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Perception and Performance of Electrical Stimulation for Proprioception

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Abstract— **Proprioception, yielding awareness of the body's position and motion in space, is typically lacking in prostheses and supernumerary limbs. Electrical stimulation is one technique that may provide these devices with proprioception. This paper first investigates how the modalities of electrotactile cues, such as frequency and intensity, are perceived. Using the results, we designed and compared several comfortable and perceptible feedback mappings for spatial cues. Two experiments were conducted using a 16-electrode bracelet worn above the elbow to provide electrical stimuli. We found that subjects could localize the stimulating electrode with a precision of ± 1 electrode (110 mm) in all feedback conditions. Moreover, within the range of pulse intensities perceived as comfortable, the participants' performance was more sensitive to changes in frequency than in intensity. The highest performance was obtained for the condition which increased both intensity and frequency with radial distance. These results suggest that electrical stimulation can be used for artificial proprioceptive feedback, which can ensure a comfortable and intuitive interaction and provides high spatial accuracy.**

I. Introduction

Proprioception, the sense of the presence and kinematics of body segments is known to play a central role in movement planning and execution [1]. The lack of proprioceptive sensory feedback in current prostheses and supernumerary limbs may impede their control and result in a large mental load [2]. Various artificial sensations such as vibration [3], skin deformation [4] or applied pressure [5] have been explored to integrate haptic feedback and facilitate the control of a robotic limb. However, only a few studies have investigated the effect of artificial proprioception on control performance.

Force proprioceptive feedback based on the motion of the participant's finger resulted in a clear performance improvement in both sighted and unsighted conditions during a virtual finger pointing task [6]. Application of skin stretch feedback allowed subjects to place a virtual object highly accurately, within several degrees of its target [7]. Vibrotactile feedback has been studied through arrays of tactile units, showing that artificial proprioception could enhance participants' perceptual ability [8]. Finally, electrotactile stimulation was successfully employed to provided feedback to control a supernumerary finger [9].

Electrotactile feedback has been extensively used in a number of applications, e.g for sensory replacement [10]-[16], for tele-operated systems [17] and for the control of supernumerary limbs [9]. Electrical stimulation can be delivered, with different level of invasiveness, at the surface of the skin through depolarising surface electrode [10], directly at the nerve level using implanted electrodes [18] or underneath the skin, using subdermal electrodes [19]. The first method is the most common one as this approach is non invasive, it can compensate for various forms of lost sensations, including proprioception [20], and is the focus of this work.

Compared to other substitution methods, electrical stimulation requires compact equipment and relatively low power [20]. A current pulse delivered through the skin causes a depolarisation of the afferent eliciting a sensation, where quality and intensity will be affected by the electrical signal's parameters and by the locus of stimulation [13]. The sensation can thus be encoded by modulation of the current amplitude, frequency or pulse width. Despite being well studied as a tactile feedback mode, limited studies address electrotactile feedback's perception and acceptance from a user perspective [10], [20]. Nonetheless, characterizing the effect of each stimulation parameter is essential to provide an effective, useful and comfortable feedback system.

This article investigates how the parameters of electrical stimulation affect user perception and performance. The perception of characteristics such as frequency and intensity were first studied within a static task. Based on these findings, we developed different strategies to map electrical stimuli to a 2-dimensional grid displayed on a screen. The user's performance was then evaluated and compared between different feedback mappings.

II. Methods

Two pilot studies evaluated the perception and usage of electrotactile feedback for human-robot interaction. The SETREC committee (Imperial College London) approved all experimental procedures involving human subjects (review reference number 21IC6935). The studies were carried out using the CLASS system (Tecnalia, ES) with multi-field electrodes. The electrodes consist of 16 flexible fields, arranged as a bracelet that can be activated independently. For the first experiment, only one electrode was used, see Fig. 1A. For the second experiment, 15 electrodes were used as one electrode was required for grounding. The electrodes are adjacent to one another with dimension 110x200 mm. Each can deliver a square current pulse with a 100 μs pulse width. A MATLAB application was implemented to map the stimulation to an area of the monitor as shown in Fig. 2A and described in section II-B.

