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Design and validation of sensory feedback strategy for extra limbs

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ABSTRACT

Extra limbs (XLs) can be described as additional robotic extremities developed to assist or enhance the user abilities in specific situations. In recent years, they have been built for both impaired and healthy subject applications. In both cases, one of the significant challenges remains the lack of sensory feedback. Indeed, in the absence of tactile and proprioceptive feedback, the user has to rely heavily on visual input during the device control, which undermines usability and increase the cognitive effort needed to complete tasks. Implementing a sensory substitution solution can provide the missing proprioceptive and tactile feedback information to the user, increasing the usability of the whole system, and promoting its embodiment. This project aims to develop and test a sensory substitution display capable of providing proprioceptive and contact information to the user. The display will be used with a pre-existing XLs simulation platform that integrates virtual reality with a bimanual Exoskeleton, at the Campus Biotech (Geneva). To reach the goal, new hardware and software have been proposed after an extensive literature review. A tactile display relying on a hybrid feedback strategy to provide both proprioceptive and contact information was developed. It used a tactor composed by a servo and a lever system, capable of exercising a variable pressure on the skin of the subjects to provide proprioceptive information, and a coin-shaped vibrator to encode contact events. The efficacy of the proposed design and different encoding strategies have been tested in three experiments: psychometric assessments, investigating the sensorial perception on the trunk; encoding strategies evaluation, aimed at determining which strategy is the most suitable for communicating information; and an integration test, to understand limitations and to assess possible improvements of the system. The device was found capable of providing haptic feedback effectively when used in a controlled environment, but limitations emerged when used with the final setup suggesting that a tuning process on both the experimental protocol and encoding strategy is necessary to increase usability.

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LIST OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 STATE OF THE ART

1.1 Introduction

Extra limbs (XLs) are additional robotic extremities designed to assist the user abilities in specific situations or enhance his abilities (Parietti and Asada 2016). In recent years, they have been built for both impaired (Hussain et al. 2018) and healthy (Parietti and Asada 2016) subject applications; in both cases, the lack of sensory feedback remains the most significant limitation. Indeed, in the absence of tactile and proprioceptive feedback, the user has to rely heavily on visual input during the device control, which implies a usability loss and an increase in the mental effort needed. Implementing a sensory substitution solution can provide the missing proprioceptive and tactile feedback information to the user, increasing the usability of the whole system, and promoting its embodiment.

1.2 Existing technologies for sensory substitution

1.2.1 Targeted sensory impairment

Sensory impairment may be due to a large number of causes: traumatic accidents, neurodegenerative diseases, innate physical condition and a large number of other pathologies as strokes and sensory neuron disease (SND). In each one of these cases, the patient loses the ability to correctly retrieve information by one sensory modality, entirely or partially. For example, the amputation of a limb can lead to a lack of proprioception, sense of touch and force feedback, which can cause insecurity in the usage of a prosthesis and the increasing in the metabolic cost of daily tasks (Petrini et al. 2019); spinal cord injured (SCI) patients lose the ability to move and feel below the lesion due to damaged nerves and blind people must rely on the remaining senses for the accomplishment of every performed task. As proposed in the firsts Bach-y-Rita's works, sensory substitution (SS) technologies come to these people aid, replacing the missing or malfunctioning sense or relocating the sensory feedback, allowing them to achieve a better movement, for example reintroducing a gait information feedback (Crea et al. 2015); to decrease the amount of energy used during a task, like in (Petrini et al. 2019); allowing them to get better rehabilitation protocols, as presented in (Pan, Yoon, and Hur 2017); or to perceive a sensation that was not perceivable anymore, as the floor texture in a paraplegic patient’s case (Shokur et al. 2016). These technologies find application in other fields that are not linked to the world of impaired people, as the SS for enhancement (Havinga et al. 2006) one

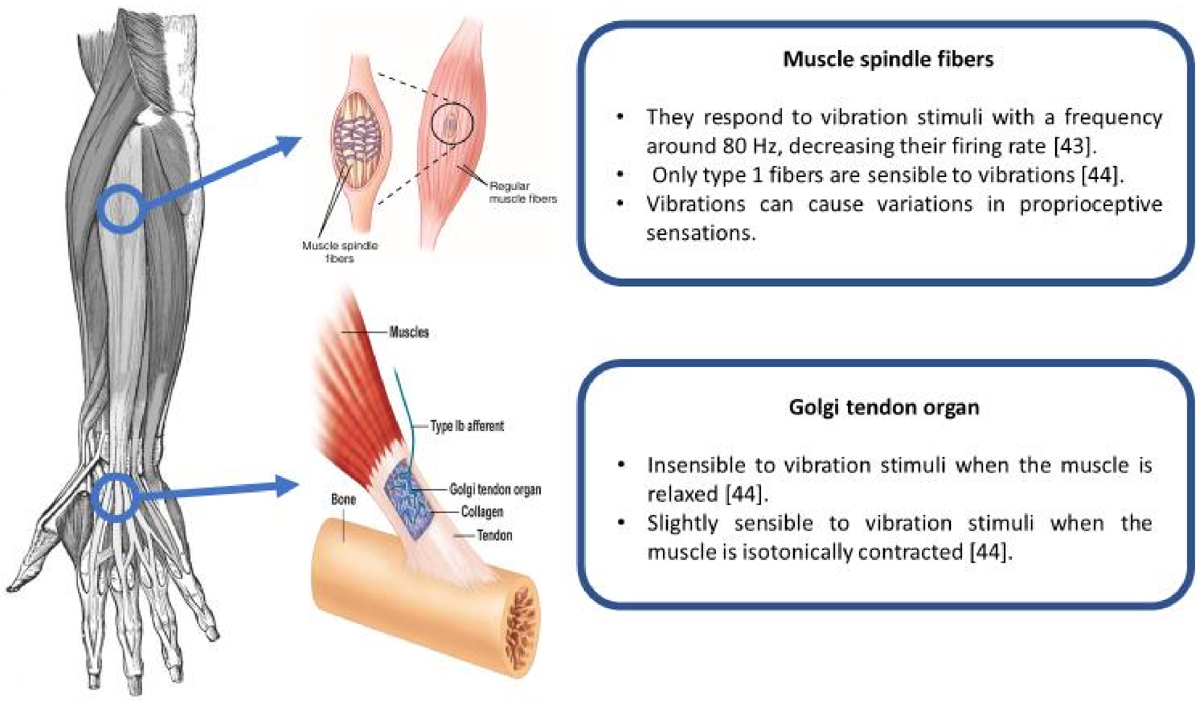


Figure 1 - Muscle mechanoreceptors and their response to typical feedback stimuli.

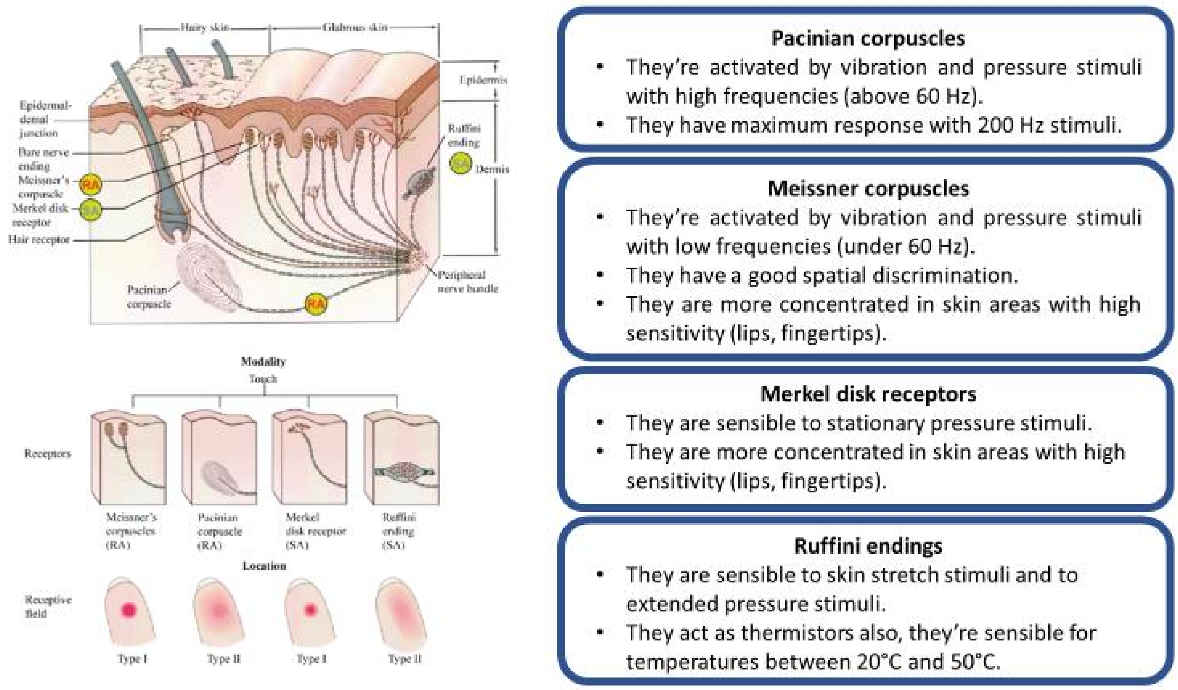


Figure 2 - Skin mechanoreceptors and their response to typical feedback stimuli.

