Imperial College London

SENSORY FEEDBACK FOR SUPERNUMERARY LIMBS

MPHIL

Camille Mirka BLONDIN

DEPARTMENT OF BIOENGINEERING

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Statement of Originality

I hereby declare that this submission is my own work, is free of plagiarised material and has not been submitted for a higher degree to any other University or Institution.

Camille Blondin, October 20th 2021

Copyright Declaration

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Abstract

Supernumerary robotic limbs (SL) are devices developed to increase human capability. For this to happen, SLs should assist users with minimal cognitive effort and be controlled both independently and in combination with the user's natural limbs. Despite the development of many SL, their application is limited by a lack of easy-to-use and intuitive controllers. Integrating somatosensory feedback in the control loop could improve this issue. In particular, providing artificial proprioception, a somatosensory modality important for motor control, could help SL users to integrate the SL into their planning and body schema.

My objective is to find strategies to deliver intuitive and understandable proprioceptive feedback from a SL. To do so, I investigated possible ways of providing artificial proprioceptive feedback using 2degrees of freedom (DoFs) tactile cues delivered through *electrical stimulation* and *vibration*. I designed a set of mappings that provide position cues from a virtual arm for each feedback modality. Two studies, one for each modality, were conducted.

In the first study, I observed that the intensity of electrical stimulation affected its perception and comfort. I then found that it was easier to differentiate frequency variations than intensity variations. This study brings new insights into electrical stimulation perception and mapping design, considering comfort is rarely addressed in previous studies.

In the second study, I compared two mappings, task space and joint space, for the feedback and control of a virtual arm. Although I did not observe any effect on the performance, I found that the task space mapping was preferred and better understood than the joint space mapping.

Furthermore, a novel vibration feedback device was designed and tested to deliver 3DoFs position cues. The study showed that it is possible to transmit feedback at the torso and back, a location that few studies have considered. Moreover, this study proposes a novel strategy to provide 3DoFs feedback using vibration alone.

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Acronyms

CDA continuous decomposition analysis

DoFs degrees of freedom

EDA electrodermal activity

ISCR integrated skin conductance response

M median

MAD median absolute deviation

SCL skin conductance level

SCR skin conductance response

SD standard deviation

SL Supernumerary robotic limbs

TPDT two point discrimination threshold

VR virtual reality

Chapter 1 Introduction

The idea of augmenting human capabilities using robotic devices has been long theorised, however only recently had it caught serious interest in the research community. Supernumerary robotic limbs (SL), which are robotic devices designed to be incorporated as extra limbs, could be used to enhance human capabilities, allowing their users to achieve actions otherwise impossible with their natural limbs. For SL to be used in combination and independently of natural limbs new intuitive control strategies must be developed. Providing SL with artificial proprioception (an important aspect of human motor control) would greatly affect their usability and the intuitiveness of their control. Lack of sensation and in particular lack of proprioception from robotic devices make their use fully dependent on visual feedback, which increases the mental load necessary to operate them. This thesis aims at investigating ways of providing artificial proprioception for SL control exploiting the idea that it will allow a more natural control and promote device embodiment.

1.1 Literature Review

1.1.1 Supernumerary Limbs

SLs have been mostly developed for tri-manual operation [1], to provide body support [2, 3, 4] or as a solution to attenuate the effects of neuromotor impairments [5]. The SLs designed for the first two categories aim to help the user in manual work by minimising the human load or supporting their body. Such systems allow users to perform specific tasks safely and stably, but their control is limited by being either fully automated with no user input [3], coupled with natural limb kinematics [2] or a combination of both [4]. Thus, allowing for a reliable task-oriented control but failing to make the SL flexible for general usage.

SLs designed for neuromotor impairments comprise of supernumerary fingers including those developed by [6], and by [5], and more recently by [7]. Using human-inspired control strategies (Bio-Synergies, EMG, or foot pressure based respectively), the supernumerary finger/s can increase human dexterity allowing the user to overcome limitations imposed by their own body mechanics.

For use in daily life, artificial supernumerary limbs should assist users with minimal cognitive effort and be controllable both independently and in combination with the natural limbs. Ideally, the SL should be perceived by the user as their own. While the potential of this technology is clear, this aspect has not yet been realised.

Attempts have been made to improve user experience and device control by integrating supernumerary fingers with vibrotactile force feedback [8]. However, due to its small scale and the use of only vibrational feedback, the application to higher DoFs is limited.

1.1.2 Embodiment

The integration of any supernumerary system into the body representation is a critical consideration for human augmentation. Indeed, it has been shown that integrating a non-corporeal object to the existing body schema can increase the intuitiveness of its control [9]. This idea, known as embodiment, could transform the user experience and move the SL domain a step closer to what is depicted in science fiction. Yet, so far, little effort has gone into implementing and understanding the embodiment of SLs.

The idea that a tool, rather than a supernumerary limb, could become part of one's body schema is well studied [10]. [11], showed that this phenomenon was critical for the efficient use of an assistive device. Hence, they believe it is how spinal cord injured patients can calculate accurate spatial requirements needed for their wheelchair to pass through confined regions. Moreover, this idea inspired research on surgical tools enhancing human actions, since it is believed that an efficient tool embodiment is essential for optimal performance of the surgeon [12].

Although well known, the neural mechanisms underlying the concept of embodiment are not well understood and remains controversial [13]. While the self-appropriation of tools to perfect their use is undeniable, it is still unclear whether they can be embodied as additional parts of the body schema.

Object embodiment is a complex process that consists of the object existing within the borders of our body [14]. At least two main aspects are involved: *ownership*, the sense that the object belongs to us; and *agency*, the feeling of initiating and controlling the actions of the object [15]. To elicit agency, feedback confirming that intentions lead to actions is required. Having realistic feedback then is useful for eliciting ownership. In theory, the closer the feedback is from the one we receive from our natural limb, the strongest the feeling of embodiment.

Thus far, most of the efforts to enhance embodiment have been undertaken in the domain of upper limb prostheses. The focus has been directed toward cosmetic appearance via the development of realistic skin-like and multi articulating prosthetic hands design. However, these efforts are not sufficient to elicit ownership feelings. Additionally, prostheses require the development of consistent action-perception relationships [16] stressing the importance of agency in eliciting ownership sensation. For example, studies inspired by the rubber hand illusion, have been able to demonstrate that the illusion of control of a virtual reality (VR) limb coupled with expected congruent visual feedback could enhance ownership feeling [17].

Therefore, establishing effective control as well as providing consistent sensory information are both thought to be important for enhancing embodiment.

1.1.3 Somatosensory Feedback

The somatosensory system is one of the major systems that allows us to receive information from our environment. The somatic senses include the sense of touch, proprioception (the haptic sense of position and velocity of body segments and applied muscle forces), haptic perception and the nociceptive stimulus of pain.

These senses enable humans to perform a variety of tasks in the real world with dexterity and precision. Together with vision, the senses of touch and proprioception are especially useful for fine motor control when, for example, reaching and grasping an object. In turn, the nociceptive system is of particular importance to prevent damages to the body. Through pain, we can identify the location and intensity of the noxious contact and react accordingly.

Traditionally controlled purely through visual servoing, conventional prostheses demand continuous visual feedback without making any use of the somatosensory system, greatly affecting their usability. Restoring sensory feedback is key to enriching the artificial limb user experience and control [13]. The same idea can be applied to the field of teleoperation, where the aim is to transmit the sensations recorded at the end effector to the operator [18].

When providing sensory feedback for prostheses, natural sensory pathways are exploited to make the artificial feedback feel as natural as possible. However, for SLs, these natural pathways are nonexistent and new strategies need to be used. Therefore, questions such as where to place the feedback and how to make it useful without interfering with the sensory feedback from the natural limbs are raised. So far these questions have not been addressed and only a few studies focused on sensory feedback for SL [8, 19].

Proprioception

Proprioception plays a central role in the human motor control system, especially in movement planning and execution [20]. It gives knowledge of body segment position, motion and applied muscle forces derived from a combination of afferent channels, including joint angle receptors and cutaneous mechanoreceptors. For this reason, it is a multifaceted and complex form of haptic sensation [21]. Its complexity makes it arduous to replicate. Therefore, few studies focus on proprioception as a feedback modality for performing tasks. Among these, the main goal is to improve prosthetic use by decreasing the need for visual cues [22] with the idea that an ideal artificial proprioceptive signal would provide sufficient information for competent performance without other sensory inputs. Artificial proprioception was provided using tactile cues such as electrical stimulation [23], vibrations [24] or skin stretch [25]. Although these methods provide a sensation different from natural proprioception (sensory substitution), these studies show clear benefits for upper-limb prostheses users.

Similarly, integrating SLs with artificial proprioception could allow the user to integrate it into their body schema resulting in better control. However, for this to happen, new strategies specific to SL should be implemented to provide intuitive and continuous feedback. In particular, SL can have high numbers of DoFs, therefore, there is a need to investigate how to encode high dimensional information throughout the user's body without impacting their natural performance. Such encoding would allow the development of new devices capable of integrating multimodal somatosensory feedback.

Haptic Feedback

Haptics — the sense of touch — enables humans to have a sense of their surrounding environment allowing them to manipulate and explore it. To achieve similar abilities from robotic limbs, numerous efforts have been made to integrate haptic feedback into robotic control loops. So that robot's interaction with its environment can be transmitted through haptic sensations to its user, various strategies exist. The elicited sensations can either realistically mimic the real interaction, which is the case for texture-rendering devices [26], or transmit the information through coded cues, i.e. sensory substitution [27].

Electrotactile Feedback has been extensively used as a means to provide feedback for sensory replacement [28, 29, 24], for teleoperated systems [30] and more recently for supernumerary limbs [19]. It has also been shown that this method could be used to substitute for various lost sensations, including proprioception [23].

Vibro-tactile Feedback is another commonly used source of sensory information. It has mostly been studied for haptic sensation in myoelectric prostheses. For example, vibration cues were used for grasp parameters such as force control [31] or hand opening feedback [24]. More recently, vibration feedback was used to provide artificial proprioception [32] and it was integrated into the control loop of a supernumerary finger providing force feedback [8].

Other strategies include kinesthetic or force feedback, which has shown to be very practical for teleoperation control; Skin stretch feedback, which consists of applying shear forces to the skin or pressure feedback, to transmit, for example, grasping feedback for prosthesis control.

An example of use for each of these feedback techniques is provided in table 1-1. Moreover, the pros and cons of using each method for SLs application are discussed further.

Table 1-1: Feedback selection: elimination process

Feedback Type	Wearable	Not Fingertip Restricted	Intuitive	Ref
Kinesthetics	**X**	**X**	✓	[33]
Vibro-tactile	✓	✓	✓	[32, 24, 34]
Pressure	✓	✓	✓	[35, 36]
Electro-tactile	✓	✓	✓	[37, 38, 39, 19]
Skin stretch	✓	✓	✓	[40, 41, 42, 43]

1.2 Haptic Feedback for SLs

SLs are active devices attached to the user's body, therefore providing haptic feedback for SLs poses specific challenges:

1. *Selecting a wearable system for sensory feedback.* A SL is an augmentation of the user's body, and therefore sensory feedback should not interfere with the natural limbs to ensure they can be used with it.

2. *Delivering intuitive artificial proprioception.* SLs need tactile cues to convey proprioceptive feedback. Since this may be unintuitive, clear and intuitive mappings must be developed.

3. *Choosing an appropriate placement to convey sensory feedback.* Because SLs are not parts or replacing parts of the natural body, there is no clear location to convey the feedback.

4. *Ensure safe use and user's feeling of safety.* Strategies need to be developed to notify the user of a potentially hazardous situation.

To address these challenges, a literature search was conducted to identify the features that were crucial for SL control. It was found that the device: i. should be wearable; ii. could be used without interfering with the natural limbs; iii. could convey cues

with, at least, 2DoFs intuitively. Each item was considered fulfilled (marked with a ✓) if at least one example of an application for which the statement was true was found in the literature. Existing strategies to provide feedback from an artificial limb were investigated and compared given these three criteria as shown in Table1-1.
First, strategies that did not meet all three criteria were ruled out.

- *Kinesthetic devices* are a type of haptic device that exert forces or torques on their user [44]. They can provide a sensation of movement and force, which can be used for texture and shape recognition [45]. Kinesthetic feedback can be extremely realistic, but its application typically requires its user to manipulate a handle, thus requiring the use of hands. Moreover, kinesthetic devices are typically grounded and are generally larger compared to tactile displays. This does not make them great candidates to be integrated with SL.

Then, the remaining methods were investigated further and compared. A summary is provided in Table 1-2.

- *Vibro-tactile feedback* activates the mechanoreceptors of the skin and can be used to provide feedback for various tasks. Vibration cues require low powered actuators and can easily build on wearable devices. Typically vibrations are used in smartphones to notify the user of an incoming message or call. Vibration cues were also used to provide grasp information for a VR grasping task [24] or to provide position cues for a prosthetic arm [32]. For prosthetic use, vibration actuators are generally placed on the arm or forearm but they can be placed elsewhere on the body when required by the application. For example, vibration cues were used on a shoe sole to provide navigation assistance to blind participants [34]. Being low cost, easy to implement and lightweight, vibro-tactile feedback represent an interesting modality for SL control. However, understanding vibration cues often requires memorizing a code in order to interpret the meaning of each

Table 1-2: Feedback selection: pros and cons

Feedback Type	Wearable	Placement Restriction	Intuitive	Additional Comment
Vibro-tactile	Lightweight Low powered Easy to make wearable	No Placement Restriction	Sensation not natural Demand a learning phase	Limited resolution
Pressure	Lightweight Wearable cuff	Arm and leg restriction when worn as a cuff	Natural sensation	Limited number of DoF when used as a cuff Task specific
Electro- tactile	Lightweight Low powered Easy to make wearable	No Placement Restriction	Sensation not natural Demand a learning phase	Uncomfortable/ painful Calibration required
Skin Stretch	Wearable prototype exist	Placement restricted by the prototype shape	Natural sensation	Prototype is bulky Placement could be limited to forearm or leg

set of vibrations. Therefore, strategies need to be developed to provide cues that can be intuitively understood by the user.

- *Pressure feedback* has been used for both prosthetic arms [35] and legs [36] through the use of a hydrolic pressure system and pneumatic controlled air balloon actuators respectively. [35] found that providing the same pressure feedback to the robotic grasping force of the prosthetic could reduce grasping error. This method presents the advantage that it can provide sensory patterns similar to those in a natural grasping hand. While pressure cues can be intuitive to provide for grasping feedback, using a simple cuff would limit the number of

DoFs that can be transmitted. Therefore a thorough design should be thought of for it to be used for artificial proprioception.

- *Electrotactile feedback* is a commonly used method that allows for the activation of afferent nerves through the application of a depolarizing current. While this method has also been used with invasive techniques [46, 47], the most common one is to use non-invasive electrodes at the surface of the skin. Electro-tactile feedback can be used to report different types of sensations on different parts of the body. [37] used an electrode array placed on the tongue to provide balance-related cues to stroke participants; [38] managed slip control using an electro-tactile array on the lumbar area of the back; [39, 19] targeted the forearm for electrical stimulation using an electrode array to transmit different patterns and proprioception information respectively. Therefore, electro-tactile feedback can be used to report a wide range of sensations and is versatile in terms of body location. These qualities make it an interesting choice for SLs application. However, contrary to pressure feedback, sensations elicited via electrical stimulation are often reported as unnatural and can be considered uncomfortable if not tuned properly [48]. For this reason, a throughout investigation on the different parameters of stimulation and how they are perceived should be considered for each specific location of stimulation before designing an electro-tactile feedback device.

- *Skin stretch feedback* works on the principle of imparting localized skin stretch either in the lateral direction or using a rotation motor. The idea is to take advantage of the fact that skin stretch is one of the perceived sensations which contributes to the sense of proprioception. [40] designed a device that can be mounted on a participant's arm or leg, typically near a joint. The device is wearable and is composed of a two points rotational motor that can provide feedback consisting of positive or negative rotation angles. Differences in both intensity and velocity can be perceived by the user which allows providing intuitive proprioceptive cues. The design proposed by [40] presents clear advantages to provide intuitive proprioceptive cues for a prosthetic arm. However, both placement and the number of DoFs that can be transmitted would be limited as the device is quite bulky and would only be able to provide information relative to the motion of a single joint. Additionally, skin stretch can also be used to simulate friction to place an object in a precise position and orientation [42, 43]. Typically, a shear force is applied to the user's finger pad or the user's forearm [49], similar to the skin deformation that occurs naturally during haptic interactions. With this method, two DoFs of shear can be displayed allowing for directional cues and making this method promising for artificial proprioception.