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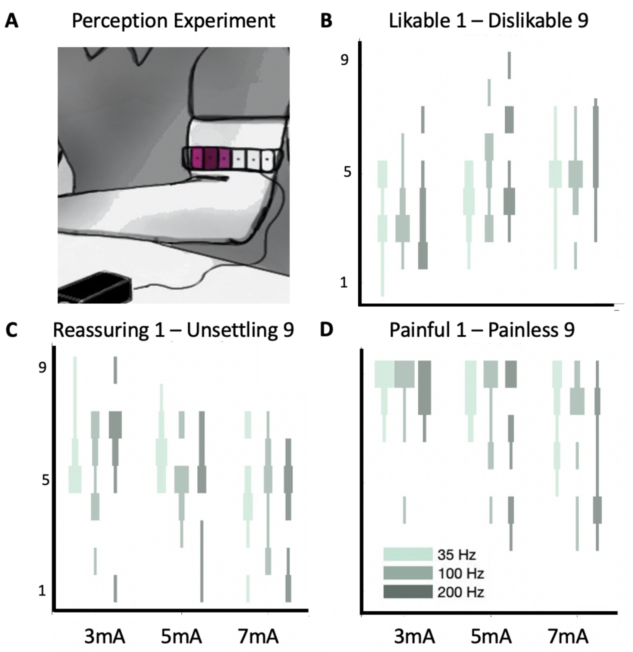

Fig. 1. A: Experimental setup of the perception experiment. One of the three stimulating electrode (in pink) is selected before the experiment. B: Likable – Dislikable. C: Reassuring – Unsettling. D: Painful – Painless. Feedback perception on 9-point Likert scale. The block width is proportional to the number of participants selecting that answer.

In a first *perception experiment*, the influence of the amplitude and frequency of electrical stimulation on the subject's perception was investigated. This was to determine stimulation ranges providing comfortable and easy to differentiate cues. For this purpose, we used questionnaires (see Fig. 1 B-C) to evaluate the effect of different stimuli.

In a second *proprioception experiment*, the subject's ability to associate the feedback to spatial locations was studied using 5 different mappings (see Table I). We evaluated the participants' performance, success perception as well as acceptance of the feedback conditions using the same questionnaire as in the perception experiment.

A. Perception Experiment

10 subjects (three female, aged 27.2 ± 3.15) without known sensorimotor impairment participated in this study. For each participant: i) informed consent prior to participating was provided; ii) the stimulation device was attached to the left arm at elbow level; iii) three adjacent electrodes, on the top of the arm, were activated individually with low amplitude current to select a comfortable electrode positioning for the rest of the experiment (see Fig.1A); and iv) a total of 15 trials were performed in a randomised order.

For the stimuli we used three levels of pulse frequency $\{35, 100, 200\}$ Hz and five levels of intensity $\{0, 1, 3, 5, 7\}$ mA. Each trial consisted of a single stimulation (2 s duration) with a combination of both parameters. After each trial, a questionnaire of 9-point Likert items was filled characterising the perception of the pulse. If subjects felt stimulation (first question), then they were asked to answer the feedback characterisation questions.

A binomial item logistic regression was used for stimulation perception, while a two-way repeated measurements Aligned Ranks Transformation (ART) ANOVA [21] was used to analyse the other questionnaire items. If a factor or interaction was significant, post-hoc paired Wilcoxon signed-rank test with the Bonferroni adjustment was used to compare single levels of the factor.