and the SS for telemetry one (Shang et al. 2013); in the first case the main objective is to provide additional information to healthy subjects, while in the second case the objective is to compensate the missing sensory feedback caused by the telemetry system. For example, as demonstrated in a work by Cincotti and colleagues, it is possible to implement vibrotactile feedback in a Brain-Computer Interface (BCI), to provide continuous information about directions during a navigation task (Cincotti et al. 2007). In (Havinga et al. 2006) instead, is described how a belt with built-in vibrators is used to provide navigation instructions in low visibility conditions. All the applications and technologies presented in this work rely on external devices only, providing the feedback sensation stimulating muscle and skin receptors. There are two types of muscle receptors (*figure 1*): muscle spindle fiber and Golgi tendon organ; the first one is located between the other muscle fibers and provides information about the length of the muscles, while the second is placed near the tendons and provides feedback about the force exercised by the muscle. Panician corpuscle, Meissner corpuscle, Merkel disk receptor and the Ruffini ending are the principal mechanoreceptors instead (*figure 2*): the first is activated in response to vibration and pressure stimuli with frequencies above 60 Hz, the second responds to low frequencies vibration stimuli (below 60 Hz), the third to stationary pressure stimuli and the last one is excited by skin stretch or extended pressure stimuli. The distribution and density of skin mechanoreceptors changes accordingly to the body area and function: sensitive parts such as the fingertips and the lips will have a higher density of Merkel disk receptors and Meissner corpuscles, that have higher spatial selectivity and are responsible for the discriminative touch, while less sensitive body parts, as the back of the leg, will have a higher concentration of Pacinian and Ruffini receptors.

1.2.2 Hardware

Recent advances in electrode interfacing with the central or the peripheral nervous system via implantable electrodes have made possible to stimulate sensory pathways to create close to natural haptic sensation. However, these technologies (necessitating surgery) are so far only used in the clinical environment for patients with a severe sensory-motor deficiency (principally amputees, spinal cord injury patients). As the final goal of the current project is to propose sensory modalities for healthy subjects for a extra limb application, we will investigate exclusively non-invasive approaches for sensory feedback. The sensory substitution technology, outside the virtual reality and entertainment world, is in a very early stage of development and most of the solutions proposed are still prototypes. They rely on custom made hardware and software, designed ad hoc for specific applications, such as but not limited to lower limb amputees, upper limb amputees, spinal cord injured patients and BCI. Nevertheless, several non-invasive strategies have been successfully explored to date. Hereafter they are described with respect to the interface transducer technology employed:

- Force feedback technology → It acts on our muscles spindle fibers and Golgi tendon organs and it is generally used for non-portable devices, due to its dimensions; this feedback is normally used in teleoperation or virtual reality application to provide force response during the execution of a movement. Two examples are presented in (Luciano et al. 2011) and (Shang et al. 2013), in which, respectively, a virtual environment for the training of thoracic pedicle screw placement and a teleoperation system for needle insertion use a force feedback system to mimic the insertion resistance.
- Pressure feedback technology → It relies on actuators capable of exerting a force on the skin surface activating Meissner's corpuscles and Merkel disk receptors, they could be inflatable chambers as in (Abd et al. 2018) and (Fan et al. 2009) or mechanical actuator as in (Quek et al. 2014); in the latter is presented a 3 degrees of freedom (DoF) tactor capable of exerting both normal and tangential forces, providing richer information at the expense of a bulkier structure. These kinds of devices are very effective in providing stimuli with a slow variation in time and can be used in combination with other systems capable of better represent stimuli that vary faster as presented in (Abd et al. 2018), where a feedback device is used to provide to the user information about the grasping force of a hand with pressure feedback and sliding direction of the object with vibrotactile feedback.
- Vibrotactile feedback technology → It can provide a large amount of different information depending on the encoding, the placement and the application of the device. The vibration can be generated by different typologies of actuators and motors as magnetic actuators (Cincotti et al. 2007), eccentric mass rotors (EMR) (Jones, Lockyer, and Piateski 2006) or linear resonant actuators (LRA) and it is usually provided at a fixed

frequency between 100 Hz and 250 Hz (Jones, Lockyer, and Piateski 2006), acting on Pacinian corpuscles situated in the dermis or on muscle spindles if the frequency is low. Magnetic actuators are similar in principle to audio speakers: the current flowing in their coil pushes a central structure against the skin, generating the vibration sensation; an example is provided in (Cincotti et al. 2007), where C-2 tactors produced by Engineering Acoustic are used to provide feedback in a BCI application. Instead, EMR rely on an off-axis weight mounted on the rotor to generate the vibration and they are inexpensive, easily miniaturisable and allow to control vibration frequency and amplitude (they are coupled in ERMs) by controlling the motor speed; R1 rototactor (Steadfast Technologies) is an example of a vibrator designed for haptic feedback applications, but many systems use motors designed for other purposes as presented in (Jones, Lockyer, and Piateski 2006), in which the R1 rototactor and two other motors (a coreless cylindrical permanent magnetic micro-vibration DC motor and a pancake pager motor), designed for cell phone applications, are compared to determine the best choice for providing vibrotactile feedback on the torso. LRAs are composed by a mass and a spring, but the vibration is not caused by rotation as in the eccentric mass motor case, but by a linear movement; they are more complex if compared to EMR because they need an AC driving signal and the vibration frequency and amplitude are not coupled, but they can provide faster and stronger feedback. The vibrotactile feedback technique is largely the most studied and used because of its cheapness, efficiency and simplicity; moreover is possible to take advantages of phenomena like the apparent movement (the impression of feeling a moving vibration between two vibrators sequentially activated) or the phantom tactile sensation (Israr and Poupyrev 2011), thanks to which is possible to create continuous feedback, to create complex stimulation patterns and transfer a large amount of information. Due to its versatility, this technology has been used in several applications.

- Electrotactile feedback technology → it is a non-invasive technology, but in some situations, it can generate discomfort or a pricking sensation (Zhang et al. 2015). The hardware necessary for this kind of stimulation can change, but the two fundamental parts are the electrodes and the electrical stimulator. The first one can be composed by single electrodes or by electrodes arranged in matrixes placed on the skin surface, these are usually made with copper (Zhang et al. 2015) or Ag-Cl (Wang et al. 2019); the use of gels depends on the material of which they are made, but to prevent chemical reactions or puncturing sensations a hydrogel could be used (Zhang et al. 2015). The electrical stimulator generates the current, controlling its amplitude, frequency and waveform; for electrotactile feedback systems, the maximum current amplitude is of the order of tens of μA (Hasegawa, Sasaki, and Tsukahara 2012), the frequency is between 30 Hz and 400 Hz (Wang et al. 2019), depending on the provided sensation, and the used waveform is usually a square pulse with a width between 20 μs and 600 μs (Wang et al. 2019); examples of commercially available stimulators are the AMPI Master 9 used in (Wang et al. 2019) and the ones produced by the UNIQUE MEDICAL. Unlike the other ones, this technology stimulates not only the skin mechanoreceptors but also the nerves and can produce a wider range of sensations, like vibration and pressure, only varying the stimulation frequency, amplitude and pulse-width. Moreover, the stimulation point density can be higher compared to the vibrotactile technique, as it is presented in (Li et al. 2017), and the feedback can be provided on smaller skin areas as is presented in (Hasegawa, Sasaki, and Tsukahara 2012).

