject stated if the stimulations were delivered on the same stimulation site or on another one. The frequency and amplitude of stimulation was the same for all the vibels involved in the experiment. The experiment was divided in different sessions; within each session the site of stimulation used as comparison was the same, and the subjects were informed about this. The trials were developed with two different distances *d* between the near vibels: 1.5 cm and 3 cm. In the experiment with *d* equal to 3 cm three subjects were involved, and ten trials were performed for each comparison site, in case of *d* equal to 1.5 cm six subjects were involved and sixteen trials for each comparison discrimination site were developed. A 75% discrimination threshold was used in order to evaluate the subjective discrimination capability.

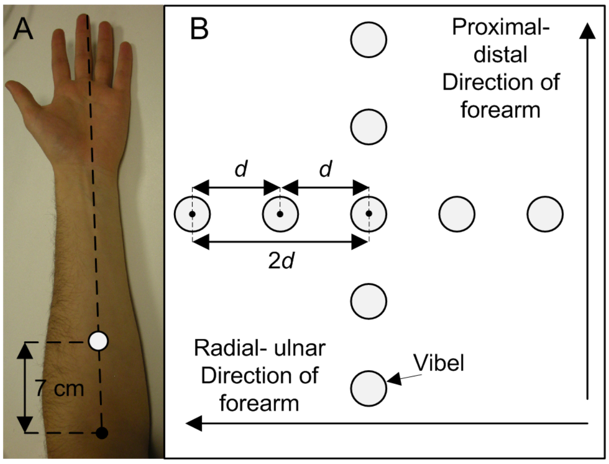

Figure 3. Placement of vibels on the volar part of forearm for amplitude and frequency discrimination (A) and for discrimination of stimulation sites (B) experiments

## IV. RESULTS

Table I shows the force amplitude obtained by varying the number of active motors for the 3 frequencies investigated in the experiments. The amplitudes in the case of two or three active motors did not correspond exactly to twice and three-times the amplitude of one motor; such values resulted attenuated. Results relative to experimentation with subjects are presented in sections IV A-C.

TABLE I. MEAN AMPLITUDE BY VARYING FREQUENCY AND ACTIVE MOTORS

| **Mean freq. [Hz]** | **Mean amplitude (MEAN±SE) [N]** | | |
|---|---|---|---|
| | *1 motor* | *2 motors* | *3 motors* |
| 156 | 0.86 ±0.01 | 1.57±0.01 | 2.11±0.03 |
| 140 | 0.68 ±0.01 | 1.18±0.02 | 1.70±0.02 |
| 122 | 0.49 ±0.01 | 0.88±0.03 | 1.25±0.01 |

### A. *Amplitude Discrimination*

Fig. 4 shows the mean percentage of discrimination for all subjects, for both the frequencies and all combinations of stimuli (1 vs. 2 motors, 2 vs. 3 motors and 1 vs. 3 motors). The mean discrimination percentage was above 75% discrimination threshold. The amplitude discrimination percentage for 1 vs. 2 motors was between 75 and 80 %, in other two cases was above 90 %. The 3 way ANOVA showed that the difference in the responses across the two frequencies and subjects, was not statistically significant; statistical differences were found instead among the combinations of stimuli ($p < 0.001$).

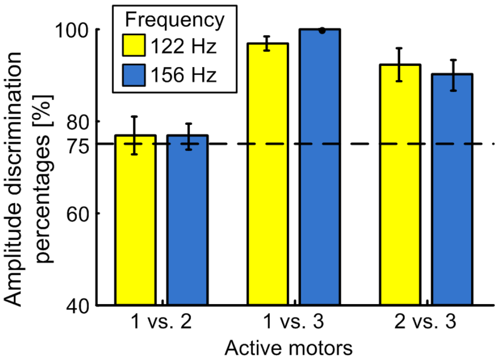

Figure 4. Mean amplitude discrimination percentages (MEAN±SE) for all subjects. The dotted line indicates the 75% discrimination threshold