TABLE I Feedback conditions

Cond	R1	R2	R3	R4
II35	Th 35 Hz	Th+1 mA 35 Hz	Th+2 mA 35 Hz	Th+3 mA 35 Hz
II100	Th 100 Hz	Th+1 mA 100 Hz	Th+2 mA 100 Hz	Th+3 mA 100 Hz
IF	Th+2 mA 35 Hz	Th+2 mA 90 Hz	Th+2 mA 145 Hz	Th+2 mA 200 Hz
IIF	Th 35 Hz	Th+1 mA 90 Hz	Th+2 mA 145 Hz	Th+3 mA 200 Hz
2I2F	Th+1 mA 35 Hz	Th+1 mA 200 Hz	Th+4 mA 35 Hz	Th+4 mA 200 Hz

Description of the 5 feedback mappings for radial level R1 to R4: II – increase intensity, IF – increase frequency, IIF – increase intensity & frequency, 2I2F – 2 intensities & 2 frequencies. TH – Threshold, the min value in mA that was felt during the calibration for each electrode.The feedback for angular position was given by the position of the activated electrode.

B. Proprioception Experiment

10 healthy right-handed subjects (four female, aged 26.54 ± 3.75) took part in the proprioception experiment. The electrotactile system was attached to their non-dominant arm at elbow level. To ensure consistency between subjects, the non-dominant hand was immobilised in a custom-made structure. Electrical stimulation from the bracelet was mapped to the monitor as shown in Fig. 2A. Each electrode around the upper arm (E$\{1-15\}$) corresponded to one polar segment on the grid (S1 to S15). The radial coordinate (r), which was discretized in four radial levels (R1 to R4 as shown in Fig. 2A), was mapped using one of the five coding scheme described in Table I. The whole range of position was divided in 16 sections (S1 to S16) and four radial levels (R1 to R4).

Each electrode was then calibrated for the minimal perceptible stimulation amplitude (sensitivity threshold, see Fig. 2B). The calibration started at 1 mA amplitude and stopped once the participant confirmed that they felt a stimulation, during which the frequency was fixed at 35 Hz. Then each electrode was stimulated one after the other until the participant confirmed homogeneous stimulation from all electrodes. For each of five randomized conditions, a training and testing session with a concluding questionnaire was performed.

1) Training Phase: Participants received a stimulation while the corresponding grid segment was highlight (see Fig. 2A), so that they had a visual representation of the active stimuli. The grid was circle-shaped and had 64 cells (16 sections (S1 to S16) $\times$ 4 radial levels (R1 to R4)). 16 stimulations were provided sequentially, following the