- Ultrasound (US) feedback technology (*figure 3*)→ this technique uses a matrix of US emitters to create localised air perturbations, these can be perceived with skin receptors, as the Meissner's ones, even without touching the device; the main application is the replication of surface textures (Teslasuit 2018).

Figure 3 - Example of a US feedback device.

- Thermal feedback technology → it is a technique based on transferring heat from the device to the skin and vice-versa causing the activation of the Ruffi and Krause and bulb receptors in our skin using the Peltier effect of one or more thermocouple. The implementation and the design of these devices are simpler, if compared to the other technologies presented and there is no need for a large number of actuators to provide good sensation, but for sensory substitution applications, this system is not particularly suitable, due to its energy inefficiency and to its response delay (Teslasuit 2018), nevertheless in (Gallo et al. 2015) is presented a device prototype for telemanipulation tasks. Even if SS devices are not widespread, it is possible to find some commercial system such as The Wave Bracelet and the Reon Pocket, that are personal wearable thermostats.
- Stiffness feedback technology → as explained in (Ishizuka and Miki 2015) and (Ishizuka, Rorenzoni, and Miki 2014), this feedback technique uses a magnetorheological fluid to mimic different objects stiffness (*figure 4*). It is possible to use it for the developing of tactile displays capable of reproducing human tissue consistencies, useful for training doctors in palpation test (Ishizuka, Rorenzoni, and Miki 2014), essential in small tumour detection.

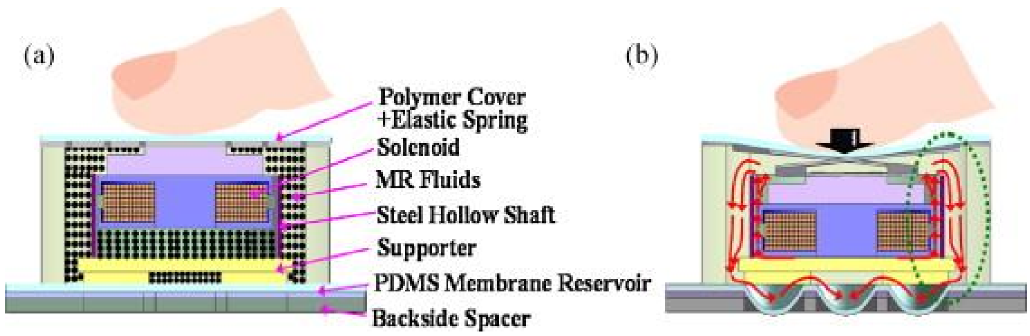


Figure 4 - "Schematic illustration of the working principle and mechanism of stiffness display: (a) before pressing and (b) after pressing." (Yang, Kwon, Lee et al. 2010).

- Skin stretch feedback technology → This kind of feedback provides simple information to the user stretching his skin and activating the Ruffini corpuscles accordingly. The skin stretching is usually achieved via the movement of a stepper, DC or servo motors.

1.2.3 Placement

When it comes to providing haptic feedback, the placement of the system on the skin surface has a key role regarding usability and embodiment of external devices such as prosthesis, XLs and exoskeleton; nevertheless, there is not a general rule for its placement and it changes accordingly to the application, the user's condition or pathology and accordingly to the type of the feedback technology used (*figure 5*). Another element that must be considered is the mechanoreceptor distribution and density in different body parts: glabrous skin areas tend to have a higher concentration (up to 500 corpuscles per cm^3 in the fingertips) of Meissner's corpuscles and Merkel disks, that are responsible for discriminative touch sensations, while in hairy skin areas receptors with large receptive fields are prevalent. Nevertheless, in a work by Cesini et al. (Cesini et al. 2020) is demonstrated how the abdomen and lower back locations, even if they have a less spatial and temporal resolution regarding vibrotactile stimulation, can allow achieving good performances during the walking activity and that the perception of vibration stimuli is not affected by the gait phase events, as it happens for systems placed on the thigh. Another useful example is proposed in (Zhang et al. 2015), where the difference in performances of two electrotactile feedback systems, one providing somatotopic feedback and

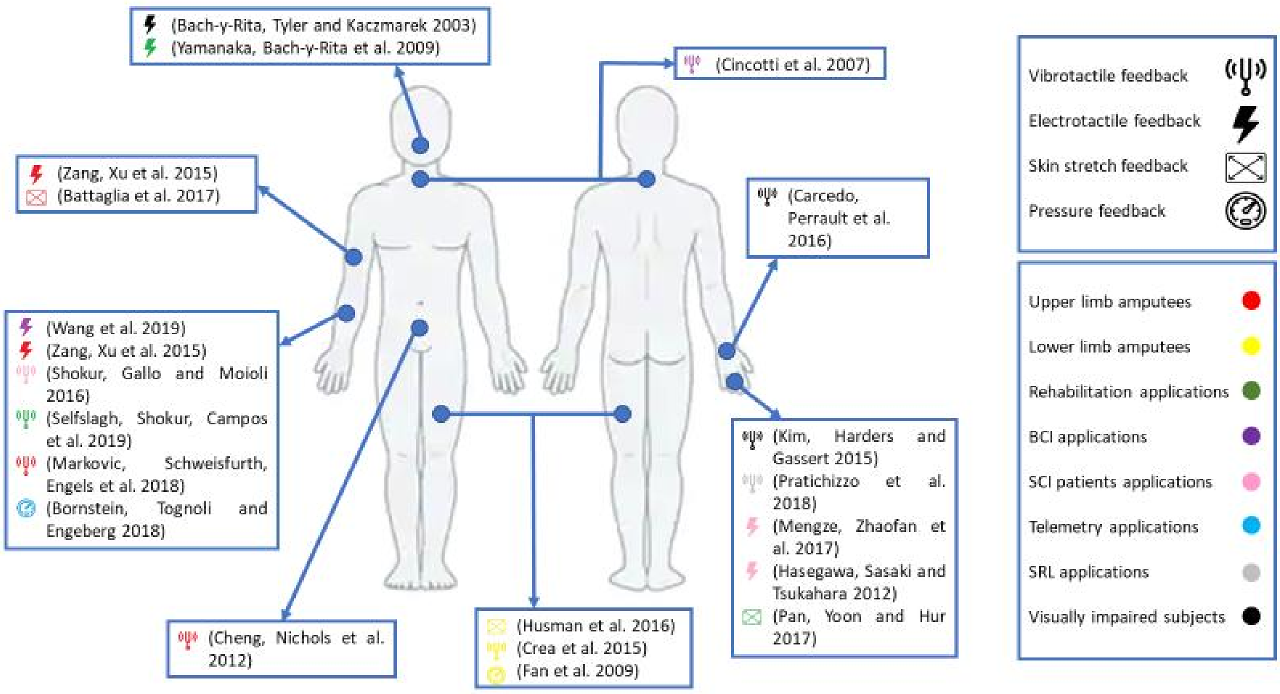


Figure 5 – Placement and application of the feedback devices considered in this work.

the other a non-somatotopic one, are compared in the case of an upper limb amputee with phantom digit sensation. The results show better performances in the somatotopic case. Also, the performance gap between the two placement increases with the increase of the number of used channels. Usually, in literature, the somatotopic feedback is preferred for amputee application (see (Fan et al. 2009), (Crea et al. 2015), (Husman et al. 2016), (Battaglia et al. 2017)), but some studies, reviewed in (Cheng et al. 2012), suggest that the performances in fingers, torso and forearm are comparable with a vibrotactile feedback device, despite the greater number of mechanoreceptors in the fingers. In light of this, in (Cheng et al. 2012), it has been preferred the torso location compared to the forearm one to guarantee fewer interferences during daily living activities, while in (Markovic et al. 2018) the vibrotactile feedback has been placed on the contralateral forearm due to the encumbrance of the socket on the amputee's arm. It is necessary to say that, even if in some cases the performance in somatotopical and non-somatotopical feedback is similar, the non-somatotopical case needs longer training time, because the user must learn the new feedback mapping. In the case of SCI patients, the somatotopic feedback is not a viable solution and it is imperative to deliver information to the user on a body part that's not affected by paralysis: forearm (see (Shokur et al. 2016), (Donati et al. 2016), (Selfslagh et al. 2019)) or fingers (see (Hasegawa and Ozawa 2014), (Li et al. 2017)) are the most common solutions. The fingers placement is used in other applications like rehabilitation (Pan, Yoon, and Hur 2017) and for supernumerary finger control (Hussain et al. 2018); the main advantage of this placement is the high density of skin receptors, while the main drawback is linked to the small available surface, that makes bulky and complex systems based on force and vibration feedback unusable. The tongue is another possible location for small and compact systems, its receptors density is high and, in the case of electric stimulation, the needed current is sensibly lower if compared to other body areas; in two work by Bach-y-Rita (see (Taylor et al. 2009) and (Yamanaka et al. 2009)) are presented two possible applications involving tongue stimulation for patients with visual deficits and rehabilitation purposes.