Among the four modalities that were fulfilling the criterion, I selected two that had devices we had access to: *Vibro-tactile* and *Electro-tactile* feedback. Both methods had the potential to be used for proprioceptive cues for an artificial arm motion in a 2DoFs and 3DoFs space as well as could be made wearable on different placements on the user's body. This last point represents an advantage for SL application as optimal feedback placement is unknown.

1.3 Research Aim

From the literature, we can see that artificial haptic feedback can help improve the intuitiveness of user control. So far, it was predominantly used to improve prosthesis control. Proprioception aids us to move and adjusting our trajectories in space when we control our natural limbs. For this reason, proprioception, the sense of body position and motion, might be central for effective SL control. Emulating a sense as complex as proprioception is strenuous, however tactile cues may be used as a sensory substitution strategy to provide artificial proprioceptive information. Somatosensory feedback could contribute to the integration of the SLs system into the body schema, which is a critical consideration for human augmentation. Without sensory feedback, users depend on continuous visual servoing, often resulting in fatigue. In the context of developing and understanding somatosensory feedback for SLs, in this work, I selected two feedback modalities, vibration and electrical stimulation, to provide proprioceptive information through tactile cues. I tested the following:
With electrical stimulation:

1. How is the perception of electrical stimulation affected by its parameters (frequency and intensity)?
2. What combination of parameters is better understood to map proprioceptive information in 2DoFs?

With vibration feedback:

1. In a 2DoFs controlled task, is task space feedback more intuitive compared to joint space feedback?
2. Can we provide proprioceptive feedback in 3DoFs?

Chapter 2 Using Electro-tactile Feedback

Two pilot studies were conducted to evaluate both the perception and usage of electrotactile feedback for human-robot interaction. Both studies were conducted in collaboration with Dr Ekaterina Ivanova, a post-doctoral fellow in the Human Robotics group, who participated in the protocol design and conducted the statistical analysis. The present chapter was adapted from our work presented at the IEEE EMBC 2021 conference [50]. The studies were carried out using a Tecnalia system with multi-field electrodes (described in Chapter 2.1.1). The electrodes consist of 16 flexible fields, arranged as a bracelet. For the first experiment, only one electrode was used. For the second experiment, 15 electrodes were used as one electrode was required for grounding. A Matlab application described in Chapter 2.3.2 was used to map the stimulation to an area of the monitor as shown in Fig.2-4 and described in Chapter 2.3. The studies were approved by the College Ethics Committee (SETREC reference: 21IC6935).

In the first *perception experiment (2.2)* , the influence of 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, I used questionnaires and electrodermal activity (EDA) measurements to evaluate the effect of different stimuli.

In the second *proprioception experiment (2.3)*, the subject's ability to associate the feedback to spatial locations was studied for 5 different mappings. I evaluated participants' performance, success perception as well as acceptance for each mapping. A combination of metrics consisting of a questionnaire, error measurement, time and EDA measurements were used for that purpose.

The metrics are further describe in section 2.1.2 and the questionnaires can be found in the appendix section A.1 and A.2 respectively.

2.1 General Methods

2.1.1 Feedback Device

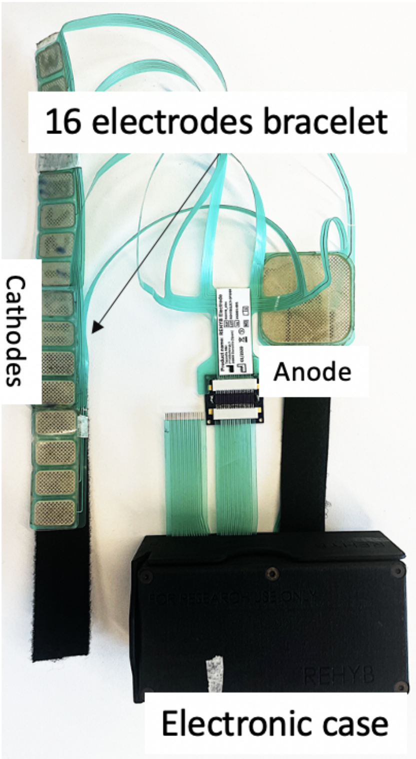


Figure 2-1: Electro-tactile device, CLASS system, Tecnalia Research Innovation, San Sebastian, Spain, 16 cathodes and 2 anodes (electrode dimension 11x20 mm) on flexible material attached to the electronic case.

The electro-tactile cues were transmitted with the CLASS system (Tecnalia Research Innovation, San Sebastian, Spain) combined with 16 field electrodes that can be activated independently. The flexible electrodes (see Fig.2-1) are aligned and can be worn as a bracelet when wrapped around the arm. Measure between two adjacent electrodes center is 11 mm. Electrodes can be modulated in both intensity and frequency independently, therefore allowing for a large number of mapping possibilities.

The stimulation module generates electrical impulses which are transmitted to the skin. The electrodes are used with hydrogel to reduce skin impedance and facilitate current delivery. The system is controlled using a custom made text-based command protocol in a variety of languages (Python, Matlab, C, etc.). Table 2-1 shows the stimulation-related configuration parameters and their ranges.

Table 2-1: Parameter of stimulation specification

Nr. of channels	16	
Pulse frequency	35 - 200 Hz	resolution of 1 Hz
Pulse Intensity	1 - 90 mA	resolution of 1 mA
Pulse width	100 - 400 μs	resolution of 10 μs
Max. output voltage	200 V	

2.1.2 Metrics

EDA measurements

Electrodermal activity (EDA) is a physiological data commonly used as a psychophysiological measurement of emotional arousal. EDA is measured as the skin conductance variation in response to sweat secretion and is composed of both tonic and phasic components.

The tonic activity, referred to as the skin conductance level (SCL), corresponds to the background level of EDA that varies slowly. In contrast, the phasic activity, referred to as the skin conductance response (SCR), is defined as a sudden and transient increase of activity in response to a specific event.

An E4 wristband (Empatica, USA) was used to record EDA and the analysis was performed using Ledalab, a Matlab open-source software [51] for EDA analysis.

After acquisition EDA data were low pass filtered (Butterworth filter with a cutoff frequency of 1 Hz) to decrease small movements artefacts. Larger artefacts that could not be removed with a filter were visually identified and manually removed (as described in [52]). Then a continuous decomposition analysis (CDA) was applied to the filtered data in order to decompose the data into its continuous tonic (SCL) and phasic (SCR) components as shown in Fig.2-2. The CDA method is based on Standard Deconvolution technique and is the recommended method to analyse skin conductance data [53]. Among the metrics extracted, two were used :

- ISCR which is the integrated skin conductance response within the response window.
- SCL which is the mean tonic activity within a response window.

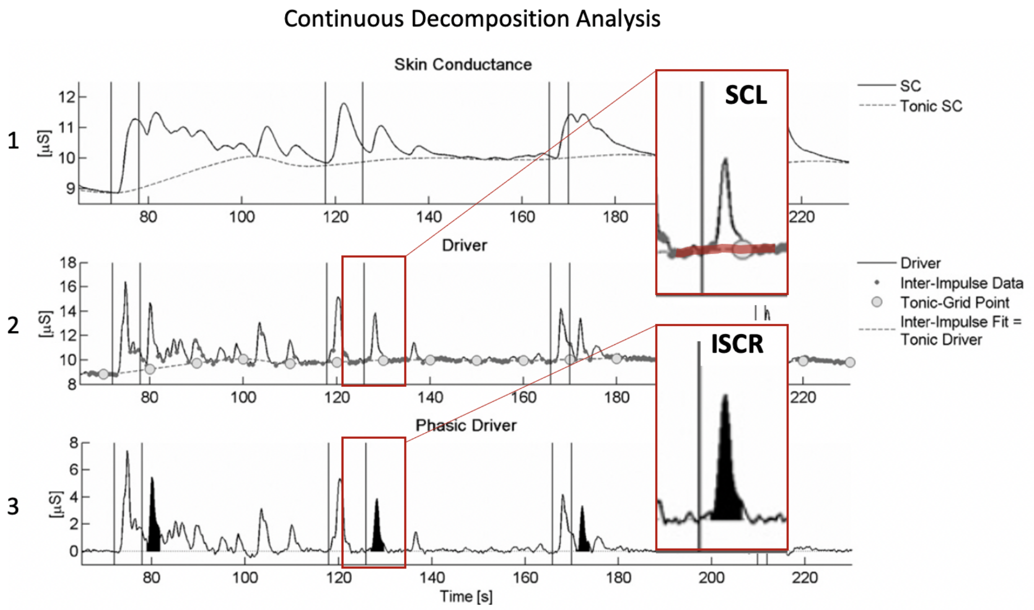


Figure 2-2: Continuous decomposition analysis (CDA) as proposed in [53]. The three steps method consists of: 1. a data deconvolution, then 2. the tonic activity is estimated and subtracted to the data so that 3. the phasic activity can be estimated. Skin conductance level (SCL) is extracted in the second step where it is defined as the mean tonic activity in the response window. Integrated skin conductance response (ISCR) corresponds to the integration of the driver's peak in the same response window in the third step.

The response window was taken from 1s to 6.5 s after an event for the *Perception Experiment* 2.2 and from 1s to 4s after an event for the *Proprioception Experiment* 2.3. The time window for the *Perception Experiment* was extended because our strategy to mark the event was less precise than for the *Proprioception Experiment*.

Questionnaires

Questionnaires were used to evaluate participants' perception of the stimulation.

For the first experiment on *perception*, the questionnaire (available as Appendix A.1) consisted of demographic questions followed by a perceptual evaluation of each stimulation. The latter consisted of 8 items that should be filled after every single stimulation. The first item assessed whether or not the stimulation could be felt in the form of a yes or no question. For the 7 remaining items, I used a Goodspeed questionnaire adapted from [54] which consists of adjectives that participants need to rate on a scale from 1 to 9:

Q2 1 - Unpredictable ———— Predictable - 9

Q3 1 - Unatural —————- Natural - 9

Q4 1 - Unsettling ————— Reassuring - 9

Q5 1 - Typical —————— Strange - 9

Q6 1 - likable —————— Dislikable - 9

Q7 1 - Pleasant ————— Unpleasant - 9

Q8 1 - Painful —————— Painless - 9

For the second experiment on *proprioception*, a similar questionnaire (Appendix A.2) was used to evaluate the perception of the stimulation after each mapping. An

Edinburgh inventory [55] was added to the demographic questionnaire and items 1 and 2 on whether or not the stimulation was felt and if it felt unpredictable were removed as they did not make sense for a train of stimulation. Items 3 to 8 were kept and were evaluated after each feedback condition. Additionally, for each conditions, participants were asked to rate their performance on a 5-items Likert scale. For this they were asked to rate from 1 (strongly disagree) to 5 (strongly agree) their ability to accurately locate the angular segment, radial segment and in general, their position on the grid. Finally general questions on participants perception of electrical stimulation were asked at the end of the experiment.

2.2 Experiment 1: Perception Experiment

2.2.1 Protocol

10 subjects (three female, aged 27.2 ± 3.15). For each participant: i) informed consent before 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; and iv) a total of 15 trials were performed in a randomised order. For the stimuli I used three levels of pulse frequency $\{35, 100, 200\}$ Hz and four levels of intensity $\{1, 3, 5, 7\}$ mA plus a sham stimulation at 0 mA. Each trial consisted of a single stimulation (2 s duration) with a combination of both parameters. After each trial, a questionnaire was filled out to characterize 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 ART ANOVA [56] was used to analyse the other items.

If a factor or interaction was significant, a post-hoc paired Wilcoxon signed-rank test with the Bonferroni adjustment was used to compare single levels of the factor.

2.2.2 Results

A two-predictor logistic model was fit to the data to test the subject electrotactile feedback likelihood to stimulation intensity and frequency relationships. 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, sham stimulation (0mA) and pulse intensities of 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 ($\beta_2 = 0.003$, $p < 0.7090$).

An ART ANOVA revealed that pulse intensity significantly influenced the participant's response for the "reassuring – unsettling" scale (Fig. 2-3C, $F(2,69) = 7.19973$, $p = 0.00145$), 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. 2-3B), 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 pusle with 7 mA ($Z = -3.6272$, $p = 0.0001$) or 5 mA ($Z = -2.7212$, $p = 0.01373$), but no difference was otherwise

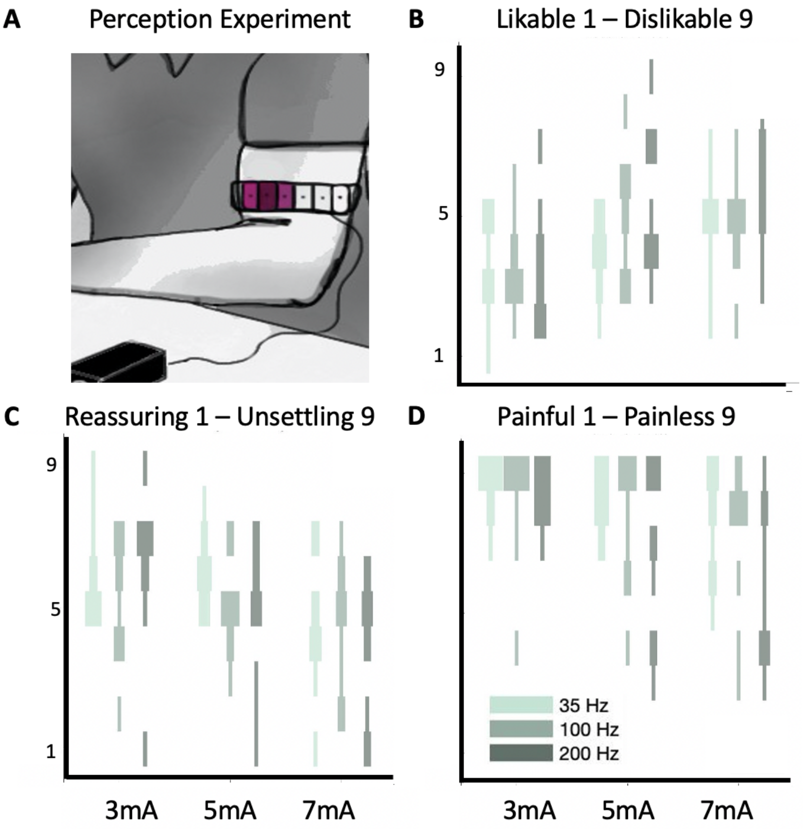


Figure 2-3: A: Experimental setup of the perception experiment. One of the three stimulating electrode (in pink) is selected before the experiment. B: Likable – Dislikable. C: Reassuring – Unsettling. D: Painful – Painless. Feedback perception on 9-point scale. The block width is proportional to the number of participants selecting that answer.

found ($Z = -1.2714$, $p = 0.6582$). The "painful – painless" scale rating (Fig. 2-3D) 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 ($p > 0.1$).

Results from Electrodermal Activity

To evaluate the physiological response to different amplitudes and frequencies of the electrotactile feedback I analysed event-related ISCR metrics. An ART ANOVA showed that the phasic activity of the EDA was not influenced by neither of these factors ($F(4, 125) = 0.48491$, $p = 0.74678$ for amplitude, $F(2, 125) = 0.49161$, $p = 0.61282$ for frequency and $F(8, 125) = 0.91551$, $p = 0.50607$ for the interaction of both). Only three participant from ten showed an event based ISCR response in the first experiment. Indeed, the median of ISCR over all groups was quite small, $M = 0.0256$, median absolute deviation $MAD = 0.0332$, interquartile range $IQR = 0.0843$, so that the ISCR was relative small in most cases. Therefore, either this measure is not suitable for evaluating the emotional state of subjects for this type of stimuli, or the range of stimulation was not provoking an emotional response.

2.3 Experiment 2: Proprioception Experiment

2.3.1 Additional Metrics

Error

To account for the performance for the *proprioception experiment* the error was calculated as the radial, angular or total difference between the interpretation and the stimulation position as described in Fig.2-4. I differentiated the angular error, which can indicate the spatial resolution and the radial error which assessed the mapping efficacy to transmit the radial information.

Click Time

The time it took for participants to give their answer from the moment the stimulation was received was recorded and referred to as the click time. The click time or completion time can indicate the cognitive load of a task and of its difficulty [57].

2.3.2 Experimental Set Up

To evaluate the different mappings between sensory cues and robot position, a simple *Matlab* application was developed. This application was used to compare and select the most appropriate mapping for a task. Both performance and intuitiveness of the mapping were considered and evaluated through error measurements, the average time taken to identify the position and questionnaires.