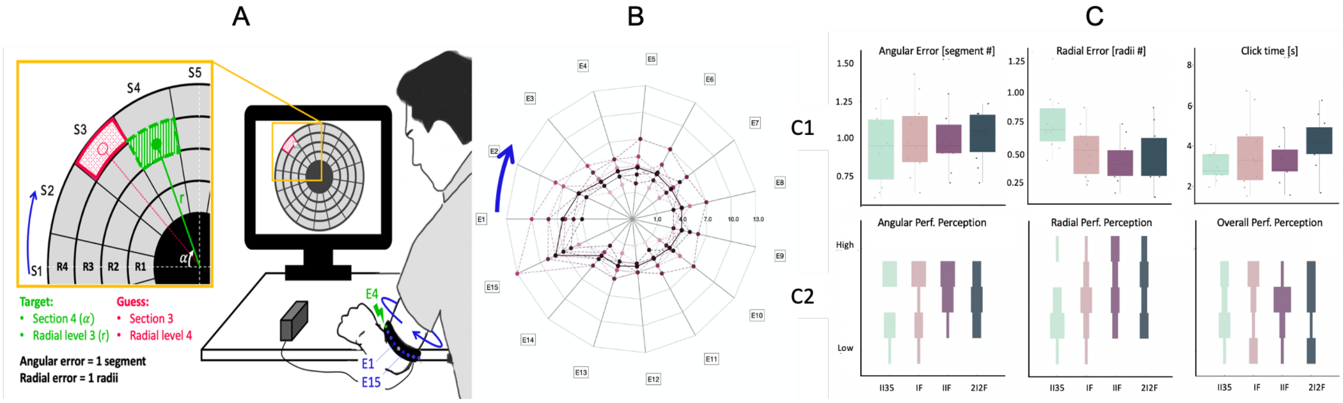

Fig. 2. A: Experimental setup of the proprioception experiment. The subjects were wearing the CLASS device around their left (non-dominant) arm. A stimulation that corresponds to a target area (green) was received and the subject interpreted its encoded placement on the grid (red). The grid was divided in 16 sections (S1 to S16) and four radial levels numbered as shown (R1 to R4). The error was calculated as the radial, angular or total difference between the interpretation (red) and the stimulation position (green). B: Electrode placement and sensitivity threshold in mA for all subjects. C1: Performance results. C2: Subjective performance perception (rated from 1 (low performance) to 5 (high performance) on a Likert scale) in distinguishing between angular sections, radial sections or overall location of the stimulation.

vertical and, then, horizontal axis on the screen. This was used to present the subject the mapping from the feedback to the monitor, no additional information was provided.

2) Testing Phase: 30 unique stimulations were presented in a randomized order, each was 2 s long and associated to one of the 64 cells. For each condition, the stimulation parameters were determined by the mapping as described in Table I. After each stimulation, the participant had to click on the segment that they attributed the stimulation to.

3) Analysis: The angular, radial and total segment errors, as well as the reaction time, were used to evaluate the performance. Angular/radial error was calculated as the number of segments/radii between the correct and subject responses, as shown in Fig. 2A. The total error then represented the total difference in the amount of segments and radii. To compare the true to the perceived performance, the questionnaire was analysed and correlated with the objective measures. We also analysed the feedback characterisation question and compared different conditions regarding their likability, perception of reassurance and pain.

With the smaller sample size and not normally distributed data, a non-parametric repeated measures Friedman test of differences was used for each metric. For pairwise comparisons between single feedback conditions, post-hoc paired Wilcoxon sign-rank tests were employed and the Holm-Bonferroni adjustment was used to control the family-wise error rate. For objective values, the observations for each subject were averaged over all trials in a block.

The differences between conditions II35 and II100 were compared separately using a paired Wilcoxon sign-rank test. These two conditions presented the same modality with two different frequencies, which were chosen based on the results of the first experiment, see section II-A.

III. Results

A. Perception Experiment

A two-predictor logistic model was fit to the data to test the relationship between subject's electrotactile feedback likelihood and stimulation intensity as well as frequency. This showed that the log of the feedback perception likelihood was positively correlated to intensity ($\beta_1 = 2.540$, $p < 0.0001$), such that the higher intensity was more likely to be recognised. At 0 mA (the model intercept with $\beta_0 = -5.184$) the odds of the feedback being recognised were $e^{-5.184} = 0.006$ and for each subsequent intensity level, the odds increased by $e^{2.540} = 12.68$. From this model, pulse intensities of 0, 1 mA are more likely to be unidentified. Therefore, these levels were not considered in the subsequent analysis. No relationship between perception and frequency was found ($\beta_2 = 0.003$, $p < 0.7090$).

ART ANOVA revealed that pulse intensity significantly influenced the participant's response for the "reassuring – unsettling" scale (Fig. 1C, $F(2, 69) = 7.19973$, $p = 0.00145$), while the effect of frequency and the interaction of both factors were not significant (both $p > 0.2$). Post-hoc analysis showed that at the highest intensity level (7 mA) there was an overall shift of the feedback perception towards "unsettling": feedback of 7 mA perceived was more unsettling than 3 mA ($Z = 3.7902$, $p = 0.0001$) and 5 mA ($Z = 2.7339$, $p = 0.0132$). No difference between 3 mA and 5 mA was detected ($Z = 2.0291$, $p = 0.1234$).