1.2.4 Encoding strategy

The encoding strategy allows the user to perceive the information acquired by device sensors translating it in a set of different stimuli, for time, position, duration and intensity, that the person can discern and interpret. The encoding of biological signals is complex and variable and the suitable solution depends on many factors: type of the information, placement of the device, feedback technology implemented, system objective, and device conformation (matrix, array or single stimulation points). Moreover, is possible to divide the presented encoding strategies into two main classes: **intuitive encoding approaches (I)** and **abstract encoding approaches (A)**; these differ for the quantitative of information that they are capable of transmitting and for the amount of training needed by the user to achieve optimal performances. Complex strategies have a higher information rate transfer at the expense of a less intuitive encoding and of longer training time.

1.2.4.1 Upper limb encoding strategies

- Vibrotactile feedback → this technique is very pliable and it is possible to use a wide variety of encoding strategies. In (Abd et al. 2018) and (Cheng et al. 2012) are presented two examples, respectively intuitive **(I)** and abstract **(A)**. In (Abd et al. 2018) it is showed an armband capable of providing force feedback with 3 pressure actuators and slippage feedback with 3 or 5 vibrators, these last ones were activated sequentially to elicit the sensation of a moving vibration around the arm in either a clockwise or anti-clockwise direction, accordingly to the slippage direction. In (Cheng et al. 2012), instead, an array composed of 4 vibrators is used to communicate to the user the percentage of a movement done by a virtual hand, by changing the envelope frequency of the motors. Two encoding techniques are presented: the decoupled one, in which 1 vibrator communicates the thumb position and the other 3 the remaining fingers configuration, and the synergies one, in which every muscular synergy is characterized by an activation pattern of the device. Despite the synergies technique seems more complex, results showed higher performances (80% of correct classifications) using this encoding, but the users needed more time to achieve good results and to provide the answers. Another example is presented in (Markovic et al. 2018), where a commercial hand prosthesis, instrumented with a force encoder and 3 position encoders, communicate with an armband on the contralateral forearm to provide feedback about the current hand modality, the fingers contact and the exercised force. The encoding used relies on small vibration bursts, to communicate the chosen modality or the touch sensation, and on the variation of the intensity to provide grasping force feedback (*figure 6*); the modality revelated to be perceived as intuitive **(I)** and useful by the users, but it had an effective impact only in complex motor tasks.

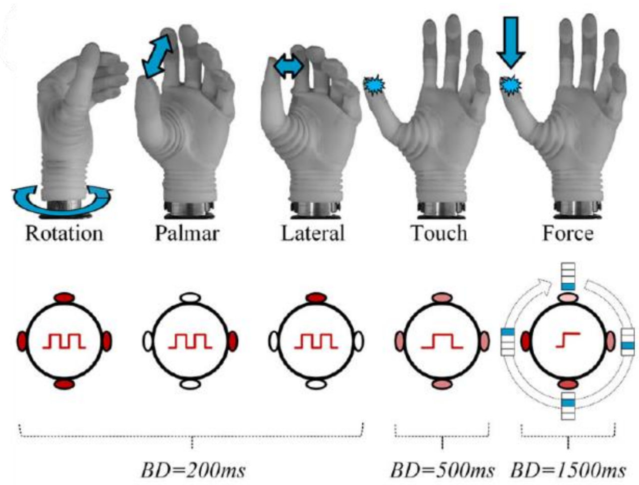


Figure 6 - Placement of the system and feedback encoding presented in (Markovic, Schweisfurth, Engels et al. 2018).

- Electrotactile feedback → this approach allows for varying the provided sensations by modulating the current intensity and frequencies: with frequencies between 60 Hz and 400 Hz, the user perceives a pressure stimulus, while frequencies between 35 Hz and 60 Hz trigger a vibration sensation (Wang et al. 2019). Moreover, stimulating directly the nerves and bypassing the mechanoreceptors (Wang et al. 2019), is possible to take advantage of phantom limb sensations in amputees providing very real-like sensations without stimulating the stump directly(Zhang et al. 2015). In (Wang et al. 2019) is presented an intuitive **(I)** way to encode 3 sensory pathways, fingertip pressure, slippage and proprioception information, using an electrode matrix placed on the forearm. The sketch map of electrical stimulation is shown in *figure 7*. The carried on experiments show good performance results with an average of pressure intensity recognition of 66%, an average classification of the sliding direction in slippage mode of 95% and all the testers have been able to classify the feedback mode with an accuracy between 81% and 93%. Instead, in (Zhang et al. 2015), it was possible to acquire a phantom map of the residual limb and provide 500 μs pulses at 100 Hz to give the user a fingertip touch feedback. The paper tests 3 configurations with respectively 1, 3 and 5 stimulation channels: as expected, increasing the number of channels leads to a drop in performance, but allowing the device to have a higher information rate transfer. This is probably the most intuitive **(I)** encoding strategy, the only disadvantage is that it is limited to amputees with phantom fingers sensations.

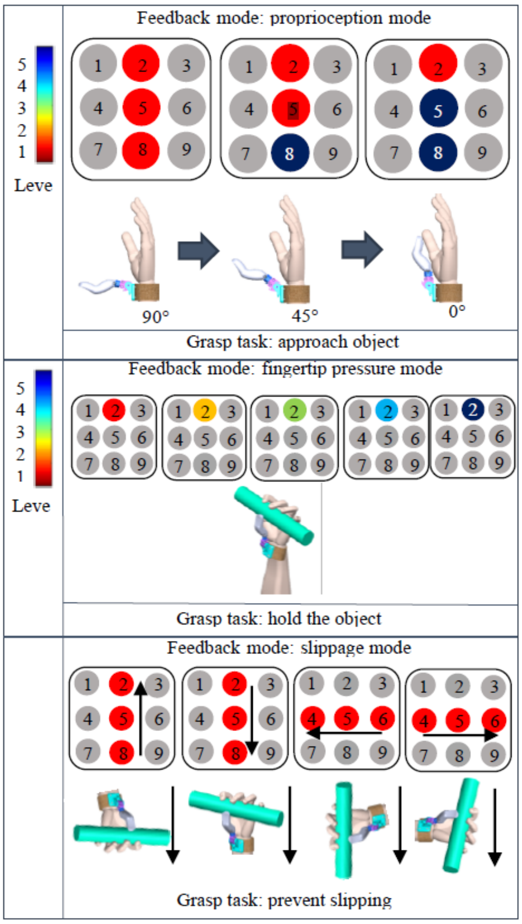


Figure 7- The three sensory feedback modes presented in (Wang et al. 2019).

- Skin stretch feedback → in (Battaglia et al. 2017) a servo motor is used to deform the forearm skin proportionally to flexion degree of the fingers in a hand grasping motion; the approach is simple, intuitive **(I)** and inexpensive, but it achieves good performances: the users were indeed able to discriminate the different size of 6 spheres with an average accuracy of 73%.