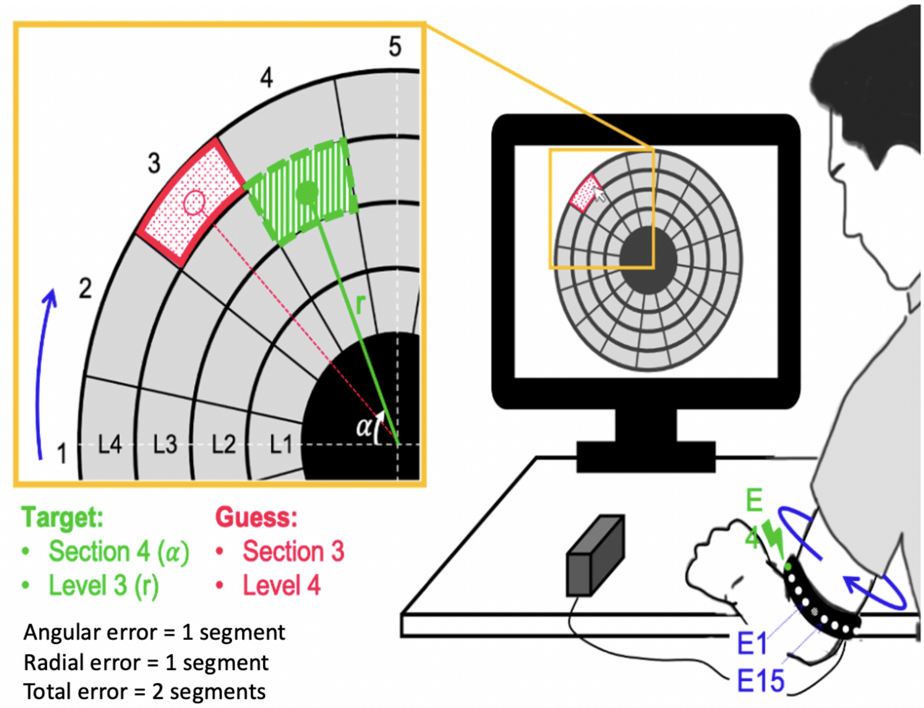
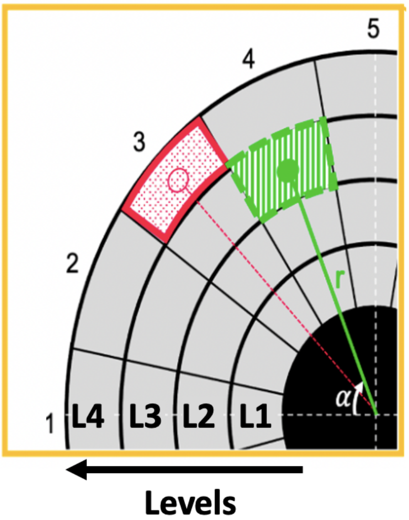


Figure 2-4: Experimental setup of the proprioception experiment. The subjects were wearing the electrical stimulation device around their left (non-dominant) arm. A stimulation that corresponds to a target area (green) was received and the subject interpreted its encoded placement on the grid (red). The grid was divided in 16 sections (S1 to S16) and four radial levels numbered as shown (L1 to L4). The error was calculated as the radial, angular or total difference between the interpretation (red) and the stimulation position (green).

Figure 2-4 shows the experimental set-up used for the experiment. The *Matlab* application was used to evaluate each sensory cue-position mapping. Participants were stimulated with a tactile cue on their arm and had to interpret the corresponding position on the on-screen 2D grid. A total of 64 cells (16 sections x 4 levels) were mapped to the feedback system.

2.3.3 Protocol

10 healthy right-handed subjects (four female, aged 26.54 $\pm$ 3.75) took part in the proprioception experiment. The electrotactile system was attached to their non-dominant arm at elbow level. Participants' handedness was assessed using the short version of the Edinburgh inventory as described in [55]. To ensure consistency between subjects, the non-dominant hand was immobilised in a custom-made structure. The E4 watch was attached to the same wrist *[Different from the first experiment as I saw that free wrist motions could create artefacts in the EDA signal].* Electrical stimulation from the bracelet was mapped to the monitor as shown in Fig.2-4. 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 (L1 to L4 as shown in Fig.2-4), was mapped using one of the five coding scheme described in Fig.2-5. Building on the results obtained during the *perception experiment (2.2)*, each mapping was designed so that the intensity of stimulation was kept as low as possible to maximize participant's comfort. Moreover, since the effect of frequency level was unclear, the frequency levels were chosen so that the difference between them was maximized. The whole range of position was divided in 16 sections (S1 to S16) and four radial levels (L1 to L4).



Cond	Intensity mA L1|L2|L3|L4	Frequency Hz L1|L2|L3|L4
II35	Increase with level Th|Th+1|Th+2|Th+3mA	Constant 35Hz
II100	Increase with level Th|Th+1|Th+2|Th+3mA	Constant 100Hz
IF	Constant Th+2mA	Increase with level 35|90|145|200Hz
IFF	Increase with level Th|Th+1|Th+2|Th+3mA	Increase with level 35|90|145|200Hz
2I2F	low low high high Th+1|Th+1|Th+4|Th+4mA	Low high low high 35|200|35|200Hz

Figure 2-5: Description of the 5 feedback mappings for radial level L1 to L4: 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 the angular position was given by the position of the activated electrode.

Each electrode was calibrated for the minimal perceptible stimulation amplitude. 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 as shown in Figure 2-6.

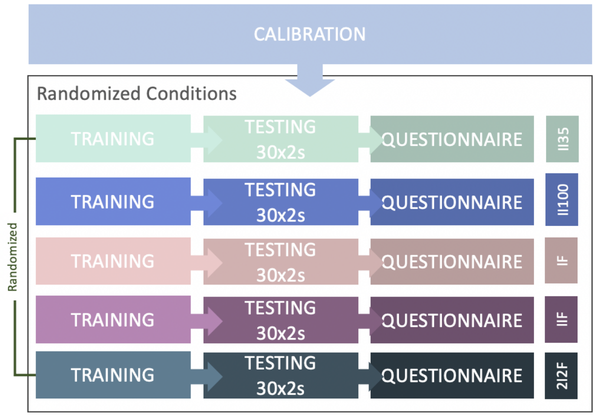


Figure 2-6: Proprioception Experiment flowchart. After calibration, each condition is tested in a randomized order. For each condition, participants perform a training session, a testing session (30x2s trials) and fill out a questionnaire.

- Training: Participants received a stimulation while the corresponding grid segment was highlighted (see Fig. 2-4), so that they had a visual representation of the active stimuli. The grid was circle-shaped and had 64 cells (16 angles $\times$ 4 radii). 16 stimulations were provided sequentially, following the vertical and, then, horizontal axis on the screen.

- Testing: 30 unique stimulations were presented in a randomized order. Each was 2 s and associated with one of the 64 cells. The stimulation parameters were determined by the mapping described in Table 2-5. For each stimulation, the participant had to click the segment that they attributed the stimulation to.

2.3.4 Results

To evaluate the subjects' performance with different feedback conditions, the angular, radial and total errors, as well as reaction time, were analysed. The angular/radial errors were calculated as the number of section/levels that the subject's response deviated from the correct response (see Fig. 2-4). The total error is the sum of both, angular and radial errors, and represents the total difference in the amount of sections and levels between subjects' and correct responses. To compare the actual performance with the perceived success, the 5-point Likert scale was analysed and correlated with objective measures. We also analysed the subjective judgment of each feedback type and compared different conditions regarding their likability, perception of pain and unsettlement.

Due to the small sample size and the fact that the data for most of the metrics was not normally distributed, a non-parametric Friedman test of differences among repeated measures was conducted for the analysis of each metric. For the pairwise comparisons between single feedback conditions, a post-hoc paired Wilcoxon sign-rank test was employed and the Holm-Bonferroni adjustment was used to control the family-wise error rate. For the statistical analysis of the objective values, the observations for each subject were averaged over all trials in a block. Additionally, the differences between feedback conditions II35 and II100 were compared separately with paired Wilcoxon sign-rank test. These two conditions are presenting the same feedback modality with two different frequencies, which were chosen based on the results of the previous experiment (*perception experiment*, Chapter 2.2).

Performance

No differences between feedback conditions II35 and II100 were found, therefore only feedback II35 was considered for subsequent condition comparisons.

A Friedman test revealed no significant difference for the angular (Fig.2-7B1, $\chi^2(3) = 2.6633\, p = 0.4465$) or total errors over the mappings ($\chi^2(3) = 6.4839\, p = 0.0903$). On average, the segment error was one in 67.2754 % of the missed trial over all groups (between group standard deviation (SD) = 2.6001). In contrast, the radial error difference between groups (see Fig. 2-7B2) was significant ($\chi^2(3) = 17.9070\, p = 0.0005$): in condition II35 ($median(M) = 0.6833$, median absolute deviation (MAD) = 0.19768) subjects had higher error compared with conditions IIF ($M = 0.4$, MAD

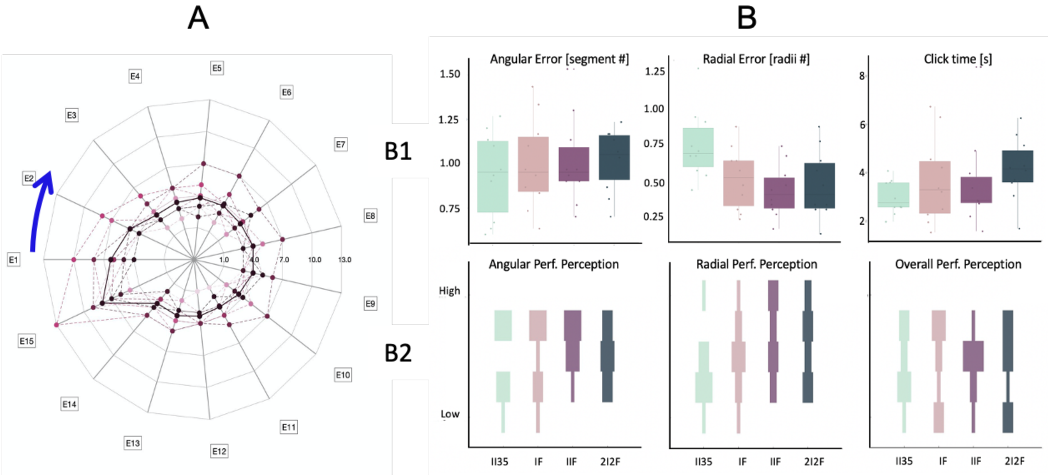


Figure 2-7: A: Sensitivity threshold (mA) for all subjects. B: B1: Performance results. B2: Subjective performance perception (rated from 1 (low performance) to 5 (high performance) on a Likert scale) in distinguishing between angular sections, radial sections or overall location of the stimulation.

$= 0.1167$) and 2I2F ($M = 0.4$, MAD $= 0.1333$, both with $p < 0.04$). Moreover error in condition IF ($M = 0.5167$, MAD $= 0.1667$) 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.
A significant influence of the feedback type on the reaction time was found using a Friedman test (Fig.2-7B1, $\chi^2(3) = 8.280\, p = 0.04057$). 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).

Perception of performance

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. Although, a Friedman test did not reveal any differences between the mappings in 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. 2-7B2 it can be seen that the perception of success is lowest in II35 and the highest in IIF. This reflects the objective measures (Fig. 2-7B1): radial error in II35 was higher than the other conditions and IIF tended to have the best performance.

Perception of feedback

Participants were asked to rate the feedback conditions on the same scales as in the experiment 1: (1) “unsettling – reassuring”, (2) “likable – dislikable”, (3) “painful – painless”. Friedman test showed that feedback condition did not have an influence on the subjects' perception regarding scale (1)($\chi^2(3) = 3.040$, $p = 0.3855$) and (2)($\chi^2(3) = 1.7308$, $p = 0.6301$). However, the groups were different on the scale “painful – painless” ($\chi^2(3) = 9.3673\, p = 0.02479$). Post-hoc revealed the largest differences between the feedback II35 ($M = 9.0, MAD = 0.0$) comparing to condition IF ($M = 8.0, MAD = 1.4826$) and 2I2F ($M = 8.5, MAD = 0.7413$), which were not significant after the adjustment for multiple comparisons (both $p > 0.2$). This tendency shows that all feedback conditions were not associated with pain or discomfort.

Electrodes Placement and Sensitivity Threshold

To analyse the relationship between electrodes placement and electrotactile feedback sensitivity, I compared the calibration thresholds. A Friedman test revealed significant ($\chi^2(14) = 67.344$, $p < 0.0001$) differences between the electrodes. Placement of the electrodes and their thresholds are presented in Fig.2-7A 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 $p < 0.5$).

Results from Electrodermal Activity

To evaluate the emotional state of the subjects during each feedback condition, I used non-specific ISCR and SCL. SCL also reflects a change in cognitive activity [58]. Both metrics were not significantly influenced by the feedback type ($\chi^2(3) = 1.56\, p = 0.6685$ for ISCR, $\chi^2(3) = 0.6\, p = 0.8964$ for SCL).

2.4 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.

I 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, I decided to compare different mappings that transmitted the proprioceptive cues with different combinations of pulse intensity and frequency (see Fig. 2-5).

No significant difference between the conditions could be observed from the angular error. Moreover, the section was missed by one in almost 70 % of the cases for all the conditions. This indicates that the stimulation could not be accurately determined, but could still be guessed in its vicinity with a precision of ± 1 electrode (11 mm). The precision obtained was worse than in [59] at the forearm in a two point discrimination threshold (TPDT) experiment where they found a TPDT of 9.48 mm. This lower spatial resolution could partially be explained by the electrodes that were used (Figure 2-1) 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 [23], 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 observation is consistent with [59] findings stating that there is a frequency at which participants find it easier to discriminate between two different stimulus but this frequency varies greatly among participants. For the condition IIF, with the best radial error, the success rate in differentiating the four radial levels was $63\% \pm 12.3\%$. This is lower than the $86.6\% \pm 11.4\%$ success rate that was found in [32] to discriminate between four vibration levels. The radial error 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 setup 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 best performance. This condition also corresponded to the highest subjective perception of success.

In conclusion, participants could localize the stimulating electrode with a precision of ± 1 electrode (11 mm) in all feedback conditions. This precision could be improved with the use of concentric electrodes. 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 (IIF). The participants were naive to the mapping pattern and were not given any verbal explanation on how the position cues were transmitted. This shows that the strategy choose to deliver the feedback was intuitive as it could be understood with no verbal explanation. This is promising for the application of electrotactile feedback as a mean of intuitive human-robot interaction. Results of the EDA data analysis were not significant. SCRs were not correlated with high frequencies or amplitude as was expected. In both experiments, the tonic level was increasing with the trial order/ time but was not correlated with other factors. This could mean that, in general, the tonic level increases with time which could be due to a change in temperature, or just that the E4 wristband needs more time to record a clear baseline. Moreover, the fact that I didn't detect any significant correlations with SCRs can show that the device was not causing any significant sympathetic response. The values of the SCRs are really small in average which is coherent with the questionnaire data showing the stimuli were not perceived as extremely painful or unsettling.

Chapter 3 Using Vibration Feedback

A study was conducted to compare the effect of task and joint space proprioceptive feedback on the control of a virtual robot arm. The feedback was delivered using an 8 vibro-motor bracelet positioned on the participant's upper arm (see Chapter 3.1). The artificial arm was controlled in 2DoFs with a keyboard controller as described in chapter 3.2. For both types of feedback, four conditions consisting of different haptic and visual feedback were tested. Both the intuitiveness and performance of the task for each type of feedback were evaluated and compared. This study was conducted under college ethical approval (SETREC reference: 21IC6935).

3.1 Feedback Device

Figure 3-1: Vibro-tactile device with 8 vibromotors from [32]

Vibration cues were used to provide artificial proprioception. The device, borrowed from [32] consists of an 8 vibro-motors bracelet (see Fig.3-1) and can be worn around the forearm or above the elbow. The intensity of vibration of each motor can be controlled independently to provide proprioceptive cues. This allows for the design of different mappings to transmit information relative to a robot position either in task space or in joint space.

3.2 Experimental setup

Simulation Interface

To conduct the experiment, I used an on-screen simulation of a robotic arm. The simulation consists of a virtual Panda arm (Franka Emika) simulated in *Gazebo* through a *ROS* interface. The simulation was adapted from [60] and provides exposed controllers and real-time robot state feedback.