For feedback likability (Fig. 1B), there was again a significant influence of intensity ($F(2, 69) = 10.0258$, $p = 0.0002$), but not of frequency ($F(2, 69) = 1.9755$, $p = 0.1465$). Subjects liked the 3 mA pulse more than the pulse with 7 mA ($Z = -3.6272$, $p = 0.0001$) or 5 mA ($Z = -2.7212$, $p = 0.01373$), but no difference were otherwise found ($Z = -1.2714$, $p = 0.6582$).

The "painful – painless" scale rating (Fig. 1D) was affected by both intensity ($F(2,\, 69) = 15.0787,\, p < 0.0001$) and frequency ($F(2,\, 69) = 5.4265,\, p = 0.0065$). Feedback with an pulse intensity of 7 mA was perceived more painful than the two other conditions ($Z = 3.3392,\, p = 0.0008$ for comparison with 3 mA and $Z = 2.3833,\, p = 0.0355$ with 5 mA), lower intensities were not significantly different ($Z = 2.2496,\, p = 0.0791$). Moreover, the 35 Hz pulse frequency was less painful than the 200 Hz for all intensity levels ($Z = 3.2264,\, p = 0.00146$). No other difference were found ($p > 0.1$).

B. Proprioception Experiment

1) Performance: No differences between feedback conditions II35 and II100 were found in angular error ($Z = -1.0515,\, p = 0.3281$), radial error ($Z = 0,\, p = 1.0$), total error ($Z = -0.84515,\, p = 0.4688$) or reaction time ($Z = 0.28006,\, p = 0.8438$). Therefore, only feedback II35 was considered for subsequent condition comparisons.

A Friedman test revealed no significant difference for the angular (Fig. 2C1, $\chi^2(3) = 2.6633\, p = 0.4465$) or total errors over the mappings ($\chi^2(3) = 6.4839\, p = 0.0903$). On average over all groups, 67.2754 % of the incorrectly guessed trials were missed by one angular segment. In contrast, the radial error difference between groups (see Fig. 2C1) was significant ($\chi^2(3) = 17.9070\, p = 0.0005$): in condition II35 subjects had higher error compared with conditions IIF and 2I2F (both $p < 0.04$), error in condition IF was also smaller than condition II35, however, this was not significant ($p = 0.058$). Even for the II35 mapping, which possessed the largest radial error, however, the radial error had less than one level difference with the target position (median $M = 0.6833$, median absolute deviation $MAD = 0.19768$).

A significant influence of the feedback type on the reaction time was found using a Friedman test (Fig. 2C1, $\chi^2(3) = 8.280\, p = 0.04057$). However, pairwise post-hoc analysis revealed no significant differences between the groups (all $p > 0.05$). The largest contrast was found between conditions II35 and 2I2F ($Z = -2.4973,\, p = 0.059$, comparing $M = 2.7481,\, MAD = 0.9339$ for condition II35 and $M = 4.1379,\, MAD = 1.1466$ for condition 2I2F).

2) Perception: To compare how participants perceived their accuracy with each feedback condition, they were asked to rate their angular, radial and total performance on a 5-point Likert scale. Conditions II35 and II100 were again found to be indifferent for each rating (all $p > 0.05$), therefore, only condition II35 was used for subsequent comparison.

Although, a Friedman test did not reveal any differences between the mappings in the perception of angular ($\chi^2(3) = 1.9138\, p = 0.5905$) or total error ($\chi^2(3) = 0.33871\, p = 0.9526$), the differences in radial error were significant ($\chi^2(3) = 9.5070\, p = 0.02326$). For the mapping IIF subjects perceived their radial accuracy higher than in II35, but the comparison was not significant after the Holm-Bonferroni adjustment ($Z = -2.4558,\, p = 0.1070$, comparing $M = 2,\, MAD = 0.7413$ for condition II35 and $M = 3.5,\, MAD = 1.4826$ for condition IIF). From Fig. 2C2 it can be seen that the perception of success is lowest in II35 and the highest in IIF. This reflects the objective measures (Fig. 2C1): radial error in II35 was higher than the other conditions and IIF tended to have the highest performance.