1.2.4.2 Lower limb feedback encoding strategies

- Pressure feedback → in (Fan et al. 2008) is presented a simple and intuitive **(I)** feedback system for lower limb prosthesis users that consists of 4 balloon actuators placed on the thigh and linked to 4 force sensor under the prosthesis sole, respectively mounted at the heel, at the toe and in a medial and lateral position. The actuators have a monotonic vertical input pressure proportional to the sensed force. Despite the simplicity, the users were able to recognize different activation sequences and various pressure levels with an average accuracy above 90% and to recognize the movement of an operator with a 95.8% accuracy.
- Vibrotactile feedback → it is one of the most used solutions and it has the advantage of being able to be positioned everywhere. An effective and intuitive **(I)** way to inform a paraplegic user, wearing a lower limb exoskeleton, about the gait phase is described in (Shokur et al. 2016): 2 arrays placed on the forearms activate sequentially 3 cone-shaped vibrators, to elicit an apparent movement sensation and provide information to the user about the swing or the stance phases. The activation patterns are presented in *figure 8*. The SCI patients involved in the experiments preferred the feedback provided during the stance phase, but each one had different performances if the apparent movement was

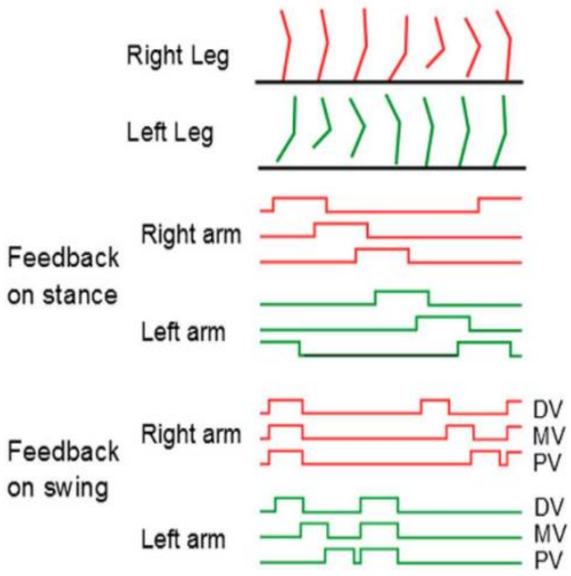


Figure 8 - Activation pattern of the vibrators presented in (Shokur, Gallo and Moioli 2016).

proximal to distal or vice versa; to uniform all the results the distal to proximal modality has been chosen. This paradigm has been tested providing the feedback on the forearm on the same side of the leg or the opposite: the same side paradigm revelated to be more performing. Instead, in (Crea et al. 2015) is presented a very simple and intuitive **(I)** way to provide feedback to a lower limb prosthesis user regarding the start of the 3 different gait phases; the system relies on a pressure-sensitive insole to measure the pressure distribution on the sole and to detect the transition between two phases, at this point one of the three vibrators is activated to transmit the information to the amputee.

- Electrotactile feedback → in (Li et al. 2017) and (Hasegawa, Sasaki, and Tsukahara 2012) are presented two possible encodings for this feedback type, both of them are abstract **(A)**, but excellent performances can be achieved after training. (Li et al. 2017) describes a methodology to provide proprioceptive feedback to a paraplegic exoskeleton user via an electrodes matrix placed on a finger, this changes the stimulation point accordingly to the leg position during a step, describing an S-shaped trajectory (*figure 9*). Tests showed how, thanks to the device, the patients were able to walk faster (0.43 m/s faster) and to make more symmetrical steps compared to the no-feedback condition. Also the second before mentioned work (Hasegawa, Sasaki, and Tsukahara 2012) proposes a feedback system for paraplegics exoskeleton users, but in this case, a set of 18 electrodes, 9 for each hand and arranged as shown in *figure 10* is used. It provides to the user information about the hips angles, which is encoded by matching a specific angle to

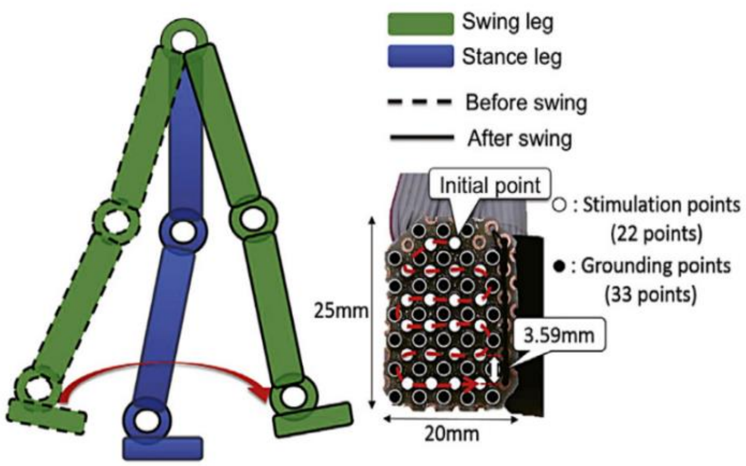


Figure 9 - Stimulation trajectory during the leg movement (Mengze, Zhaofan et al. 2017).

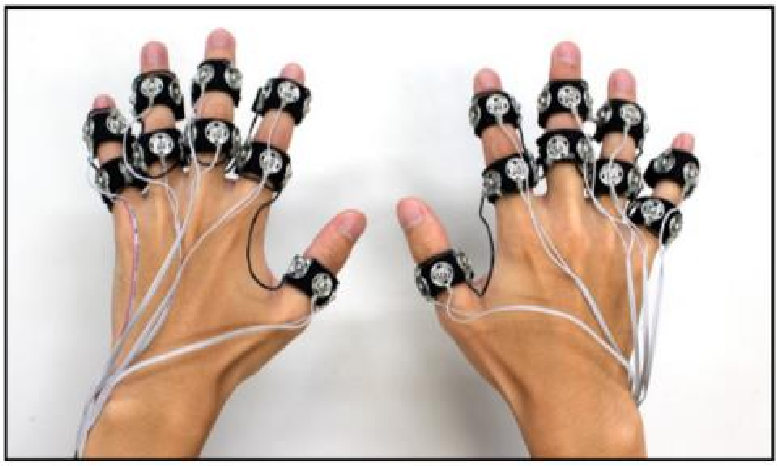


Figure 10 - Electrode placement presented in (Hasegawa, Sasaki and Tsukahara 2012).

the activation of 1 or 2 electrodes on the ipsilateral hand. The tests performed with the device revelated a resolution around 5° for the hips angles and allowed the three users to correctly identify the hip position with an accuracy rate above 90%.

- Skin stretch feedback → despite it is intuitive **(I)**, this technique is one of the less used, probably because it is harder to provide complex feedback and stimulation patterns to the user with it if compared to other techniques, such as vibrotactile and electrotactile ones. The only example present in literature was (Husman et al. 2016), which proposes a simple system to provide to the amputee information about the toe-off and heel-strike instants. A rubber belt, in contact with the thigh skin, is used for stretching the skin for 50 ms, 150 ms, 300 ms or 400 ms when one of the two events happen; with all the stretch durations the gait phases revelated to be recognizable with an accuracy above 98%.

1.2.4.3 Texture encoding strategies

- Vibrotactile feedback → in (Shokur et al. 2016) is presented an encoding strategy to permit to an SCI patient to discriminate different surface textures using an array composed of 3 vibrators and placed on the forearm. The experimental protocol allowed the testers to set the stimulation parameters, amplitude and timing, several times for 3 surfaces: grass, sand and paved street. Then, after a training session, the stimulation patterns were tested by providing the stimulation without visual feedback. Most of the patients were able to discriminate the different textures. This encoding may seem abstract because it renders 2D information in 1D space, but the fact that each user chose very similar stimulation parameters among thousands of combinations suggests that the strategy is quite intuitive **(I)** instead.

1.2.4.4 Encoding strategies for training and rehabilitation applications

- Vibrotactile feedback → (Ruffaldi et al. 2009) provides an example of one of the possible usage of haptic feedback in sports: it describes a system to train the rower to follow an optimal trajectory with their hand; the device relies on a vibrator which intensity is directly proportional to the error between the actual hand trajectory and the optimal one. This is a very intuitive **(I)** and simple feedback encoding, but it represents a perfect example of how these technologies could be used to improve performances in a wide range of applications.
- Skin stretch → in (Pan, Yoon, and Hur 2017) is presented an intuitive **(I)** and portable device that could be useful to provide additional feedback to people suffering from a sensory deficit and to allow them to maintain a better posture. The system uses a small DC motor, placed on the fingertip, which direction and velocity are proportional to the difference between the pitch angle and a reference angle, defined as the average pitch angle of the subject during upright standing (*figure 11*). Unfortunately, despite the simplicity of this strategy, performances are not optimal and the system needs several improvements.