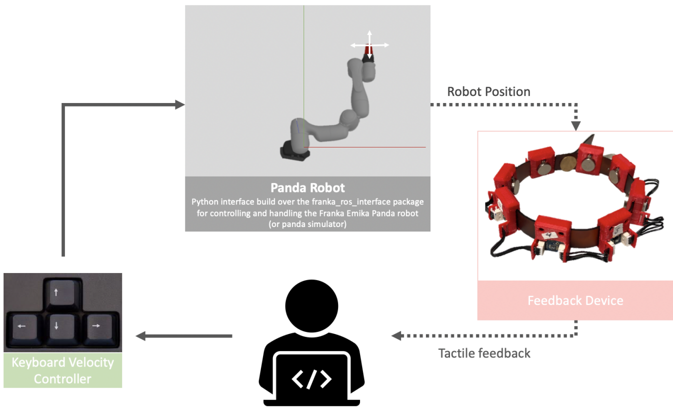


Figure 3-2: Diagram of the ROS implementation set up. The Gazebo simulation of the Panda robot is controlled by the user through keyboard cues. The robot position is translated into tactile cues which are transmitted to the user via the vibro-tactile device.

Control

The panda arm was controlled by the participant with a 2DoFs keyboard velocity controller as shown in Fig.3-2. Two controllers were designed, one in task space and one in joint as shown in Fig.3-3.

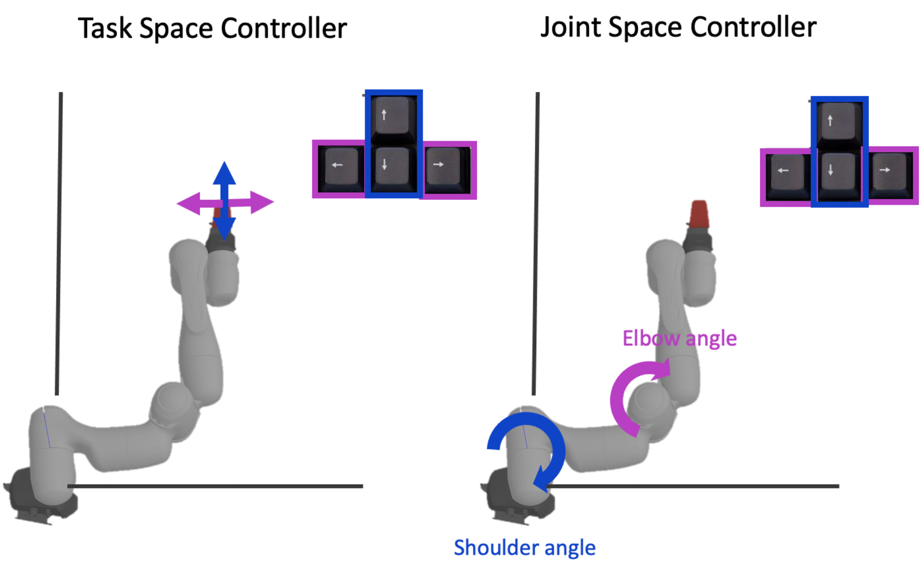


Figure 3-3: Task space and Joint space keyboard controllers.

In the *task space condition*, the participant controls the panda arm end-effector in the x-y directions. The keyboard arrows are mapped to the Cartesian directions. In the *joint space condition*, the participant controls the shoulder and joint angles of the robotic arm. One pair of arrow keys (left/right) is mapped to the angular aperture of the shoulder angle and the other pair (up/down) is mapped to the elbow angle. In both cases, the z plane is fixed throughout the entire experiment so that the robot remains on a 2D plane.

Feedback mappings

The robot positions were mapped in real time to the sensory feedback device that was connected through a serial port. I used two mappings for the feedback, one in task space and one in joint space, as shown in Fig.3-4.

For the *task space mapping* (Fig.3-4A), the 8 vibration motors are mapped to the polar position of the end-effector of the panda arm. Each motor (M1 to M8) corresponds to one polar segment on the grid. Therefore, a motor is activated when the end-effector's angle α is in the corresponding segment. The radial coordinate (r), which

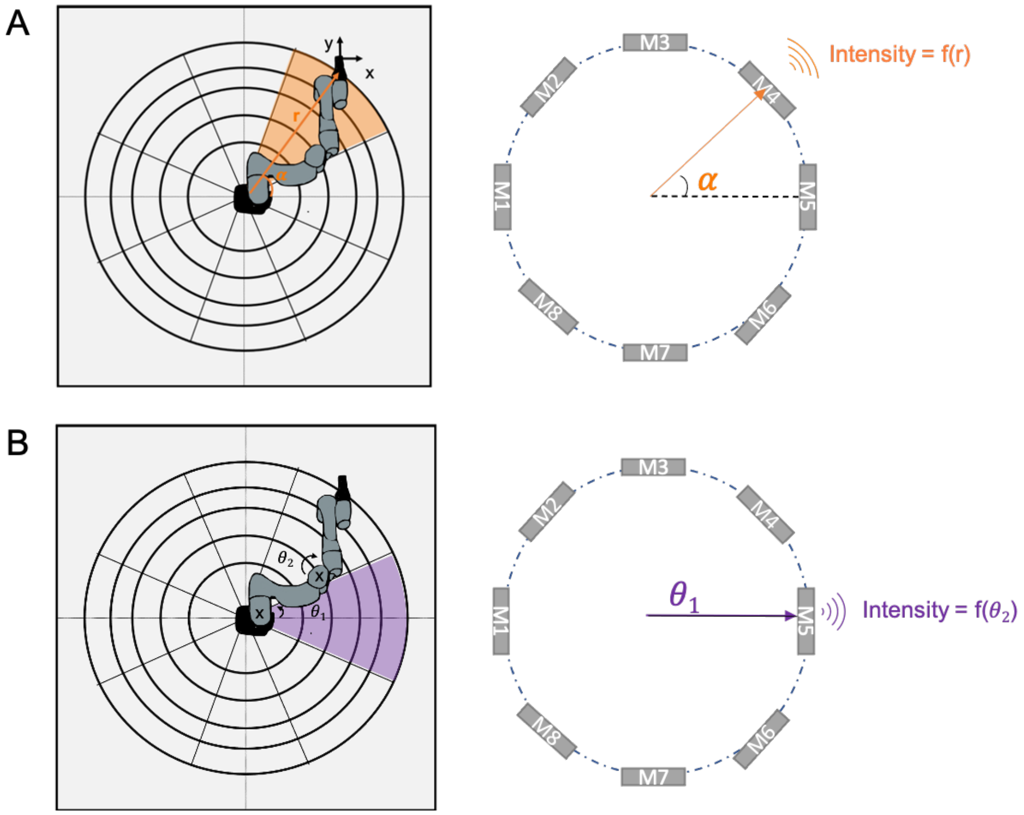


Figure 3-4: A: Task space mapping; end-effector position $\{\alpha, r\}$ and tactile cues. B: Joint space mapping; joint positions $\{\theta_1, \theta_1\}$ and tactile cues.

corresponds to how extended the arm is, defines the intensity of stimulation out of four intensity levels (radial levels). The intensity of the levels was increasing linearly from the center.

The same mapping strategy was previously used in [32] with the same vibration device. I choose the single motor activation strategy among others because it was the most simple one and there was no significant advantage of using another one.

For the *joint space mapping* (Fig.3-4B), the vibrations are mapped to the shoulder, θ_1, and elbow joint, θ_2, of the panda arm. Once again, each motor (M1 to M8) corresponds to one polar segment on the grid. A motor is activated when the shoulder joint angle θ_1 is in the corresponding segment. The elbow joint angle, θ_2, is then proportional to the intensity of stimulation which is as previously divided in 4 levels. This joint space mapping was selected before the experiment among 6 others in the context of a co-supervised MSc project conducted by Paula Bernardo. This mapping was chosen as the most intuitive and the easiest to use, based on reaction time and performance measurements on 3 subjects during a preliminary feedback mapping evaluation.

Task

The simulation consisted of a reaching task, during which a target (red cube) is presented and disappears once it is reached. To complete the task, participants need to reach the target within a time limit. The target can appear in 20 different positions distributed randomly on the map. The virtual robot appearance was manipulated to provide different types of visual feedback, eg. the robot was shown or not. The virtual arm is shown in Fig.3-5.

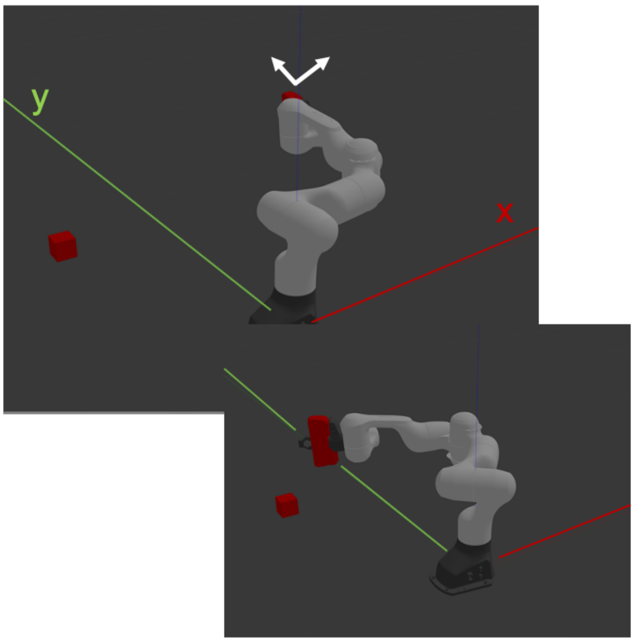


Figure 3-5: Reaching task with the Panda Simulation. The panda arm is controlled with a keyboard velocity controller. To complete the task, the user has to reach the red cube, located on the same z-plan.

3.3 Metrics

Questionnaires

I used a custom questionnaire to evaluate the participants' perception of their performance and their preference concerning different mappings (Appendix A.3). The questionnaire consisted of demographic questions followed by a perceptual evaluation of the participants' performance for each mapping strategy (task or joint space) and each feedback condition (V, VT, T, NF). 7 items were evaluated on a Likert scale from 1 (Strongly agree) to 5 (Strongly disagree). The questions were relative to the participant's understanding of the feedback (for example *I felt like I understood the directions from the tactile feedback* and *I felt that I knew the position of the robotic arm in each moment of time during the trials*) and if it helped them perform the task (for example *I felt that the tactile feedback was useful to accomplish the task*). Additionally they were asked about which of the feedback they most relied on among the *Visual*, *Tactile* and *Keyboard cues* and how much they used each of them during each condition. Finally, the last part of the questionnaire focused on the comparison of task and joint space feedback with a combination of multiple-choice questions and a 5-items Likert scale.

Performance

To evaluate the performance during each condition the error was computed as the distance, in number of segments, between the last position of the robot end-effector and the position of the target. Similar to the studies presented in Chapter 2, the error was measured both in the angular and radial directions as this information was conveyed in different ways (mapping between position cues and feedback is described in Fig.3-4). Additionally the time to reach target and the total distance travelled were saved for each trial.

3.4 Protocol

6 participants (two female, aged 27.5 ± 4.41) enrolled in the study. For one participant, the data was corrupted and couldn't be used for performance assessments. Each participant repeated the experiment twice in a random order, once with the feedback and controller in task space and once in joint space. The participants were recruited amongst Imperial College's students, who were all naive to the experiment and the feedback device.

The 8-unit vibro motors bracelet described in chapter 3.1 was used to transmit the proprioceptive cues from the virtual Panda arm (chapter 3.2). The feedback bracelet was worn above the elbow, as this placement could be easily mapped in the same plan as the virtual robot. The simulated robotic limb was controlled via a keyboard controller. The motors on the bracelet were mapped to the monitor as explained in chapter.3.2.

The experiment protocol is shown in Figure 3-6. At the start of the session, a calibration was conducted to determine the minimum perceptible intensity of stimulation for each motor. Then, the experiment was repeated twice, once in task space and once in joint space for both feedback and control. Each time participants performed training and a testing phase and filled a questionnaire. The phases unfolded as follows:

- Training: participants could freely control the robotic limb for 2 x 60 seconds while receiving real-time position feedback from the bracelet. At the end of the first 60 seconds, participants were asked to explain the mapping between the vibro-tactile cues and the 2D positions. An explanation was provided if the mapping could not be guessed correctly.

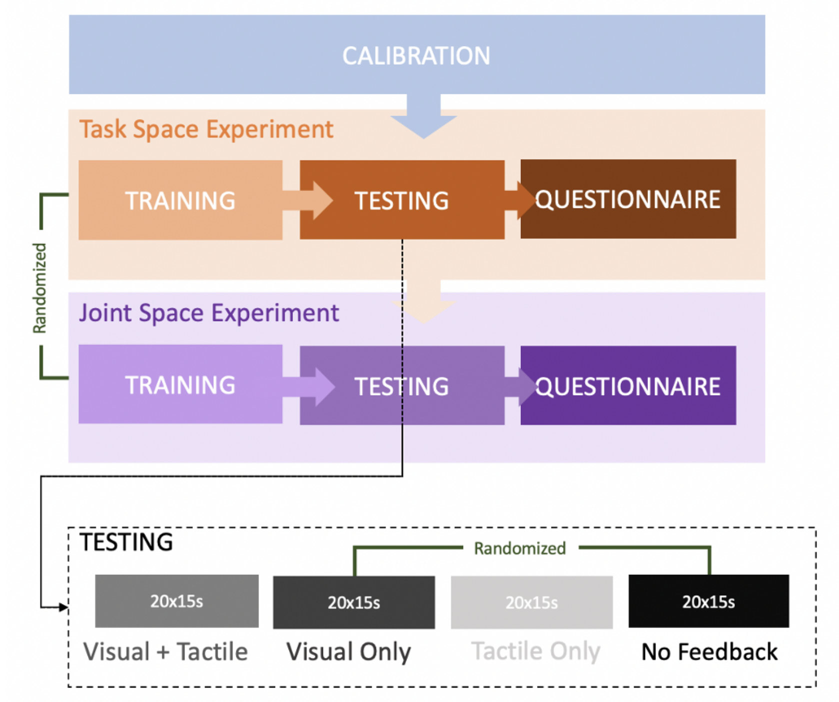


Figure 3-6: Experiment flow chart. A calibration phase is followed by both joint and task space experiments (random order). During each experiment, a training phase is followed by a testing phase before a questionnaire is filled. During the testing phase, 20x15s trials are presented for each of the 4 conditions. Each experiment starts with a first block of 20 trials from the visual + tactile feedback condition. Then, the remaining of the trials (20 per conditions) are performed in a randomized order.

- Testing: participants performed a reaching task in 4 conditions

    1. VT: Visual + Tactile feedback
    2. V: Visual feedback only
    3. T: Tactile feedback only
    4. NF: No visual nor tactile feedback

Each condition contained 20 trials, during which one target, randomly selected among 20, was presented. A trial finished when the target or the time limit (15s) was reached. The first condition's 20 trials (VT) were performed first in one block. The three other conditions were randomized at the trial level.

For both experiment the time to reach target, total distance travelled and performance was computed. Both angular and radial errors were considered. Because of the small sample size, the data were not normally distributed. Therefore, a non-parametric, two samples Wilcoxon test was used to calculate statistical significance. Results of the test were considered significant if the p-value was lower than 0.05.

3.5 Results and Discussion

3.5.1 Learning Effect

A linear regression approach was used to evaluate if a learning effect could be observed during the visual conditions (condition V&VT). The time to reach target (TRT) and the total distance travelled (TDT) were fitted across time for each trial in chronological order (n = 40). No significant learning effect was observed for either experiment; task space : TDT: $\{ \rho = -0.081, \beta = 0.619 \}$; TRT: $\{\rho = -0.296, \beta = 0.0639 \}$; joint space: TDT: $\{\rho = -0.018, \beta = 0.91 \}$; TRT:$\{\rho = -0.156, \beta = 0.335 \}$. Although no effect was observed, in joint space participants would take significantly more time (pvalue = 3.63 e-14) and travel more distance (pvalue = 1.43 e-34) compared with task space.

3.5.2 Performance

The participants' performance was compared between the conditions and the two experiments. The error is presented as the average number of segments from the target. When visual feedback was provided (V and VT), the task could be performed within the time limit in most cases (V:97% and VT: 100% success rate in task space and V:96% and VT:97% success rate in joint space), with a low angular (task space: VT:0.07 $\pm$ 0.255, V:0.05, $\pm$0.218; joint space : VT:0.09 $\pm$ 0.286, V:0.07 $\pm$ 0.255) and radial error (task space : VT:0.07 $\pm$ 0.255, V:0.12 $\pm$ 0.325; joint space : VT:0.23 $\pm$ 0.420, V:0.19 $\pm$ 0.392). The error was significantly higher in joint space (pvalue=0.00109) compared to task space during the VT condition.