3) Electrodes Placement and Sensitivity Threshold: To analyse the relationship between electrodes placement and electrotactile feedback sensitivity, we compared the calibration thresholds. A Friedman test revealed significant ($\chi^2(14) = 67.344,\, p < 0.0001$) differences between the electrodes. The electrodes were contrasted with a post-hoc paired Wilcoxon signed-rank test with Benjamini-Hochberg adjustment for multiple comparisons. Placement of the electrodes and their thresholds are presented in Fig. 2B and can be seen that the threshold for electrodes E1, E2 and E15 are different from the other values: They are significantly higher for E1 than for E3 - E14 (all $p < 0.5$), higher for E2 than for E3 and E11 - E14 (all $p < 0.5$) and for E15 compared to all other electrodes (all $p < 0.5$).

IV. Discussion

The first study analysed the perception of pulse intensity and frequency stimulation. The results showed that while pulse intensity had a significant effect on perception (stimuli of higher amplitude were considered more painful, disturbing and disliked), the effect of frequency was less clear. The preference for particular amplitudes was subject specific, but the lowest frequency (35 Hz) was perceived to be less painful compared to the highest (200 Hz) over all amplitude levels.

We concluded from these observations that it was necessary to restrict the amplitude range to design a comfortable feedback modality. To limit pain resulting from the feedback, in the second experiment, the maximal pulse intensity range was kept between threshold + 4 mA and calibration was performed at 35 Hz. Since the effect of frequency on feedback perception was unclear, we decided to compare different mappings that transmitted the proprioceptive cues with different combinations of pulse intensity and frequency (see Table I).

A relatively high accuracy was obtained for all conditions. We differentiated the angular error, which can indicate the spatial resolution and the radial error which assessed the mapping efficacy to transmit the radial information. No significant difference between the conditions could be observed for the angular error. Moreover, in almost 70 % of the incorrectly guessed trials the target was missed by one angular segment over all the conditions. This indicates that the stimulation could not be accurately determined, but could still be guessed in its vicinity. This low spatial resolution could partially be explained by the electrodes of the system that was used (CLASS system, Tecnalia, ES) which were originally intended for functional electrical stimulation and muscle contraction rather than tactile feedback. This may influence the ability to localise the stimulation. As suggested in [20], a concentric electrode design might be more suited for this application.

For radial error, the mapping with increasing intensity, II35, had the worst performance. This was similar for II100, demonstrating that a higher frequency did not make the stimulation more distinguishable. This is likely affected by the discrete nature of the stimulation. Two stimulations of the same level but applied at a different placement were difficult to compare as they could be perceived differently, even after calibration. In a set up with continuous stimulation, the intensity variations may be easier to distinguish. There was no significant difference between other conditions, however, the click time was larger for mapping 2I2F compared to II35. This could indicate that a higher cognitive load was needed for 2I2F since it required subjects to remember a pattern. Although accuracy for mapping IIF was not significantly better, this mapping was often the most preferred and tended to show the highest performance. This condition also corresponded to the highest subjective perception of success.

In conclusion, a relatively high accuracy was obtained for all mappings when presenting 30 random ordered discrete stimuli to be localized on a 64 cells grid. The participants were naive to the mapping pattern and were not given any verbal explanation on how the position cues were transmitted. The manipulation of only pulse intensity (group II35) was less efficient compared to other options suggesting frequency modulation may be a more suitable parameter to provide a clear feedback without risking an increase in discomfort These results show the potential of electrotactile feedback to provide artificial proprioception in both proprioceptive applications [8] and applications involving the use of additional limbs [22], [23].

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