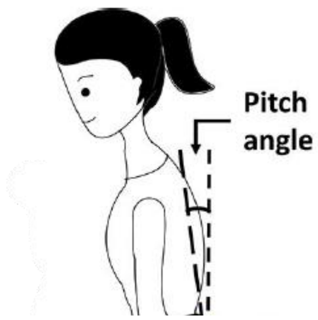


Figure 11 - The considered pitch angle (Pan, Yoon and Hur 2017).

1.2.4.5 BCI feedback encoding strategies

- Vibrotactile feedback → encoding approaches for BCIs can differ a lot depending on the system application. In (Cincotti et al. 2007) an intuitive **(I)** system is presented; it is composed by a series of vibrators placed around the neck and it is capable of providing proprioceptive feedback about a virtual hand position; the conducted tests revelated that direction and intensity of the stimuli were recognisable and that the user was able to identify the virtual hand movement with an accuracy between 70% and 80%.

1.2.4.6 Extra limbs encoding strategies

- Vibrotactile feedback → As for BCI applications, the encoding approach could potentially be very different depending on the system application. However, there are only few studies to date addressing sensory feedback for XLs. An example is presented in (Hussain et al. 2018), where the HRing system is presented; it is a ring composed by a vibrator and two servos that allows the user to control opening, closening and grasp force of a extra finger. Two short vibration bursts are provided when the finger comes in contact with the object and when the opening procedure is started respectively, while the user can select the grasping force by relying on the feedback provided by the two servo motors, that squeeze the user’s finger proportionally to the force applied by the extra limb. A previous work (Hussain et al. 2015) on the same supernumerary finger system aims to compare different encoding strategies instead, using a ring with an EMR mounted on; three strategies are tested: vibration bursts on making and breaking contact with the grasped object, continuous vibration proportional to the exerted force and vibration bursts on contact and when the exerted force is 2 N and 4 N. The three encodings were tested evaluating the performances during a grasping task and results showed that despite the performances were practically the same in the three cases, users perceived the first and third strategies as more effective, probably due either to a saturation effect on the skin receptors or to the fact that the very rich information provided in the second condition can be difficult to be understood by the user.

1.2.4.7 Encoding strategies for blinds support devices

- Vibrotactile feedback → blind people aids can provide mainly navigation or colour information and can be implemented in very different devices; an intuitive **(I)** way to encode distance information is proposed in (Kim, Harders, and Gassert 2015), where an array of 4 vibrators, mounted on the white cane, changes stimulation parameters accordingly to the obstacle position. Three encoding strategies are proposed: (i) the temporal variation, (ii) the temporal and spatial variation and (iii) the temporal, spatial and intensity variation (*figure 12*). Tests have been performed with all the three methodologies and in the cases of proximal-to-distal vibration and distal-to-proximal vibration; results showed good performances especially using the temporal and spatial variation encoding and the temporal, spatial and intensity variation encoding. Instead, the work described (Carcedo et al. 2016) proposes a device capable of providing colour information to colourblind people. Using an armband with 3 vibrators, spatiotemporal patterns were delivered to the subject to encode up to twelve colours of the RGB wheel.

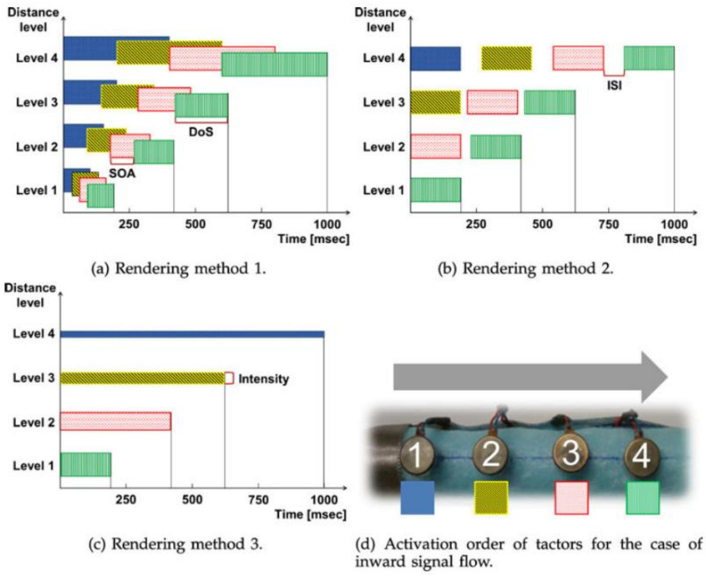


Figure 12 - the vibrators placement and the encoding strategies proposed in (Kim, Harders and Gassert 2015) . (a) Tactile apparent movement. Tactors are activated sequentially with temporal overlap (bars are shifted vertically for better visibility), distance is encoded by varying duration. (b) Consecutive activation of a varying number of tactors, distance is encoded by the number of activated tactors. (c) The tactors are mapped to the individual distance levels, and each tactor renders a distinct duration and intensity.

The system has an abstract approach **(A)**, but the average identification is 81.6%, pretty high considering the complexity of the information transmitted.

1.2.5 Commercially available technology

Haptic feedback is, in all its forms, a young technology and most of the commercially available devices belong to the virtual reality and entertainment class; nevertheless, is possible to find some startups and companies that are trying to adapt existing products for medical, rehabilitation or sensory enhancement applications. Here are presented some of the most interesting applications:

- Sensei™ Robotic Catheter System →it is a catheter insertion system developed by ForceDimension that uses a 3 D.O.F. haptic device to control the tip of the catheter and to provide force feedback to the operator in real-time.
- ExoBeam →it is a wearable assistive device for patients with movement disorders developed by MedExo Robotics, it uses lasers beams to guide patients movements and can provide vibration feedback and audio cues to help the user to maintain a normal walking pace, to guide the stride or the speed.
- Wayband → produced by WearWorks, it is a smart bracelet, connected to the smartphone, that guides the user to the destination using only vibrations; it is thought for blind or visually impaired people.
- Delta 1 →it is a wearable device produced by Iterate Labs that provides insights into likely indicators of strain or repetitive motion injuries. It is fabricated to be mounted on the worker's gloves and to provide feedback when they are not performing a safe movement.
- Falcon → it is a USB haptic device tinked for a wide range of applications and capable of providing force feedback to the user. It is produced by Novint technologies inc.
- Spidersense →it is a haptic jacket developed with blind people in mind: the device uses 12 ultrasonic sensors to scan the environment and provide tactile feedback to the user.

- Epsim™ and Lapsim → these are two surgery simulators, for epidural injections and laparoscopic operation respectively, produced by the Yantric Inc. They rely on a Phantom 3D system to provide force feedback during the simulations.
- ROWCUS →it is a rowing system composed by a proximity sensor and a haptic feedback chest-belt, it is task is to inform rowers of incoming obstacles.
- Reon Pocket →it is a personal wearable conditioner, produced by Sony, that allows the user to regulate its temperature exploiting the Peltier effect.
- The Wave Bracelet → it is a personal thermostat in the form of a bracelet, produced by Embr; it can cool or heat by 5 degrees the user's wrist, changing its temperature perception. It relies on the Peltier effect as the Reon Pocket.

1.3 Applications of sensory substitution

In the sensory substitution technology, the end-user application is the aspect that most of all leads the hardware, software, placement and encoding strategy choices; nevertheless, this technology is very pliable and easily transferable to many fields of study and this has led to a wide variety of research and commercial applications. It is possible to identify two main categories: applications for impaired subjects and sensory enhancement or augmentation ones.

1.3.1 Applications for impaired subjects

These devices pursue the objective of compensating one or more sensory deficit of the user. The feedback system can be designed to be used in activities of daily living, allowing the user to perform some tasks better, or it can be designed for rehabilitation purposes, therefore to be used in a controlled environment to improve the physical condition of the patient.

- Lower limb amputees applications → lower limb amputations are by far the most common ones and have a great impact on a person condition, even if a modern prosthesis is used: they lead to improper balance and increased injury due to falling (Fan et al. 2009), to an increased walking metabolic cost and to a reduction of the walking speed (Petrini et al. 2019), patients can experience phantom limb pain (Petrini et al.