During the two blind conditions (T and NF) the error was higher compared to the visual conditions (VT and V). Radial error (task space: T:0.68 $\pm$ 0.798, NF:0.73 $\pm$ 0.834; joint space : T:1.0 $\pm$ 0.74, NF:0.92 $\pm$ 0.832) was higher than the angular error (task space: T:0.35 $\pm$ 0.589, NF:0.4 $\pm$ 0.748; joint space : T:0.58 $\pm$ 0.666, NF:0.59 $\pm$ 0.679) both in joint and task space conditions. No significant effect of the tactile feedback in condition T compared to condition NF was found. However, both angular (0.00103) and radial error (0.0032) were significantly larger in joint space compared to task space during the blind conditions.

3.5.3 Perception

At the end of the experiments, participants were asked to compare the task and joint space experiments. 3 out of 6 participants found it easier to control the robot and felt more in control when using the task space controller. 1 participant found the joint space easier and the others felt that it was the same. 5/6 participants stated that they could understand the feedback better during the task space experiment. Moreover, when asked if the feedback was useful during condition T, 4/6 participants agreed, 1 strongly agreed and 1 was neutral in task space while only 3 agreed in joint space (1 was neutral and 2 disagreed) .

Additionally, participants were asked which feedback they relied upon during each condition (visual feedback, tactile feedback or keyboard cues). During conditions V and VT, in both experiments, all participants selected the visual feedback. During condition NF, participants relied on keyboard cues to estimate their position. Finally, during condition T, 50% of the participant said they used the keyboard cues and the rest said they relied on tactile feedback.

3.6 Discussion

This study builds on the work from Alva 2020 [32] which demonstrated that vibration feedback can be used to transmit 2 DoFs position cues for a prosthesis. Using the same device as presented in Alva 2020, this work aim was to compare joint space versus task space feedback during a control task. I hypothesized that having control that matched the feedback would give agency to participants and increase their understanding of the feedback. Subjective questionnaires and performance assessments were used to determine which feedback and control strategy was the most intuitive and helpful to participants.

Control strategy

I observed that for the visual conditions (V, VT), the time to reach the target and the distance travelled were larger for the joint space. Moreover, the radial error was significantly larger using this space.

These two observations suggest that the joint space controller was less intuitive to use. Similarly, in blind conditions (T, NF), larger errors (both angular and radial) could be observed in the joint space. This suggests that participants were getting lost more easily with the joint space setup.

Feedback strategy

In task space, the effect of tactile feedback on the performance during the conditions without visual feedback (T, NF) was not significant. Moreover, the classification accuracy obtained for the radial level $48\% \pm 9.2\%$ was significantly lower compared to the $86.6\% \pm 11.4\%$ accuracy that was obtained by Alva 2020 with the same device. This suggests that the feedback did not help the participant to find the target. Since I used the same device and mapping as Alva the difference must be explained by differences in the experiment.

This difference could arise from the choice in the placement of the vibration bracelet. In this experiment, the bracelet was worn on the upper arm at the elbow level when it was worn on the forearm in Alva's experiment. Although placement can affect sensitivity, it is unlikely that it is the only factor that affected the performance results.

Therefore, I hypothesised that participants were able to rely on the keyboard cues to estimate their position. Thereby, they would not need tactile feedback as they could compensate for it. This is supported by the questionnaire results. During the tactile condition without visual feedback (T), 50 % of the participants said they were using keyboard cues to navigate. Moreover, I observed that even in the condition with no feedback at all, participants were still able to find the target with a 35% success rate. Showing that participants were still good at knowing where they were without feedback. This should be taken into consideration in future experiment design. The task should be designed so that haptic feedback needs to be used.

In joint space, the same observation could be made, the feedback did not help the participants in the tactile condition (T) compared to the condition with no feedback (NF). However, in joint space, the controller was less intuitive to participants. Therefore they would get lost more easily and could not rely on the keyboard cues as much. The lack of observable effect of the tactile feedback on the performance shows that the joint space feedback mapping used was not intuitive. Indeed, the success rate for condition T (15%) was even worst than condition NF(20%). This is supported by the questionnaire in which the majority of participants reported a preference for the task space feedback and found the joint space feedback difficult to understand.

Moreover, Noccaro 2020 [61] also obtained significantly better performance using vibration feedback in Cartesian space compared to joint space.

Chapter 4 Towards 3DoFs Proprioceptive Feedback

Based on the previous studies of Chapters 2 & 3, a novel 3DoFs vibration feedback device was designed and tested. The device was developed and tested by William Faust in the context of his MSc. More details on the device design and hardware can be found in his thesis [62]. The experiment design was largely based on the previous study (Chapter 2) and conducted under my co-supervision. The data analysis and figures presented in this chapter are my doing. This study allowed us to test:

- if 3DoFs vibration feedback could be understood, and
- if feedback could be provided intuitively at the torso.

This study was conducted under college ethical approbation (SETREC reference: 21IC6935).

4.1 Feedback Device

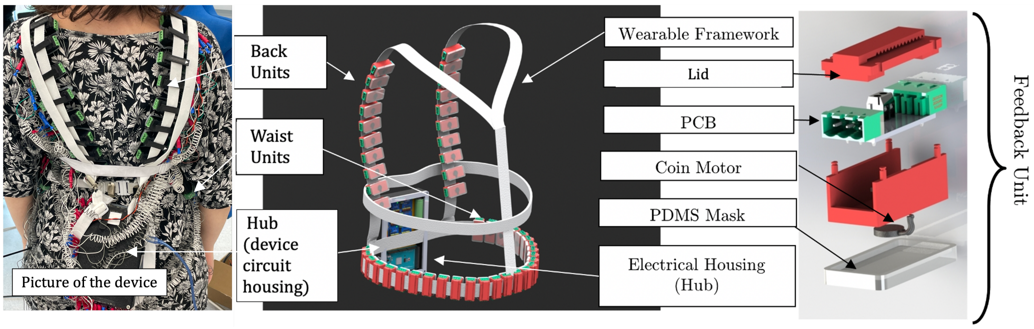


Figure 4-1: Left: Picture of the device; Middle: Global view of the device and its components the back units, waist units and the Hub. Right: Components within each unit as an exploded view, showing the unit casing, internal electronics, and biocompatible mask.

4.1.1 Device Outline

The device as shown in Figure.4-1 consists of three components: the wearable framework, vibration units which are placed both on the back and waist, and the control hub.

The wearable framework was designed to be modular and accept as many units as needed. In the context of this experiment, the number of units, 22 around the torso and 16 along the back, was defined by the smallest participant's size. The device was designed to be adjustable to participant shape and size and could be worn above or under the clothes.

The vibration units comprise the individual vibrotactile module. Each module independently conveys a magnitude of vibration and the complete system encodes 3 task space dimensions within the vibration of equispaced units: the angular section (waist location), radial distance (vibration strength) and height (back location). This feedback strategy is motivated by the findings from the previous experiment (Chapter 3), where I found that polar coordinates were more intuitive to decode for users compared to joint coordinates.

Finally, *the control hub* houses most of the device's electronics. It provides power and acts as the system master through an onboard processor which controls the actions of the vibration units via PWM lines. While the units can provide continuous vibration over a wide frame of different amplitudes, based upon previous work[32], five vibration levels are used to provide radial feedback to ensure that users can distinguish the different vibration levels.

4.1.2 Hardware Design

Unit Design

Figure 4-1 depicts an exploded view of a single unit. The unit shell consists of a lid (A), nylon casing (C) and mask (E). The shell is attached/detached to the wearable framework using a clip fixed to the lid. It is then fixed to the skin or clothing via the 'mask' of (Polydimethylsiloxane). This provides a compliant, bio-compatible interface between the user's skin and a unit, which can be disinfected for sterility.

The vibrotactile feedback is then generated through the PCB (B) and vibrotactile motor (D). The coin motor is powered through the onboard PCB, where the power and grounding lines are fed from the neighbouring unit. The PWM line connection is provided from the control hub to the unit, with bullet connectors on both sides.

Wearable Framework

The wearable framework for unit mounting is provided by an elastic belt and suspender bands. Under-leg straps prevent the translation of this belt. A rear strap joins the two suspender bands, preventing translation of the height units, and serves as a mounting location for the device's control hub.

Control Hub

Most electronics are concealed inside the control hub. This houses the Arduino control unit, PWM expanders, battery, charger, remote relay, and fuse. The PWM expanders, controlled by the onboard Arduino with the I2C standard, facilitate the large number of PWM lines needed for full control of the device's units. Four expanders were chained together facilitating up to 64 units connected at any one time, which is sufficient for this device's iteration. These expanders provide the potential for easily modifying the device to allow up to 900 units, more than would be required.

In the worst-case scenario, 4 units are going at full power constantly, 2.85 hours of continuous use is expected (with a 20% margin of safety) from the onboard 2600mWh Lithium-Polymer battery. With 2 units at a regular power, 14.443 hours is instead expected. Averaging across different use cases, an average time of 8.65 hours can be expected from the onboard battery. Experimental testing supported this claim.

The control hub is fabricated from nylon to increase impact and wear resistance, with a clip that allows it to be fixed onto the wearable framework. To increase ease of use, a radio frequency relay was implemented allowing the user to toggle device power using a remote control.

4.2 Experimental Setup

A modified version of the *Matlab* application described in section 2.3 was used to conduct the experiment. The application, shown in Figure.4-2A, was used to evaluate the mapping between sensory cues and positions. Participants were stimulated with a tactile cue from one or multiple vibration units and they had to interpret the corresponding position on the XY axis and the Z-axis.

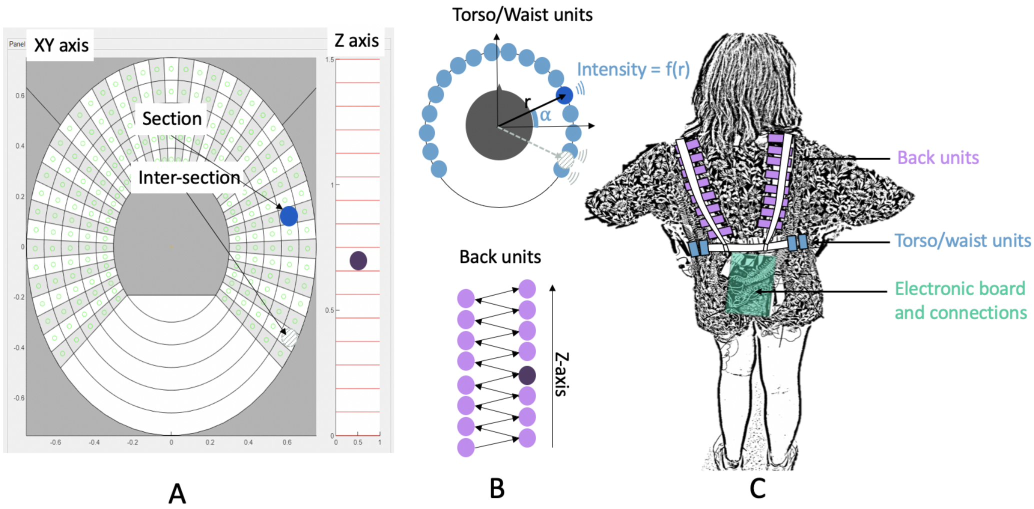


Figure 4-2: A: User interface, XY plan and Z-axis corresponding to the available task space positions. B: Mapping of the XY plane with the torso units & Mapping of the Z-axis with the back units; C: back view of the device worn above clothes.

A circle-shaped grid (Fig.4-2A) was presented on the on-screen where the number of sections corresponding to the number of units used around the waist/torso + the inter-unit intervals (number of units -1). Moreover, a scale corresponding to the possible positions along the z-axis which was the same as the number of back units was presented.

The mapping, described in Fig.4-2, encodes 3 task space dimensions: angular information is encoded through the waist location, each section corresponds to a single unit being activated and each inter section corresponds to the two adjacent units being activated together; radial information is encoded through 5 levels of vibration strength; height information is encoded through the back location, each level on the z-axis corresponds to a single back unit being activated.

4.2.1 Metrics

Questionnaires

I used a questionnaire to evaluate participants' perception and acceptance of the device. This questionnaire (Appendix A.4) was adapted from the previous questionnaires of Chapters 2.3&3). It consisted of three parts. The first part focused on demographic questions. The second part was relative to the subject's perception of the vibration feedback and its understanding. The same adjectives as in Chapter 2.3 (Goodwill questionnaire [55]) were presented on a 9-items scale. Additionally, 5-items Likert questions on the clarity of the feedback and its general perception were added. Finally, the last part focused on user feedback. Multiple-choice questions were used such as *"The movement of my arms and legs was obstructed by the device"*, *"I felt like the device was comfortable to wear"* or *"The device felt heavy to wear"* .

Performance

To account for the performance, the error was calculated as the radial, angular or height difference between the interpretation and the stimulation segment position. The same strategy as described in Fig.2-4 was used with an additional dimension. Similarly as for the previous studies, I differentiated the angular error, which can indicate the spatial resolution around the waist/torso, the radial error which assessed the efficacy to transmit the radial information and the height error which can indicate the spatial resolution of the back. Each trial was repeated 3 times so that device repeatability was taken as the absolute Cartesian distance between the user's selected point in trial 1 and the points in trials 2 and 3.

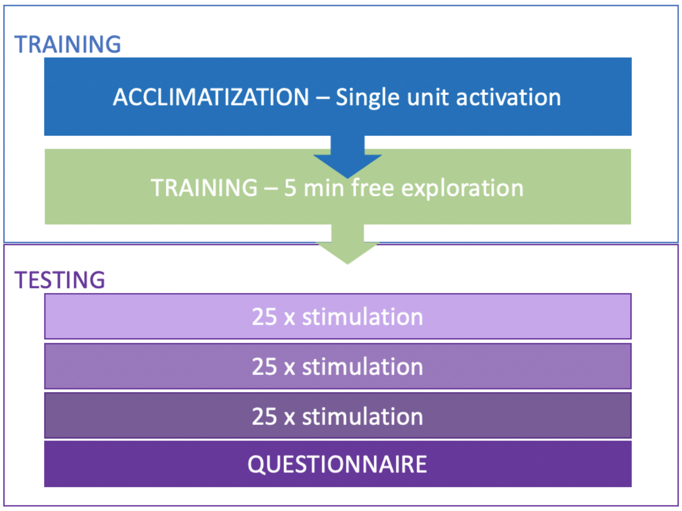


Figure 4-3: Experimental flowchart. Training phase is presented in two blocks. An acclimatization to test each single unit and a free exploration phase. Testing phase is performed 3 times and is followed by the filling of a questionnaire.

4.2.2 Protocol

10 healthy participants (four female, aged 25.5 ± 4.40) enrolled to the study. The device was adjusted on each, above their clothes. Each participant performed two blocks of training and a testing phase as shown in Figure 4-3. During the first training block (acclimatization phase), each motor was activated at all its intensities to confirm that it could be felt by the participant. We added this extra block to ensure detection of any disconnected cable or loose connection due to the fitting of the device. Then, the second training block (training) consisted of a 5 min free exploration of the space, during which the participant could move a cursor in the three dimensions to understand the position-sensation mapping described in Fig.4-2.

Finally, during the testing phase, participants received a sequence of 25 randomized stimulations, each corresponding to a position (X-Y and Z) on the on-screen grid. For each trial, they were asked to give their interpretation of the position by clicking on one segment from the X-Y plane and one segment on the Z-axis. The testing phase was repeated three times to examine accuracy and repeatability.