### B. *Frequency Discrimination*

Table II shows the frequency discrimination percentages of correct response for each subject. For eight subjects the highest discrimination percentage values were obtained when 1 active motor provided the comparison stimulation, the percentage values in such cases were greater than 70%. It should be noted that the vibration force amplitudes provided by 1 active motor were lower than that of the standard stimulation: the difference was equal to 0.18±0.02 N for 144 Hz comparison stimulation frequency and 0.37±0.02 N for 122 Hz one. For only one subject (i.e., AM) the discrimination percentages resulted best when 3 motors were active.

TABLE II. CORRECT RESPONSES PERCENTAGE FOR FREQUENCY DISCRIMINATION TRIALS

| **Subj.** | **Comparison mean frequency: 122 Hz** | | | **Comparison mean frequency: 140 Hz** | | |
|---|---|---|---|---|---|---|
| | *1 motor* | *2 motors* | *3 motors* | *1 motor* | *2 motors* | *3 motors* |
| PM | 100 | 100 | 30 | 80 | 40 | 10 |
| GB | 90 | 80 | 40 | 100 | 70 | 20 |
| MC | 100 | 80 | 30 | 100 | 60 | 20 |
| MCf | 100 | 90 | 50 | 70 | 10 | 50 |
| MD | 80 | 70 | 40 | 80 | 30 | 60 |
| LV | 90 | 70 | 40 | 90 | 20 | 0 |
| MF | 80 | 70 | 50 | 90 | 10 | 10 |
| IM | 100 | 100 | 80 | 80 | 50 | 70 |
| AM | 20 | 70 | 70 | 20 | 50 | 100 |
| **Mean** | 84 | 81 | 48 | 76 | 35 | 43 |
| **S.E.** | 9 | 4 | 6 | 7 | 7 | 11 |

The discrimination percentages for the 122 Hz comparison frequency stimulation provided by 2 active motors were also higher than 70%; in this case the force amplitude between standard and comparison stimulations were similar (mean difference equal to 0.02±0.04 N). The mean discrimination percentages resulted above the 75% threshold only when the amplitude of comparison stimulations was lower or similar with respect to the standard one. The 3 way ANOVA showed that the difference in the responses among the subjects resulted not significant. The difference was significant between the comparison frequencies ($p < 0.01$) and among the different amplitudes of vibration ($p < 0.001$).

### C. *Discrimination of Stimulation Sites*

From preliminary experiments with three subjects and distance *d* equal to 3 cm (i.e. the distances of the comparison vibel from the central one were equal to 3 cm and 6 cm) the percentages of correct responses of the subjects for the sites discrimination trials were widely above the 75% discrimination threshold. The mean percentages were equal to 88±1 % and 95±1 % for distances equal to 3 cm and 6 cm respectively (with no statistical difference between the two distances). For such reason, in order to infer on the "distance resolution" of the present device on forearm, trials with a distance *d* equal to 1.5 cm (distance from the central vibel equal to 1.5 cm and 3 cm) were performed on the last six subjects.

Fig. 5 shows the mean percentage of correct discrimination for each direction with respect to the central vibel. The ANOVA showed that the difference between discrimination percentages in the two orientations was not significant whereas the difference between the two distances was significant ( $p < 0.05$). The mean percentages were equal to 77±1 % and 85±1 % for distances of 1.5 cm and to 3 cm respectively.