2019) and the lack of sensory feedback is proved to lengthen recovery and rehabilitation times (Fan et al. 2008). The impact of these issues can be reduced by using the correct type of feedback system, that for an amputee must provide information about the gait phases and the interaction forces between the sole and the floor primarily. In literature is possible to find several examples, using a wide variety of technologies; most of the presented devices rely on external skin stimulators and on force sensors placed on an insole to communicate to the user the current gate phase (see (Crea et al. 2015) and (Husman et al. 2016)), while other can provide force feedback directly proportional to the pressures distribution on the sole (see (Fan et al. 2009) and (Fan et al. 2008)); these system typologies can both help to improve balance and confidence in walking activities. Instead, to treat the phantom limb pain condition is necessary to use more complex systems, based on implanted electrodes capable not only of providing sensory feedback but of stimulating the nerves directly and at specific frequencies, as presented in (Petrini et al. 2019).

- Upper limb amputees applications → hand and upper limb amputations involve severe disabilities and major issues in daily living compared to other amputations types and, up to now, even state of the art commercial technologies are not capable of providing comfortable and intuitive solutions for this kind of amputees, so that the abandon rate for body-powered and electric prosthesis are respectively 35% and 45% ("Why People Abandon High-Tech Prosthetics," n.d.). Accordingly to ("Why People Abandon High-Tech Prosthetics," n.d.), the first cause of abandon in hand prosthetics is the control complexity: the newest devices allow several movements but are still controlled with a couple of electrodes only and this makes the whole control strategy very intricate in case a task requires multiple modes switching. Nevertheless, robotic hands miss force and contact feedback completely, contrary to body-powered ones, making it difficult for the users to adapt the grip strength in case of fragile objects. The introduction of a feedback system can partially overcome these issues, allowing better human-prosthesis communication; the information provided can deal with proprioception (see (Battaglia et al. 2017) and (Cheng et al. 2012)), contact of the fingertips (see (Markovic et al. 2018) and (Zhang et al. 2015)), the exerted force (see (Markovic et al. 2018) and (Abd et al. 2018)) and in some experiments was even possible to encode the slippage direction of an object (Abd et al. 2018). In the case of phantom limb sensation, it is even possible to take advantage of the remaining nervous terminations to provide very real-like touch or pressure sensation using Electrotactile feedback, as presented in (Zhang et al. 2015). All of these applications are still in a research stage, most of them have not been tested in a real-life environment and it is not clear if haptic feedback could be a breakthrough in hand amputees life; interesting results about this topic have been achieved and presented in (Markovic et al. 2018), where the performances of several hand-dexterity tasks performed with and without vibrotactile feedback have been compared, revealing that feedback resulted to be useful only in complex tasks. Nevertheless, all the participants defined the feedback system as "useful, pleasant and easy to understand".

- Application for patients with spinal cord injuries (SCI) → SCI patients suffer from post-traumatic complications that are not strictly connected to the recision of the nervous pathways: neurogenic shock, cardiovascular diseases, respiratory complications, thromboembolism and heterotopic ossification (Hagen 2015). Most of these are linked to the lack of physical activity and to the impossibility of maintaining a standing position, but their effects can be limited by the use of exoskeletons for locomotion or rehabilitation, that can allow the user to walk and maintain a more physiological position. The main drawback of such devices is that no proprioception information is perceived by the user, making necessary a constant visual supervision and putting the patient at risk of fall; for these reasons, several groups are working on feedback systems capable of informing the SCI patient of the gait progress (see (Shokur et al. 2016), (Li et al. 2017), (Hasegawa, Sasaki, and Tsukahara 2012), (Hasegawa and Ozawa 2014)). In literature, the feedback is usually provided on forearms or fingers accordingly to the technology used: vibrotactile feedback that involves bulkier stimulators is often provided on the forearm (Shokur et al. 2016), while electrotactile one can stimulate areas with smaller surfaces, like the fingers (see (Li et al. 2017), (Hasegawa, Sasaki, and Tsukahara 2012), (Hasegawa and Ozawa 2014)). Moreover, in (Shokur et al. 2016), it has presented an encoding capable of providing texture information, allowing the user to discern different floor materials and surfaces while walking on them.
- Rehabilitation applications → haptic feedback can be used successfully not only for permanent applications like prosthesis but can be useful to enhance treatment and

rehabilitation processes also, especially the ones involving patients with sensory deficit or impairment. In literature is possible to find examples about applications involving SCI patients (see (Donati et al. 2016), (Selfslagh et al. 2019)), post-stroke patients (Krueger et al. 2017) and patients with neurological disorders (Pan, Yoon, and Hur 2017), but these techniques could be easily adapted to fit several other situations. Both scientific articles (Donati et al. 2016) and (Selfslagh et al. 2019) present long term rehabilitation protocols for patients with spinal cord injuries in which feedback plays an important support role, allowing the patients to rely less on visual feedback during the legs mobilization. In (Krueger et al. 2017), the ability of patients suffering from kinesthesia deficits in using vibrotactile feedback to enhance hand stabilization and reaching tasks is evaluated; in both cases, the provided feedback positively improved the performances in absence of vision. Instead, in (Pan, Yoon, and Hur 2017) is presented a small portable device for the rehabilitation of people with neurological disorders, responsible for poor balance; such system relies on a small motor that communicates the pitch angle of the trunk trough the finger skin stretch. Results showed that the augmented sensation helped the patients in reducing their postural sways and in better controlling their posture. Another application for balance improvement is presented in (Yamanaka et al. 2009), in which an electrodes matrix placed on the tongue is used to provide body orientation information to the users; all the experiment subjects showed improvements in balance performances.

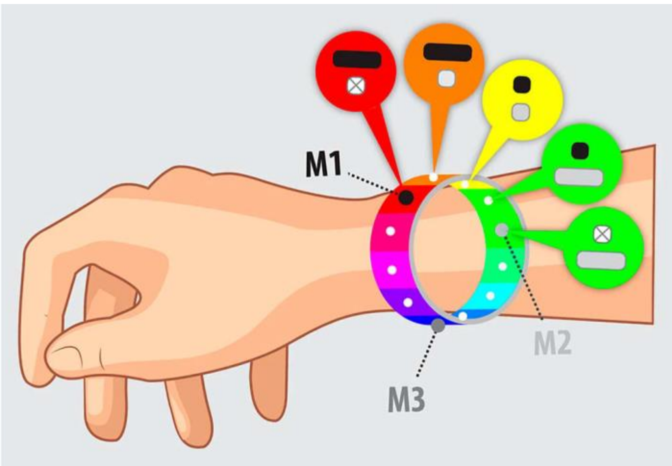


Figure 13 - The armband for colourblind people presented in (Carcedo, Perrault et al. 2016).

- Applications for people with visual deficits → pathologies that afflict sight can have a deep impact on people's lives and cause serious disabilities: blindness, colour blindness and even partial blindness do not allow proper and safe space navigation making necessary the use of external aids. The classic assistant device for blind people is the white cane, it is costless and easy to use, but its main limitation is that does not allow the user to locate the incoming obstacles until they are very close to him; an interesting improvement of it is presented in (Kim, Harders, and Gassert 2015), where a vibrotactile array placed on the handle can provide distance information of the incoming obstacles. In the article, different stimulation patterns and information encoding are analysed and in all the cases the user has been able to correctly determine the objects' distance with an accuracy rate above the 80%, suggesting that this solution could be implemented efficiently in a real-life application. Instead, in (Taylor et al. 2009) is presented an approach based on the electric stimulation, in which a 12x12 matrix of electrodes is used to transfer a recorded image to the patient's tongue allowing him to perceive visual information again. Another promising application is the wearable devices one, which objective is to provide spatial navigation information through tactile feedback; a possible solution is described in (Havinga et al. 2006): it uses a vibrotactile belt to provide direction indication and it is thought not only for blind people but for situations of low visibility also. Another interesting wearable device is WayBand, a smart bracelet connected to the smartphone capable of guiding the user to the destination using only vibration patterns; it is a commercial device produced by WearWorks. Instead, (Carcedo et al. 2016)describes an interesting solution for colourblind people (*figure 13*), which involves a series of vibrators mounted in an armband that vibrates accordingly to a specific encoding to communicate colours information to the user; the encoding strategy seems complex, but performances revelated to be very good.

1.3.2 Sensory enhancement applications

The main focus of this system is not to make up for lack of feedback of the user, but to provide an additional sensory pathway to perceive sensations or to enhance the pre-existing ones.

Nevertheless, some of these applications can be used with impaired subjects also, like the BCI or the extra limbs.