4.3 Results

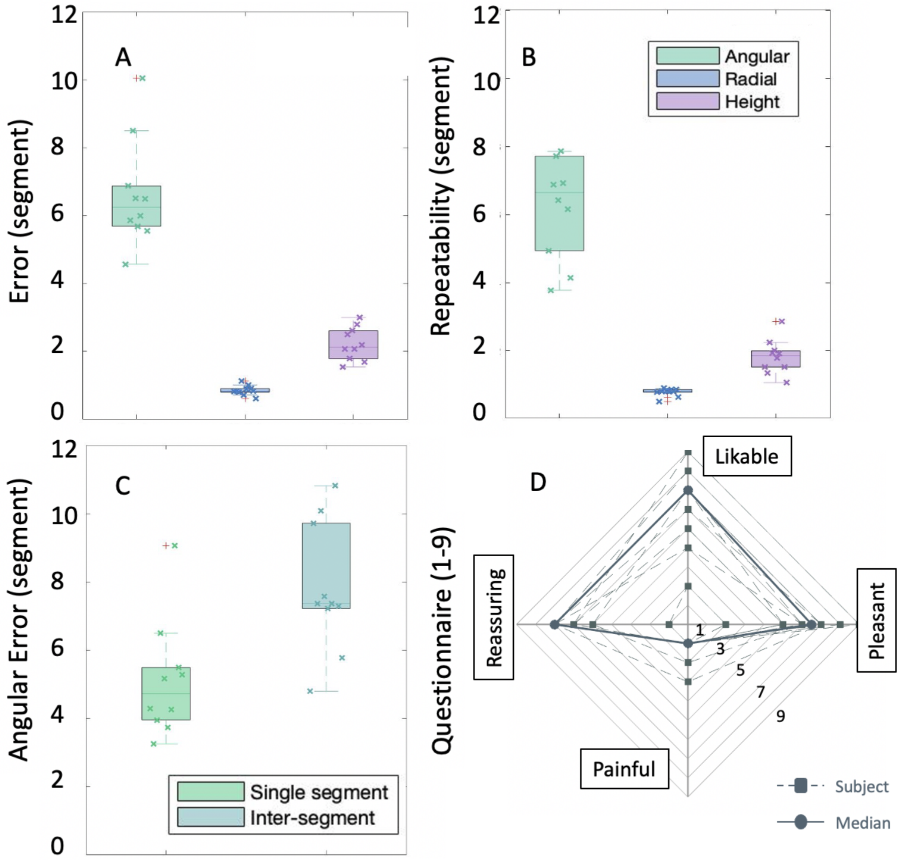


Figure 4-4: A: Error shown using the number of segments for all three dimension B: Repeatability over the three repetitions C: Comparison between angular error for the sections represented through a single vibration and the inter-sections, represented through a double vibration (2 active units). D: Questionnaire results showing participant's acceptance of the device.

4.3.1 Perception

At the end of the experiment, participant were asked to rate adjectives (on a 9-points scale) relative to their experience of the device. Among participant, the rate was high for adjectives 'Likable' (median $M = 7.0$, interquartile range $IQR = 2$), 'Reassuring' ($M = 7.0$, $IQR = 1$) and 'Pleasant'($M = 6.5$, $IQR = 2$) and low for 'Painful' ($M = 1$, $IQR = 0$). Additionally, 7/10 participants disagreed to the statement 'I found the device heavy' against 3/10 whose opinion was neutral. 3/10 agreed with the statement 'I found the device comfortable', 5/10 were neutral and 2/10 disagreed. Moreover, 7/10 participants agreed that their movements were not obstructed by the device, 1 was neutral while only 2/10 disagreed.

4.3.2 Performance

The participants' performance was evaluated in terms of error measured in segments, in all three dimensions (angular: 6.6027 ± 1.5833, radial: 0.8413 ± 0.1452, height: 2.2120 ± 0.4877, Figure.4-4A) and repeatability over the three repetitions (angular: 6.6940 ± 2.3662, radial: 0.7760 ± 0.1192, height: 1.8180 ± 0.5060, Figure.4-4B).

The angular direction was composed of 43 segments, the radial of 5 segments and the height of 16 segments. To account for the non-uniform resolution and compare between the 3 directions, error and repeatability were normalized in each dimension by the corresponding number of segments. After normalization, a one way ANOVA was performed (p = 0.1348) and no difference (p ¿ 0.1) was found between the error in the three dimensions (angular error (0.1536 ± 0.0368) was radial error (0.1683 ± 0.0290) height error (0.1382 ± 0.0305)). The same test applied on the normalized repeatability measure revealed a significant difference (p = 0.0350) between the three groups (angular, radial and height). However a post-hoc multiple comparison test, using the Bonferroni method, showed no significant difference between the groups (angular vs radial: p = 1.00, angular vs height: p = 0.0703 , radial vs height: p = 0.0703).

Additionally, angular error for single segment (mapped to a single vibration unit) was compared to the error for inter-segments (mapped to the vibration of two adjacent units) 4-2A. A t-test showed that single segment angular error (5.0879 ± 1.6959) was significantly lower ($p = 8.8518e\text{-}04$) compared to inter-segment angular error ((7.7929 ± 1.8907)) Figure.4-4C.

4.4 Discussion

This study shows that vibro-tactile feedback can be used to provide 3DoFs proprioceptive information on the back and waist/torso. The device does not interfere with natural limb motion and therefore fulfils the third requirement that was identified for supernumerary limbs application in chapter 1.2. Moreover, it can be used for both seated and standing tasks which makes it practical for a wide range of applications.

Comparisons with prior devices are limited by the scarcity of available 3DoFs proprioceptive feedback devices. Limiting comparisons to 2DoFs devices, we obtain a success rate of $39\% \pm 6.6\%$ in the radial direction, lower than observed in prior work from Alva 2020 [32] for the discrimination of 5 levels of intensity (75.7%) but greater than obtained in Chapter 3 (48%) for the discrimination of 4 levels. Therefore, in the radial direction, distinction between the 5 levels of vibration could not always be achieved, especially two adjacent levels were difficult to differentiate. To improve this, different distribution of vibration strength should be investigated.

In the angular direction, it was observed that inter-section, which were mapped through the vibration of two adjacent units, was leading to an increased error, showing that mappings including vibration of multiple units at the same time should be avoided, especially when they are placed close by. This increased confusion was not observed in [32] where they found that the best distribution of stimulation intensity was participant specific.

The maximal angular resolution of the device might be limited by the sensitivity around the torso. The trunk area was found to be less sensitive compared to the sensitivity at the forearm in a two point discrimination threshold with electriclal stimulation [59]. It is likely but unknown if the same results would apply for vibration feedback, therefore this should be investigated further.

Similarly, to maximize the height resolution, different mapping strategies should be investigated. The "zig-zag" positioning of the units could induce some confusion as it was requiering some memorization from participants. Additionally, further testing would be necessary to establish back sensitivity to optimize the number of back units.

Overall, performance results obtained showed that feedback could be understood in all three dimensions but with a lesser resolution than the device could provide.

Regarding the comfort of the device, most participants were either positive or ambivalent. People who disagreed attributed the discomfort to the pressure of the units on their skin. This issue could be improved with some minor design adaptation such as rounding up the edges of the units and adding a PDMS insulation layer. Besides that, the novel device was well accepted among participants which makes it promising to be used for SLs control.

Chapter 5 Conclusions

5.1 Contributions & Limitation

This thesis aimed to explore ways of providing somatosensory feedback to improve Supernumerary robotic limbs (SL) control. By providing an artificial sense of proprioception from a robotic limb, I hypothesized that we may be able to favour the embodiment of the external device, therefore rendering its use more intuitive and improving safety aspects that come with the use of body grounded robotic devices. SL devices come with specific challenges that restrict technologies that can be used to provide such feedback. To be adequate for SL application, the feedback modality for SL should be wearable, not interfering with the user's natural limbs and intuitive to the user. Additionally, because proprioception is thought to be important to elicit embodiment, I was looking for feedback that could convey proprioceptive information through tactile cues with at least 2DoFs.

I evaluated feedback modalities presented in the literature and compared them according to SL specific requirements. Both vibration and electrical stimulations were selected as promising methods for this sort of application.

Chapter 2 described two experiments with electrical stimulation. In the first experiment (perception experiment), I studied the perception of two parameters of stimulation (intensity and frequency). The main finding was that the intensity of stimulation had a clear correlation with a painful sensation. The effect of frequency on the perception, however, was less clear and would vary between subjects. Therefore, in the second experiment (proprioception experiment), I decided to minimize the intensity range to create comfortable mappings between stimulation cues and 2DoFs positions. Since the effect of frequency was less clear, the difference between frequency levels was maximized. 5 mappings with different combinations of intensity and frequency were tested for their performance and intuitiveness. The results showed that angular information, which was transmitted via spatial coding, was better understood compared to radial information. In the radial direction frequency levels (IF and IIF) were better differentiated than the intensity levels (II35 and II100) and it was even better if intensity and frequency were coupled (IIF and 2I2F). I also found that the mapping that required learning a pattern (2I2F) was less intuitive, as participants took more time to give their interpretation.

This experiment could be improved by setting the upper limit of the intensity range to a pain threshold as done by D'Alonzo et al.[28]. With this strategy, participants were able to code for up to 9 messages with electrical stimulation. However, this could be at cost of comfort [48], as pain threshold is a subjective measure not necessarily appropriate for long term use. While a single short stimulation at pain threshold level should be bearable, its repetition over time might cause discomfort. Therefore, I would recommend taking pain threshold over an extended time period rather than a single stimulation. Another limitation of this experiment arises from the device itself. Indeed, the CLASS system used in this experiment was intended for functional electrical stimulation (FES), therefore is not optimal to provide tactile cues. The use of concentric electrodes, as recommended in [23], would have limited the spread of the stimulation making it more concise. This improvement could improve the resolution in the angular direction.

In Chapter 3, I used vibrotactile feedback to provide position information for a virtual robotic hand moving in 2 dimensions. I compared two mappings. I found that, to control the robot, the task space mapping was more intuitive than the joint space mapping. However, conclusions on which mapping was more intuitive to provide feedback were more difficult to draw. Results from the questionnaires showed that the feedback was better understood and preferred in the task space. However, performance results did not demonstrate any advantage of using the tactile feedback (T) compared to not having any (NF) for both mappings.

In [61], Noccaro et al. obtained significantly better performance using a Cartesian mapping than a joint space mapping. The lack of performance improvement with both forms of feedback could be due to design flaws. First, our task was too easy. It was possible to find the target or to be in close vicinity without visual or tactile feedback. Choosing a task with interactions could improve this aspect as it would make the control more challenging with no feedback, therefore its effect would be clearer. Second, the tactile feedback might have been redundant. Having the participant control the robot was useful for them to learn how the feedback was delivered. However, while controlling the robot, participants could use the keyboard feedback to estimate the robot position during blind conditions. This could be dealt with by using a controller only during the training phase or by using random increments so that participants cannot rely on it. Both electrical and vibration stimulation are easy to implement, lightweight and cost-effective strategies that can be made wearable. Compared to vibration, electrical stimulation offers a wider range of possibilities for feedback mapping as frequency and amplitude of stimulation are uncoupled. However, when compared to electrical stimulation, vibration is often preferred and considered more comfortable [48].

In Chapter 4, I present a novel strategy to provide 3DoFs vibration feedback. In this study, we used the ideas explored in the previous experiments to design a wearable vibrotactile device for the torso and back. The study showed that:

1. It was possible to transmit feedback at the torso and back, a location that few studies have considered.

2. 3DoF feedback could be achieved using vibration alone.

Participants received well the device and found it to be comfortable. Moreover, participants could understand the vibration feedback in three dimensions with similar accuracy. However, this experiment, which served as a proof of concept, also revealed flaws. First, a high number of motor units were used around the waist/torso to maximize the resolution of the device. This number should be optimized for each participant to match their sensitivity around the trunk, which still needs to be studied for vibration sensation. Similar is valid for the back units. Additionally, we could improve the mapping by avoiding having multiple units active at the same time in proximity. Finally, we ould make other improvements on wearability and comfort. For example, we should rethink the design of the casing that is in contact with the skin.

5.2 Future Developments

Feedback placement

Because SLs are not parts or replacement parts of the natural body, there is no clear location to convey the feedback. Two different placements (arm and torso/back) were tested during this work in different experiments but no direct comparison was done. Both placements were chosen because they do not interfere with natural limb motion and sensation. Due to its modularity, the novel device described in chapter 4 would allow for different placement testing. Therefore feedback placement for SL control is a question that should be addressed in future work and the device would be a good candidate to use.

Hybrid system

Natural proprioception is 3-dimensional and ultimately SL should be controlled in all three dimensions. However, eliciting a sense of proprioception in 3DoFs using tactile cues is challenging as it can become fastidious to provide clear and distinct tactile information using one feedback modality. This last point was observed in the 3DoF proprioception experiment, chapter 4. Hybrid (electro & vibrotactile) systems represent an attractive solution to provide sensory feedback that can increase the number of communication streams [28]. Therefore, future development should focus on the design of hybrid systems that can elicit various types of sensation.

Pain feedback

Additionally, SLs raise specific safety aspects due to their body grounded nature. To improve these aspects, one could take advantage of the prioritized communication streams of the nociceptive pathways. In other words, using slightly painful stimulation to notify the user of an incoming danger (for instance when a limit is about to be reached) could help him make fast and appropriate decisions to avoid hazardous situations [63]. Electrical stimulation would be a promising method to provide such painful cues as it was shown that stimulation cues become unpleasant and uncomfortable at higher amplitudes. Moreover, this strategy could favour embodiment as it would be similar to the natural way our body notify us when we are reaching our joint limits.

Bibliography

[1] Jeff Denis et al. "On the design of lightweight compliant wearable arms". In: (2019), p. 5.

[2] F. Parietti, K. Chan, and H.H. Asada. "Bracing the human body with supernumerary robotic limbs for physical assistance and load reduction". en. In: 2014, pp. 141–148.

[3] D.A. Kurek and H.H. Asada. "The MantisBot: Design and impedance control of supernumerary robotic limbs for near-ground work". en. In: 2017, pp. 5942–5947.

[4] D.J. Gonzalez and H.H. Asada. "Hybrid Open-Loop Closed-Loop Control of Coupled Human–Robot Balance During Assisted Stance Transition With Extra Robotic Legs". en. In: *IEEE ROBOTICS AND AUTOMATION LETTERS* 4.2 (2019).

[5] Irfan Hussain et al. "A soft supernumerary robotic finger and mobile arm support for grasping compensation and hemiparetic upper limb rehabilitation". en. In: *Robotics and Autonomous Systems* 93 (2017), pp. 1–12.

[6] F. Wu and H. Asada. "Supernumerary Robotic Fingers: An Alternative Upper-Limb Prosthesis". en. In: *Dynamic Systems and Control Conference*. Vol. Volume 2. 2014.

[7] D. Clode. *Dani Clode Design*. en. [Online]. 2019. URL: `https://www.daniclodedesign.com/thethirdthumb`.

[8] I. Hussain et al. "Vibrotactile haptic feedback for intuitive control of robotic extra fingers". In: (June 2015), pp. 394–399.

[9] S. Manoharan and H. Park. "Supernumerary Body Schema Extension to Non-Corporeal Object by Adding Artificial Tactile Feedback using Electrical Stimulation". en. In: 2019, pp. 989–992.

[10] A. Maravita and A. Iriki. "Tools for the body (schema)". en. In: *Trends in Cognitive Sciences* 8 (2004), pp. 79–86.

[11] M. Pazzaglia and M. Molinari. *The embodiment of assistive devices from wheelchair to exoskeleton*. en. Physics of Life, 2016, pp. 163–175.

[12] Hannes Bleuler et al. "TRENDS IN SURGICAL ROBOTICS". In: (2013), p. 10.

[13] Giovanni Di Pino et al. "Augmentation-related brain plasticity". en. In: *Front Syst Neurosci* 8 (2014), p. 108.

[14] Shahar Arzy et al. "Neural Basis of Embodiment: Distinct Contributions of Temporoparietal Junction and Extrastriate Body Area". In: *Journal of Neuroscience* 26.31 (Aug. 2006), pp. 8074–8081. ISSN: 0270-6474, 1529-2401.

[15] M. Pinardi et al. "'Doublecheck: a sensory confirmation is required to own a robotic hand, sending a command to feel in charge of it'". In: *Cognitive Neuroscience* 0.0 (Aug. 2020), pp. 1–13. ISSN: 1758-8928.

[16] R. Hellman. "A Robot Hand Testbed Designed for Enhancing Embodiment and Functional Neurorehabilitation of Body Schema in Subjects with Upper Limb Impairment or Loss". en. In: *Front. Hum. Neurosci* 9 (2015).

[17] L. Bashford and C. Mehring. "Ownership and Agency of an Independent Supernumerary Hand Induced by an Imitation Brain-Computer Interface". en. In: (2016).

[18] C. Pacchierotti. "Cutaneous haptic feedback to ensure the stability of robotic teleoperation systems". en. In: *The International Journal of Robotics Research* 34.14 (2015), pp. 1773–1787.

[19] W. Wang et al. "Building multi-modal sensory feedback pathways for SRL with the aim of sensory enhancement via BCI". In: (2019).

[20] Maria C. Dadarlat, Joseph E. O'Doherty, and Philip N. Sabes. "A learning–based approach to artificial sensory feedback leads to optimal integration". In: 18 (Jan. 2015), pp. 138–144. ISSN: 1097-6256.

[21] Amy Blank, Allison M. Okamura, and Katherine J. Kuchenbecker. "Identifying the role of proprioception in upper-limb prosthesis control: Studies on targeted motion". In: *ACM Transactions on Applied Perception* 7.3 (June 2010), pp. 1–23. ISSN: 1544-3558, 1544-3965. DOI: 10.1145/1773965.1773966.