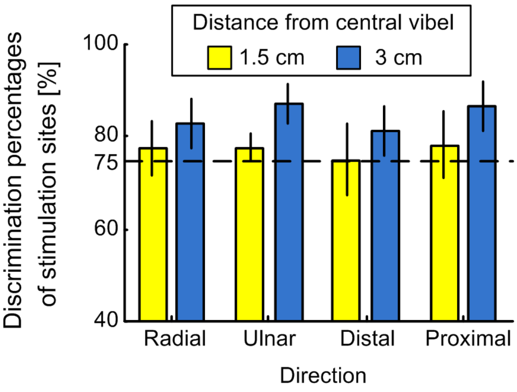

Figure 5. Mean discrimination percentages (MEAN±SE) of stimulation sites for all subjects by varying the distance and the direction of comparison vibels with respect to the central one. The dotted line indicates the 75% discrimination threshold

## V. DISCUSSION

### A. *Amplitude Discrimination*

The results on amplitude discrimination showed that the subjects were able to discriminate between the different amplitudes generated by the device. In addition a non significant difference in amplitude discrimination percentages between the different frequencies was found. Therefore, within the frequency range included between the frequencies accounted by the study, the capability of subjects to discriminate the different force amplitude exerted by the device does not change. The percentage of correct answers for 1 vs. 3 active motors trials was significantly higher than the other ones, indeed the amplitude variation in such case was the higher with respect to the other combination trials.

### B. *Frequency Discrimination*

The frequency discrimination trials seemed to be affected by the force amplitude generated by varying the number of active motors, in particular most subjects were able to better discriminate a lower frequency value when the force amplitude was lower with respect to the standard stimulation. Such results seem to partially confirm the studies of Morley [16] where the subjects perceived a lower or higher frequency based on the difference of vibration force amplitude between a reference stimulus and a comparison one, although the frequency of vibration of both stimulations were the same. In that experiment the majority of subjects perceived a lower vibration force amplitude as if it was a lower frequency.

From previous studies [14], it resulted that in a range included between 100 and 200 Hz a human subject was able to discriminate a difference of about 30 Hz. The present study confirms this finding considering that the difference between the 122 Hz and 156 Hz stimulation was properly discriminated at different amplitudes. It is interesting to note that, although the difference of frequency between the standard stimulation and the 140 Hz comparison one is lower than 30 Hz, the majority of subjects correctly discriminated it as a lower frequency stimulation when the force amplitude was lower than the standard one. At a constant number of active motors, for most subjects it is easier to discriminate the lower frequency, due to the lower force exerted.

### C. *Discrimination of Stimulation Sites*

The experiment relative to the capability of the subjects to discriminate different stimulation sites by a two-points discrimination paradigm showed that subjects were able to discriminate down to a distance equal to 1.5 cm between two vibrotactile stimuli. Since the discrimination percentage resulted near to 75% threshold, such distance might be considered as the "distance resolution". The location of the vibels along perpendicular or parallel to proximal-distal direction was not significant for the discrimination.

Several studies were carried out on the capability of localizing vibrotactile stimuli on the forearm: Cholewiak et al. [26] placed a 7 elements uni-dimensional array along the underside of the arm, while Oakley et al. [27] used a 3x3 vibrotactile array on the dorsal part of forearm. Both studies reported a mean localization rate equal to about 50% for a 2.5 cm distance between the elements. This differs with respect to our study also due to different experimental protocols (two points discrimination vs. localization trials); it is obviously more difficult to localize the stimulation precisely instead of identifying one or two different points.

## VI. CONCLUSION

In this paper a vibrotactile feedback device capable to generate different vibration force amplitudes and frequencies was presented, and the effect of such variations on subjects was analyzed. The three amplitudes that the device was able to generate, resulted discriminable for all subjects. The frequency discrimination was affected by the vibration force amplitude. The effect of amplitude could be used to improve the frequency discrimination. However, such possibility should be evaluated for each subject, and other tests should be made. The discrimination sites distance for an optimal discrimination was also investigated and identified. The placement direction of the vibels did not seem to affect the sites discrimination capability. This paper focuses on the application of the present sensory substitution system for prosthetics; the same system could be used in video-games controllers, as a means for providing feedback events or cues for rehabilitation systems, navigation guidance systems for blind or any application in which a two dimension information needs to be conveyed.

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