[22] K.J. Kuchenbecker, N. Gurari, and A.M. Okamura. *Effects of Visual and Proprioceptive Motion Feedback on Human Control of Targeted Movement*. en. 2007.

[23] Patrick L Marcus and Andrew J Fuglevand. "Perception of electrical and mechanical stimulation of the skin: implications for electrotactile feedback". In: *Journal of Neural Engineering* 6.6 (Dec. 2009), p. 066008. ISSN: 1741-2560, 1741-2552.

[24] Heidi J. B. Witteveen et al. "Vibro- and Electrotactile User Feedback on Hand Opening for Myoelectric Forearm Prostheses". In: *IEEE Transactions on Biomedical Engineering* 59.8 (Aug. 2012), pp. 2219–2226. ISSN: 1558-2531.

[25] Karlin Bark et al. "Comparison of Skin Stretch and Vibrotactile Stimulation for Feedback of Proprioceptive Information". In: Mar. 2008, pp. 71–78.

[26] Joseph M. Romano and Katherine J. Kuchenbecker. "Creating Realistic Virtual Textures from Contact Acceleration Data". In: *IEEE Transactions on Haptics* 5.2 (2012), pp. 109–119. DOI: 10.1109/TOH.2011.38.

[27] Hui Tang and D.J. Beebe. "An oral tactile interface for blind navigation". In: *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 14.1 (Mar. 2006), pp. 116–123. ISSN: 1558-0210.

[28] M. D'Alonzo et al. "HyVE: Hybrid Vibro-Electrotactile Stimulation for Sensory Feedback and Substitution in Rehabilitation". In: *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 22.2 (Mar. 2014), pp. 290–301. ISSN: 1558-0210.

[29] A. Y. J. Szeto and F. A. Saunders. "Electrocutaneous Stimulation for Sensory Communication in Rehabilitation Engineering". In: *IEEE Transactions on Biomedical Engineering* BME-29.4 (Apr. 1982), pp. 300–308. ISSN: 1558-2531.

[30] D. S. Pamungkas and K. Ward. "Tele-operation of a robot arm with electro tactile feedback". In: (July 2013), pp. 704–709. ISSN: 2159-6255.

[31] Alessandro Marco De Nunzio et al. "Tactile feedback is an effective instrument for the training of grasping with a prosthesis at low- and medium-force levels". In: *Experimental Brain Research* 235.8 (Aug. 2017), pp. 2547–2559. ISSN: 0014-4819, 1432-1106.

[32] Patrick G. Sagastegui Alva et al. "Wearable multichannel haptic device for encoding proprioception in the upper limb". In: *Journal of Neural Engineering* 17.5 (Oct. 2020), p. 056035. ISSN: 1741-2552.

[33] Claudio Pacchierotti et al. "Enhancing the Performance of Passive Teleoperation Systems via Cutaneous Feedback". In: *IEEE Transactions on Haptics* 8.4 (2015), pp. 397–409.

[34] Ramiro Velázquez and Omar Bazán. "Preliminary evaluation of podotactile feedback in sighted and blind users". In: *2010 Annual International Conference of the IEEE Engineering in Medicine and Biology*. 2010 Annual International Conference of the IEEE Engineering in Medicine and Biology. ISSN: 1558-4615. 2010, pp. 2103–2106.

[35] Patrick E. Patterson and J. A. Katz. "Design and evaluation of a sensory feedback system that provides grasping pressure in a myoelectric hand." In: *Journal of rehabilitation research and development* 29.1 (1992), pp. 1–8.

[36] Richard E. Fan et al. "A Haptic Feedback System for Lower-Limb Prostheses". In: *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 16.3 (2008), pp. 270–277. ISSN: 1558-0210.

[37] Mary Beth Badke et al. "Tongue-Based Biofeedback for Balance in Stroke: Results of an 8-Week Pilot Study". In: *Archives of Physical Medicine and Rehabilitation* 92.9 (2011), pp. 1364–1370. ISSN: 00039993. (Visited on 11/29/2019).

[38] Dana D. Damian et al. "Slip Speed Feedback for Grip Force Control". In: *IEEE Transactions on Biomedical Engineering* 59.8 (2012), pp. 2200–2210. ISSN: 1558-2531.

[39] Strahinja Dosen et al. "Multichannel Electrotactile Feedback With Spatial and Mixed Coding for Closed-Loop Control of Grasping Force in Hand Prostheses". In: *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 25.3 (2017), pp. 183–195.

[40] Karlin Bark et al. "A wearable skin stretch device for haptic feedback". In: *World Haptics 2009 - Third Joint EuroHaptics conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*. World Haptics 2009 - Third Joint EuroHaptics conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. 2009, pp. 464–469.

[41] Karlin Bark et al. "Rotational Skin Stretch Feedback: A Wearable Haptic Display for Motion". In: *IEEE Transactions on Haptics* 3.3 (2010), pp. 166–176. ISSN: 2334-0134.

[42] Michael Fritschi et al. "First evaluation of a novel tactile display exerting shear force via lateral displacement". In: *ACM Trans. on Applied Perception* (2000), pp. 118–131.

[43] Robert J. Webster et al. "A novel two-dimensional tactile slip display: design, kinematics and perceptual experiments". In: *ACM Transactions on Applied Perception* 2.2 (Apr. 2005), pp. 150–165. ISSN: 1544-3558, 1544-3965.

[44] Mildred Puerto, Emilio Sánchez, and Jorge Juan Gil. "Control strategies applied to kinesthetic haptic devices". In: Mar. 2009. DOI: 10.1109/RIISS.2009.4937918.

[45] Heather Culbertson, Samuel B. Schorr, and Allison M. Okamura. "Haptics: The Present and Future of Artificial Touch Sensation". In: *Annual Review of Control, Robotics, and Autonomous Systems* 1.1 (2018), pp. 385–409.

[46] Silvestro Micera Stanisa Raspopovic. "Restoring natural sensory feedback in real-time bidirectional hand prostheses". In: (2014).

[47] J. Dong et al. "The Short-Term Repeatability of Subdermal Electrical Stimulation for Sensory Feedback". In: *IEEE Access* 8 (2020), pp. 63983–63992. ISSN: 2169-3536.

[48] Lynette Jones and Nadine Sarter. “Tactile Displays: Guidance for Their Design and Application”. In: *Human factors* 50 (Mar. 2008), pp. 90–111.

[49] Francesco Chinello et al. “Design of a wearable skin stretch cutaneous device for the upper limb”. In: *2016 IEEE Haptics Symposium (HAPTICS)*. Apr. 2016, pp. 14–20.

[50] Camille M. Blondin et al. “Perception and Performance of Electrical Stimulation for Proprioception”. In: *2021 43rd Annual International Conference of the IEEE Engineering in Medicine Biology Society (EMBC)*. 2021, pp. 4550–4554. DOI: 10.1109/EMBC46164.2021.9630186.

[51] M. Benedek. *Analysis of EDA data using Ledalab [PDF]*. Accessed: 13–02-2021. 2021.

[52] S. Taylor et al. “Automatic identification of artifacts in electrodermal activity data”. In: Aug. 2015, pp. 1934–1937.

[53] Mathias Benedek and Christian Kaernbach. “A continuous measure of phasic electrodermal activity”. In: *Journal of Neuroscience Methods* 190.1 (June 2010), pp. 80–91. ISSN: 0165-0270.

[54] Christoph Bartneck et al. “Measurement Instruments for the Anthropomorphism, Animacy, Likeability, Perceived Intelligence, and Perceived Safety of Robots”. In: *International Journal of Social Robotics* 1.1 (Jan. 2009), pp. 71–81. ISSN: 1875-4805.

[55] R.C. Oldfield. “The assessment and analysis of handedness: The Edinburgh inventory”. In: *Neuropsychologia* 9.1 (Mar. 1971), pp. 97–113. DOI: 10.1016/0028-3932(71)90067-4.

[56] Jacob O Wobbrock et al. “The aligned rank transform for nonparametric factorial analyses using only anova procedures”. In: 2011, pp. 143–146.

[57] Siyuan Chen, Julien Epps, and Fang Chen. “A comparison of four methods for cognitive load measurement”. In: *Proceedings of the 23rd Australian Computer-Human Interaction Conference on - OzCHI ’11*. ACM Press, 2011, pp. 76–79. ISBN: 978-1-4503-1090-1.

[58] Cornelia Setz et al. “Discriminating stress from cognitive load using a wearable EDA device”. In: *IEEE Transactions on information technology in biomedicine* 14.2 (2009), pp. 410–417.

[59] Moshe Solomonow, John Lyman, and Amos Freedy. “Electrotactile two-point discrimination as a function of frequency, body site, laterality, and stimulation codes”. In: *Annals of Biomedical Engineering* 5.1 (Mar. 1977), pp. 47–60. ISSN: 0090-6964, 1573-9686. DOI: 10.1007/BF02409338.

[60] Saif Sidhik. *panda_simulator: Gazebo simulator for Franka Emika Panda robot supporting sim-to-real code transfer*. Version v1.0.0. Apr. 2020.

[61] A. Noccaro et al. "A Novel Proprioceptive Feedback System for Supernumerary Robotic Limb". In: *2020 8th IEEE RAS/EMBS International Conference for Biomedical Robotics and Biomechatronics (BioRob)*. Nov. 2020, pp. 1024–1029. DOI: 10.1109/BioRob49111.2020.9224450.

[62] William Faust. "Haptic feedback for Supernumerary Limb Control: Augmented Motor Control". MA thesis. 2021.

[63] Maxime Jeanneret et al. "A Versatile Robotic Haptic Stimulator to Study the Influence of Pain on Human Motor Control and Learning". In: Springer International Publishing, 2016, pp. 101–110. ISBN: 978-3-319-42321-0.

Appendix

A.1

Full questionnaire for the *perception experiment* chapter 2.2.

Subject ID:____

Imperial College London

Part I: Demographic Questionnaire

1. What is your gender?

☐ Male
☐ Female
☐ Other (specify)___________________

2. What is your age?

_____________years old

3. What is the highest level of education you have completed?

☐ Some high school
☐ High school graduate
☐ Trade/technical/vocational training
☐ College graduate
☐ Postgraduate degree

4. What is your primary language?

☐ English
☐ Other (specify) ___________________

5. Did you use functional electrical stimulation before?

☐ No
☐ Yes >For what purpose?___________________

6. Do you currently experience some pain in your hands or arms?

☐ No
☐ Yes >Where exactly? ☐ left arm/hand ☐ right arm/hand
☐ both hands/arms ☐ other (specify)___________________
>How strong is the pain in a scale from 0 to 10?___________________

Subject ID:______
Sequence:_______

Imperial College London

Did you feel something in your arm?

☐ No
☐ Yes

If yes: Express your agreement towards either of the attributes by ticking the square that most closely reflects your feelings during the last trial.

Nr.	The sensation during the trial felt…	1	2	3	4	5	6	7	8	9	
Q1	unpredictable	☐	☐	☐	☐	☐	☐	☐	☐	☐	predictable
Q2	unnatural	☐	☐	☐	☐	☐	☐	☐	☐	☐	natural
Q3	unsettling	☐	☐	☐	☐	☐	☐	☐	☐	☐	reassuring
Q4	typical	☐	☐	☐	☐	☐	☐	☐	☐	☐	strange
Q5	likable	☐	☐	☐	☐	☐	☐	☐	☐	☐	dislikable
Q6	pleasant	☐	☐	☐	☐	☐	☐	☐	☐	☐	unpleasant
Q7	painful	☐	☐	☐	☐	☐	☐	☐	☐	☐	painless

A.2

Full questionnaire for the *proprioception experiment* chapter 2.3.

Subject ID:______________

InputFileName:_______________

Part I: Demographic Questionnaire

1. **What is your gender?**

☐ Male
☐ Female
☐ Other

2. **What is your age?**

_________years old

3. **Do/did you ever used a device that uses electrical stimulation?**

☐ No
☐ Yes

4. **Do you currently experience some pain in your hands, or arms?**

☐ No
☐ Yes ->Where exactly?

left arm/hand   right arm/hand   both hands/arms   other (specify)__________________

Part II: Handedness Inventory

Please indicate with a check (✓) your preference in using your left or right hand in the following tasks. Where the preference is so strong that you would never use the other hand, unless absolutely forced to, put two checks (✓✓).

If you are indifferent, put one check in each column (✓|✓).

Task / Object	Left Hand	Right Hand
1. Writing		
2. Drawing		
3. Throwing		
4. Scissors		
5. Toothbrush		
6. Knife (without fork)		
7. Spoon		
8. Broom (upper hand)		
9. Striking Match (match)		
10. Opening box (lid)		

Some of the activities require both hands. In these cases, the part of the task or object for which hand preference is wanted is indicated in parentheses.

Part I: Experiment

Please indicate on a scale from 1 to 9 your agreement toward the following adjectives relative to the stimulation you receive during the trial:

	1	2	3	4	5	6	7	8	9	
Unnatural	☐	☐	☐	☐	☐	☐	☐	☐	☐	Natural
Unsettling	☐	☐	☐	☐	☐	☐	☐	☐	☐	Reassuring
Strange	☐	☐	☐	☐	☐	☐	☐	☐	☐	Typical
Dislikable	☐	☐	☐	☐	☐	☐	☐	☐	☐	Likable
Unpleasant	☐	☐	☐	☐	☐	☐	☐	☐	☐	Pleasant
Painful	☐	☐	☐	☐	☐	☐	☐	☐	☐	Painless

Please indicate on a scale from 1 to 5 your agreement or disagreement relative to the trial:

During the trial

1) … The difference between angular sections in task space was clear for me:

	1	2	3	4	5	
Strongly Disagree	☐	☐	☐	☐	☐	Strongly Agree

2) … The difference between radial levels within one section was clear for me:

	1	2	3	4	5	
Strongly Disagree	☐	☐	☐	☐	☐	Strongly Agree

3) … I felt like I could locate the stimulation on the grid accurately:

	1	2	3	4	5	
Strongly Disagree	☐	☐	☐	☐	☐	Strongly Agree

Please, describe how you perceived the stimulation in a few words or give any other comments:

____

____

Part II: Experiment

Please indicate on a scale from 1 to 9 your agreement toward the following adjectives relative to the stimulation you receive during the trial:

	1	2	3	4	5	6	7	8	9	
Unnatural	☐	☐	☐	☐	☐	☐	☐	☐	☐	Natural
Unsettling	☐	☐	☐	☐	☐	☐	☐	☐	☐	Reassuring
Strange	☐	☐	☐	☐	☐	☐	☐	☐	☐	Typical
Dislikable	☐	☐	☐	☐	☐	☐	☐	☐	☐	Likable
Unpleasant	☐	☐	☐	☐	☐	☐	☐	☐	☐	Pleasant
Painful	☐	☐	☐	☐	☐	☐	☐	☐	☐	Painless

Please indicate on a scale from 1 to 5 your agreement or disagreement relative to the trial:

During the trial

1) … The difference between angular sections in task space was clear for me:

	1	2	3	4	5	
Strongly Disagree	☐	☐	☐	☐	☐	Strongly Agree

2) … The difference between radial levels within one section was clear for me:

	1	2	3	4	5	
Strongly Disagree	☐	☐	☐	☐	☐	Strongly Agree

3) … I felt like I could locate the stimulation on the grid accurately:

	1	2	3	4	5	
Strongly Disagree	☐	☐	☐	☐	☐	Strongly Agree

Please, describe how you perceived the stimulation in a few words or give any other comments:

____

____

Part III: Experiment

Please indicate on a scale from 1 to 9 your agreement toward the following adjectives relative to the stimulation you receive during the trial:

	1	2	3	4	5	6	7	8	9	
Unnatural	☐	☐	☐	☐	☐	☐	☐	☐	☐	Natural
Unsettling	☐	☐	☐	☐	☐	☐	☐	☐	☐	Reassuring
Strange	☐	☐	☐	☐	☐	☐	☐	☐	☐	Typical
Dislikable	☐	☐	☐	☐	☐	☐	☐	☐	☐	Likable
Unpleasant	☐	☐	☐	☐	☐	☐	☐	☐	☐	Pleasant
Painful	☐	☐	☐	☐	☐	☐	☐	☐	☐	Painless

Please indicate on a scale from 1 to 5 your agreement or disagreement relative to the trial:

During the trial

1) … The difference between angular sections in task space was clear for me:

	1	2	3	4	5	
Strongly Disagree	☐	☐	☐	☐	☐	Strongly Agree

2) … The difference between radial levels within one section was clear for me:

	1	2	3	4	5	
Strongly Disagree	☐	☐	☐	☐	☐	Strongly Agree

3) … I felt like I could locate the stimulation on the grid accurately:

	1	2	3	4	5	
Strongly Disagree	☐	☐	☐	☐	☐	Strongly Agree

Please, describe how you perceived the stimulation in a few words or give any other comments:

____

Part IV: Experiment

Please indicate on a scale from 1 to 9 your agreement toward the following adjectives relative to the stimulation you receive during the trial:

	1	2	3	4	5	6	7	8	9	
Unnatural	☐	☐	☐	☐	☐	☐	☐	☐	☐	Natural
Unsettling	☐	☐	☐	☐	☐	☐	☐	☐	☐	Reassuring
Strange	☐	☐	☐	☐	☐	☐	☐	☐	☐	Typical
Dislikable	☐	☐	☐	☐	☐	☐	☐	☐	☐	Likable
Unpleasant	☐	☐	☐	☐	☐	☐	☐	☐	☐	Pleasant
Painful	☐	☐	☐	☐	☐	☐	☐	☐	☐	Painless

Please indicate on a scale from 1 to 5 your agreement or disagreement relative to the trial:

During the trial

1) … The difference between angular sections in task space was clear for me:

	1	2	3	4	5	
Strongly Disagree	☐	☐	☐	☐	☐	Strongly Agree

2) … The difference between radial levels within one section was clear for me:

	1	2	3	4	5	
Strongly Disagree	☐	☐	☐	☐	☐	Strongly Agree

3) … I felt like I could locate the stimulation on the grid accurately:

	1	2	3	4	5	
Strongly Disagree	☐	☐	☐	☐	☐	Strongly Agree

Please, describe how you perceived the stimulation in a few words or give any other comments:

____

Part V: Experiment

Please indicate on a scale from 1 to 9 your agreement toward the following adjectives relative to the stimulation you receive during the trial:

	1	2	3	4	5	6	7	8	9	
Unnatural	☐	☐	☐	☐	☐	☐	☐	☐	☐	Natural
Unsettling	☐	☐	☐	☐	☐	☐	☐	☐	☐	Reassuring
Strange	☐	☐	☐	☐	☐	☐	☐	☐	☐	Typical
Dislikable	☐	☐	☐	☐	☐	☐	☐	☐	☐	Likable
Unpleasant	☐	☐	☐	☐	☐	☐	☐	☐	☐	Pleasant
Painful	☐	☐	☐	☐	☐	☐	☐	☐	☐	Painless

Please indicate on a scale from 1 to 5 your agreement or disagreement relative to the trial:

During the trial

1) … The difference between angular sections in task space was clear for me:

	1	2	3	4	5	
Strongly Disagree	☐	☐	☐	☐	☐	Strongly Agree

2) … The difference between radial levels within one section was clear for me:

	1	2	3	4	5	
Strongly Disagree	☐	☐	☐	☐	☐	Strongly Agree

3) … I felt like I could locate the stimulation on the grid accurately:

	1	2	3	4	5	
Strongly Disagree	☐	☐	☐	☐	☐	Strongly Agree

Please, describe how you perceived the stimulation in a few words or give any other comments:

____

Please indicate on a scale from 1 to 5 your agreement or disagreement relative to your general perception of the stimulation:

I feel like Electrotactile stimulation

1) … annoys me:

	1	2	3	4	5	
Strongly Disagree	☐	☐	☐	☐	☐	Strongly Agree

2) … relaxes me:

	1	2	3	4	5	
Strongly Disagree	☐	☐	☐	☐	☐	Strongly Agree

3) … is simple to understand :

	1	2	3	4	5	
Strongly Disagree	☐	☐	☐	☐	☐	Strongly Agree

A.3

Full questionnaire used for the 2DoFs vibration experiment chapter 3.

24/07/20
Subject ID:______________
InputFileName:_______________

Part I: Demographic Questionnaire

1. **What is your gender?**
- ☐ Male
- ☐ Female
- ☐ Other

2. **What is your age?**
_________years old

3. **Do/did you usually wear a smart watch that uses vibration or other similar wearable vibrotacile device? (Vibrotactile = that produces vibrations)**
- ☐ No
- ☐ Yes

4. **Do you currently experience some pain in your hands, or arms?**
- ☐ No
- ☐ Yes ->Where exactly?

left arm/hand right arm/hand both hands/arms other (specify)_________________

Part II: Handedness Inventory

Please indicate with a check (✓) your preference in using your left or right hand in the following tasks. Where the preference is so strong that you would never use the other hand, unless absolutely forced to, put two checks (✓✓).

If you are indifferent, put one check in each column (✓|✓).

Task / Object	Left Hand	Right Hand
1. Writing		
2. Drawing		
3. Throwing		
4. Scissors		
5. Toothbrush		
6. Knife (without fork)		
7. Spoon		
8. Broom (upper hand)		
9. Striking Match (match)		
10. Opening box (lid)		

Some of the activities require both hands. In these cases, the part of the task or object for which hand preference is wanted is indicated in parentheses.

24/07/20

Part III: Experiment 1

Please indicate the extent of your agreement or disagreement with following statements:

Condition 1

1. **I felt that the time was sufficient to get to the target in each trial/in most of the trials**

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

2. **I felt that I knew the position of the robotic arm in each moment of time during the trials**

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

3. **I felt like I understood the directions from the tactile feedback**

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

4. **I felt that the tactile feedback was useful to accomplish the task**

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

5. **By guiding the robot arm, I relied mostly on:**

Visual feedback

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

Tactile feedback

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

Keyboard cues (for control)

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

6. **Select which feedback you used the most to reach the target position (Tik one box):**

- ☐ Visual Feedback
- ☐ Tactile Feedback
- ☐ Keyboard cues

Condition 2

1. I felt that the time was sufficient to get to the target in each trial/in most of the trials

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

2. I felt that I knew the position of the robotic arm in each moment of time during the trials

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

3. I felt like I understood the directions from the tactile feedback

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

4. I felt that the tactile feedback was useful to accomplish the task

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

5. By guiding the robot arm, I relied mostly on:

Visual feedback

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

Tactile feedback

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

Keyboard cues (for control)

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

6. Select which feedback you used the most to reach the target position (Tik one box):

☐ Visual Feedback
☐ Tactile Feedback
☐ Keyboard cues

Condition 3

1. I felt that the time was sufficient to get to the target in each trial/in most of the trials

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

2. I felt that I knew the position of the robotic arm in each moment of time during the trials

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

3. I felt like I understood the directions from the tactile feedback

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

4. I felt that the tactile feedback was useful to accomplish the task

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

5. By guiding the robot arm, I relied mostly on:

Visual feedback

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

Tactile feedback

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

Keyboard cues (for control)

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

6. Select which feedback you used the most to reach the target position (Tik one box):

☐ Visual Feedback
☐ Tactile Feedback
☐ Keyboard cues

Condition 4

1. I felt that the time was sufficient to get to the target in each trial/in most of the trials

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

2. I felt that I knew the position of the robotic arm in each moment of time during the trials

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

3. I felt like I understood the directions from the tactile feedback

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

4. I felt that the tactile feedback was useful to accomplish the task

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

5. By guiding the robot arm, I relied mostly on:

Visual feedback

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

Tactile feedback

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

Keyboard cues (for control)

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

6. Select which feedback you used the most to reach the target position (Tik one box):

- ☐ Visual Feedback
- ☐ Tactile Feedback
- ☐ Keyboard cues

Comparison between conditions

1. Task difficulty: order the tasks given their difficulties {1 = most difficult, 4 = least difficult}.

   Condition 1 ________
   Condition 2 ________
   Condition 3 ________
   Condition 4 ________

2. Control: order the tasks given how much you felt in control of the robot's movements {1 = I felt the more in control, 4 = I felt the least in control}.

   Condition 1 ________
   Condition 2 ________
   Condition 3 ________
   Condition 4 ________

Part IV: Experiment 2

Please indicate the extent of your agreement or disagreement with following statements:

Condition 1

7. I felt that the time was sufficient to get to the target in each trial/in most of the trials

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

8. I felt that I knew the position of the robotic arm in each moment of time during the trials

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

9. I felt like I understood the directions from the tactile feedback

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

10. I felt that the tactile feedback was useful to accomplish the task

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

11. By guiding the robot arm, I relied mostly on:

Visual feedback

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

Tactile feedback

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

Keyboard cues (for control)

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

12. Select which feedback you used the most to reach the target position (Tik one box):

☐ Visual Feedback
☐ Tactile Feedback
☐ Keyboard cues

Condition 2

7. I felt that the time was sufficient to get to the target in each trial/in most of the trials

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

8. I felt that I knew the position of the robotic arm in each moment of time during the trials

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

9. I felt like I understood the directions from the tactile feedback

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

10. I felt that the tactile feedback was useful to accomplish the task

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

11. By guiding the robot arm, I relied mostly on:

Visual feedback

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

Tactile feedback

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

Keyboard cues (for control)

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

12. Select which feedback you used the most to reach the target position (Tik one box):

☐ Visual Feedback
☐ Tactile Feedback
☐ Keyboard cues

Condition 3

7. I felt that the time was sufficient to get to the target in each trial/in most of the trials

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

8. I felt that I knew the position of the robotic arm in each moment of time during the trials

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

9. I felt like I understood the directions from the tactile feedback

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

10. I felt that the tactile feedback was useful to accomplish the task

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

11. By guiding the robot arm, I relied mostly on:

Visual feedback

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

Tactile feedback

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

Keyboard cues (for control)

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

12. Select which feedback you used the most to reach the target position (Tik one box):

☐ Visual Feedback
☐ Tactile Feedback
☐ Keyboard cues

Condition 4

7. I felt that the time was sufficient to get to the target in each trial/in most of the trials

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

8. I felt that I knew the position of the robotic arm in each moment of time during the trials

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

9. I felt like I understood the directions from the tactile feedback

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

10. I felt that the tactile feedback was useful to accomplish the task

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

11. By guiding the robot arm, I relied mostly on:

Visual feedback

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

Tactile feedback

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

Keyboard cues (for control)

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

12. Select which feedback you used the most to reach the target position (Tik one box):

☐ Visual Feedback
☐ Tactile Feedback
☐ Keyboard cues

Comparison between conditions

3. Task difficulty: order the tasks given their difficulties {1 = most difficult, 4 = least difficult}.

Condition 1 ________
Condition 2 ________
Condition 3 ________
Condition 4 ________

4. Control: order the tasks given how much you felt in control of the robot's movements {1 = I felt the more in control, 4 = I felt the least in control}.

Condition 1 ________
Condition 2 ________
Condition 3 ________
Condition 4 ________

Part V: Experiment 1 vs Experiment 2 evaluation

Please choose one option

Control

1. I felt like I was the most in control of the robot during :

☐ Joint space experiment
☐ Task space experiment
☐ Neither
☐ Both

2. I felt it was easier for me to control the robot's motion during

☐ Joint space experiment
☐ Task space experiment
☐ Neither
☐ Both

Tactile Feedback

1. I felt that I could understand the tactile feedback better during

☐ Joint space experiment
☐ Task space experiment
☐ Neither
☐ Both

2. I could have understood the tactile feedback with no additional information during experiment 1

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

3. I could have understood the tactile feedback with no additional information during experiment 2

strongly agree	agree	neutral	disagree	strongly disagree
☐	☐	☐	☐	☐

Task

1. I felt that it was easier for me to reach the target in the given time during

☐ Joint space experiment
☐ Task space experiment

- ☐ Neither
- ☐ Both

Part VI: General

Comfort

1. Did you feel any discomfort during the experiment?

- ☐ No
- ☐ Yes

2. If yes was is relative to (select all that apply):

- ☐ The Virtual reality set up (or screen)
- ☐ The Tactile feedback device
- ☐ Other (Please elaborate) ______________________________

A.4

Full questionnaire used for the 3DoFs vibration experiment chapter 4.

Subject ID:_______________
InputFileName:________________

Part I: Demographic Questionnaire

1. **What is your gender?**
- ☐ Male
- ☐ Female
- ☐ Other

2. **What is your age?**
__________ years old

3. **What is your Ethnicity**
- ☐ White
- ☐ Black or African
- ☐ Hispanic
- ☐ Asian
- ☐ Native American
- ☐ Pacific Islander
- ☐ Prefer Not To Say
- ☐ Other (Please specify) __________________

4. **Are you familiar with haptic feedback devices (including smartphone vibration, ect)**
- ☐ No
- ☐ Yes

5. **Do you have/have you ever had injury or pain in the abdomen, back, hips, or chest.**
- ☐ No
- ☐ Yes ->Where exactly?

Abdomen Back Chest Hips Other (specify)___________________

6. **What is your height**
Please specify ___________________ cm/inches

7. **What is your weight**
Please specify ___________________ kg/lb

8. **What is your waist size**
Please specify ___________________ cm/inches

9. **What is your hip size**
Please specify ___________________ cm/inches

10. **What is your Torso height**
Please specify ___________________ cm/inches

Part II: Vibration Feedback

Please indicate on a scale from 1 to 9 your agreement toward the following adjectives relative to the stimulation you receive during the trial:

	1	2	3	4	5	6	7	8	9	
Unnatural	☐	☐	☐	☐	☐	☐	☐	☐	☐	Natural
Unsettling	☐	☐	☐	☐	☐	☐	☐	☐	☐	Reassuring
Strange	☐	☐	☐	☐	☐	☐	☐	☐	☐	Typical
Dislikable	☐	☐	☐	☐	☐	☐	☐	☐	☐	Likable
Unpleasant	☐	☐	☐	☐	☐	☐	☐	☐	☐	Pleasant
Painless	☐	☐	☐	☐	☐	☐	☐	☐	☐	Painful

Please indicate on a scale from 1 to 5 your agreement or disagreement relative to the trial:

During the trial

1) … The difference between angular sections on the abdomen was clear for me:

	1	2	3	4	5	
Strongly Disagree	☐	☐	☐	☐	☐	Strongly Agree

2) … The difference between radial levels within one section was clear for me:

	1	2	3	4	5	
Strongly Disagree	☐	☐	☐	☐	☐	Strongly Agree

3) … The difference between height steps was clear to me:

	1	2	3	4	5	
Strongly Disagree	☐	☐	☐	☐	☐	Strongly Agree

1) … I felt like I could locate the stimulation on the grid accurately:

	1	2	3	4	5	
Strongly Disagree	☐	☐	☐	☐	☐	Strongly Agree

Please, describe how you perceived the stimulation in a few words or give any other comments:

____

____

____

____

Please indicate on a scale from 1 to 5 your agreement or disagreement relative to your general perception of the stimulation:

I feel like vibrotactile stimulation

1) … annoys me:

	1	2	3	4	5	
Strongly Disagree	☐	☐	☐	☐	☐	Strongly Agree

2) … relaxes me:

	1	2	3	4	5	
Strongly Disagree	☐	☐	☐	☐	☐	Strongly Agree

3) … is simple to understand:

	1	2	3	4	5	
Strongly Disagree	☐	☐	☐	☐	☐	Strongly Agree

Part II: User Feedback

1) I felt like my body temperature when using the device was

- ☐ Significantly Decreasing
- ☐ Slightly Decreasing
- ☐ Constant
- ☐ Slightly Increasing
- ☐ Significantly Increasing

2) The device felt heavy to wear

- ☐ Disagree
- ☐ Neither Agree or Disagree
- ☐ Agree

3) The movement of my arms and legs was obstructed by the device

- ☐ Strongly Disagree
- ☐ Slightly Disagree
- ☐ Constant
- ☐ Slightly Disagree
- ☐ Strongly Disagree

4) I felt like the device was comfortable to wear

- ☐ Disagree
- ☐ Neither Agree or Disagree
- ☐ Agree

5) I was able to easily control the device while using it (turn on/off, plug in charger)

- ☐ Disagree
- ☐ Neither Agree or Disagree
- ☐ Agree

6) I was able to easily tell that the haptic feedback was from the device, and not the environment.

- ☐ Disagree
- ☐ Neither Agree or Disagree
- ☐ Agree

7) I would be able to wear the device without significant discomfort for:

- ☐ <1 hour
- ☐ 1-3 hours
- ☐ 3-6 hours
- ☐ 6-9 hours
- ☐ 9-12 hours
- ☐ 12 hours +

8) The device wound not stop me from carrying out daily duties

- ☐ Disagree (Please specify duties ______________________________)
- ☐ Neither Agree or Disagree
- ☐ Agree

9) The device felt fragile and easily breakable

- ☐ Disagree
- ☐ Neither Agree or Disagree
- ☐ Agree