- BCI and extra limbs applications → BCIs and extra limbs can be implemented in applications for both impaired and healthy subjects, but in both cases, one of the major issues remains to avoid the need of constant visual feedback by the user, which implies less usability and the necessity of more attention during the usage. The use of a haptic system can provide the missing information: proprioceptive, force and touch ones. In (Wang et al. 2019) and (Cincotti et al. 2007) are presented two possible encodings for the hand position using, respectively, an electrotactile and vibrotactile system: in the first, information regarding proprioception, fingertip pressure and slippage of an object are provided to the user using a 3x3 electrodes matrix placed on the forearm; while in (Cincotti et al. 2007)is presented a feedback system composed by vibrators placed around the neck, capable of providing continuous feedback about hand position. Both of them have good performances, but in the case of (Wang et al. 2019), the chosen encoding allows to provide to the user fingertip pressure and sliding sensation in addition to the proprioceptive information. In (Hussain et al. 2018) instead, it is presented the hRing, a control and feedback system for an extra finger, designed for post-stroke patients, but that could be used by a healthy person too; the ring is able of communicating both the touch sensation and the force exercised by the extra limb using a couple of servos and a vibrator.
- Teleoperation and robotic surgery applications → both of these technologies have seen a great breakthrough in the past decades, modifying the way to work in several fields, both medical and non-medical. In the medical field, this kind of systems can improve precision and dexterity of surgeons, minimizing the patient's trauma and allowing to operate at great distances, but they also led to a progressive increase in the distance between surgeons and patients and, consequently, in a lack of tactile feedback during surgical procedures; this is hypothesized to be a great limiting factor for such applications, especially in procedures like the knot tying ones (Van Der Meijden and Schijven 2009). In literature, it is possible to find a large amount of material regarding the implementation of haptic and force feedback in teleoperation systems, for medical

(Shang et al. 2013) and non-medical (Bolopion and Régnier 2013) applications, and in robotic surgery devices (see (Van Der Meijden and Schijven 2009), (Koehn and Kuchenbecker 2015) and (Okamura 2009)); two of the most interesting articles, (Van Der Meijden and Schijven 2009) and (Koehn and Kuchenbecker 2015), investigate the real impact and utility of this technology in the medical fields. In (Van Der Meijden and Schijven 2009) are presented the results of a literature review, that shows that there is not a univocal consensus on the importance of haptic feedback, but that for robotic surgery it seems to reduce errors related to the lack of force feedback, making it a very promising research field. In (Koehn and Kuchenbecker 2015) instead, two studies are conducted, involving more than 100 surgeons and non-surgeons, to determine if they prefer to operate with a vibration and/or acoustic feedback from the instruments or not; the results showed that the majority of the participants preferred to receive vibration feedback, but not an acoustic-one.

2 DESIGN OF A SENSORY SUBSTITUTION DISPLAY FOR AN EXTRA ARM APPLICATION

2.1 Introduction

The project aimed to develop a SS display for a third arm application, capable of providing both contact and proprioceptive information during a reach and grasping task, performed in a virtual reality environment. XL systems can be built for both impaired and healthy subject applications. In both cases, the primary issue remains the need for constant visual feedback during the device control, which implies a usability loss and an increasing in the mental effort needed for complex tasks. The implementation of a SS display can provide the missing proprioceptive and feedback information to the user (Wang et al. 2019), increasing the usability of the whole system (Hussain et al. 2015) and promoting its embodiment.

2.1.1 Needs and challenges

Using a haptic display in combination with an XLs system can increment usability and reduce fatigue of the subject; nevertheless, such systems must meet some requirements to be effectively useful: the SS device must be portable and battery-powered, to allow the XL to be used in a real-life scenario; the time delay needs to be acceptable; the encoding strategy must be as intuitive as possible, to reduce training time and to guarantee good performances; and in the case of a healthy user application, the feedback system must not interfere with the natural sensory feedback pathways of the human limbs. As seen in the previous sections, there are a lot of different feedback technologies capable of providing a wide variety of information. In the XL specific case, the SS device must provide at least proprioceptive information regarding the limb and the end-effector (if present) configurations and contact information, to permit to the user to not rely always on the visual feedback and to guarantee an effecting interaction with the surrounding environment. Besides, it is possible to implement additional features, such as temperature, texture, force and slippage feedback, to enhance XL embodiment and system usability and performances in specific situations.

2.1.2 Design specifications

In this work, the XL system used is an extra arm placed on the chest; the physical arm is still in a developing stage of the design, so all the experiments will be performed in an immersive virtual reality environment. The subject will be seated wearing the Wearable Robotics ALEx bimanual exoskeleton and a virtual reality headset. This last will provide to the user the view of a three-handed humanoid from the first-person perspective, while the ALEx exoskeleton will allow him to control the two natural hands represented in the virtual environment. The third arm will be controlled with an eye-tracking system and by the user respiration: the first will allow him to lock a target by only looking at it and the latter will control movements direction, a deep inspiration will let the user move the arm toward the target, and a deep exhale will make move it toward the body. The experimental paradigm used by the researcher at the TNE laboratory at EPFL, required the comparison between two encoding strategies: a) provide information regarding the XL hand and target contact, b) communicate the supernumerary hand position relative to the target. Moreover, since the XL is designed to be used by healthy subjects, it is essential to avoid interferences between the natural and artificial sensory pathways.

2.2 Feedback technology

To choose the most suitable feedback technique for an extra arm application we compared all the known technology (*table 1*), paying attention to the most valuable characteristics for our specific implementation as portability since it is a wearable device; comfort, because the user must be able to perform several tasks without being distracted or annoyed by the device; and temporal resolution, since a too significant delay in providing the feedback can affect embodiment and ownership of the XL (*table 2*). Moreover, the SS display has been designed thinking about possible future improvements and upgrades since the current setup is not the final one and the user has control only over the third arm movement speed and direction. After considering all the possibilities, we decided to adopt an encoding strategy that relies on hybrid feedback to provide the contact and proprioceptive information: the firsts are communicated to the user using a vibrator while the seconds using pressure feedback. It has been demonstrated in (Huang et al. 2017) and (Jimenez and Fishel 2014) how vibrators and pressure actuators can be implemented together for restoring different feedback modalities in upper limb amputees without performances loss. It is also known how these feedback modalities can be used jointly with other feedback typologies, in the case of (Clemente and Cipriani 2014) temperature feedback. Nevertheless, the combined use of pressure and vibrotactile actuators allows us to avoid providing information relying on continuous vibrations only, that could be perceived as annoying by the user (Hussain et al. 2015).

Feedback techniques for SRL applications		
TECHNIQUES	PRO	CONS
Pressure feedback	• Better in providing static feedback. • 5 level of pressure recognizable. • Micro-pumps can fit in an SRL structure.	• Bulkier structure if compared to vibrotactile and Electrotactile feedback. • Small hysteresis of actuators. • Can't provide high frequency vibration feedback.
Vibrotactile feedback	• Small and portable. • Apparent movement is possible. • Phantom tactile sensation is possible. • Complex encodings are possible changing amplitude, frequency and envelope of the vibration.	• Continuous vibration can bother the user. • Continuous vibration can have a saturation effect on skin receptors.
Electrotactile feedback	• Small and portable. • Energetically efficient. • Can provide different sensation using the same electrodes. • Matrixes with a high electrode density are available.	• Stimulation can be perceived as bothering or invasive by the user. • Performances are affected by skin conditions.
Skin stretch feedback	• Simple implementation. • Can provide proprioceptive information.	• Can provide only simple information. • Bulkier structure if compared to vibrotactile and Electrotactile feedback. • Can irritate the skin.
Thermal feedback	• Peltier elements are small. • Can provide additional feedback and promote embodiment.	• Not energetically efficient. • High delay.

Table 1 – Pros and cons of different feedback techniques.

TECHNIQUES	Don't depend on system placement						Depend on the placement	FINAL SCORE
	System portability	Actuators size	System average cost	Comfort	Temporal resolution	Feedback richness	Achievable spatial resolution	
Pressure feedback	3/5	3/5	3/5	4/5	3/5	4/5	4/5	24/35
Vibrotactile feedback	4/5	4/5	4/5	3/5	4/5	5/5	4/5	28/35
Electrotactile feedback	5/5	5/5	3/5	1/5	5/5	5/5	5/5	29/35
Skin stretch feedback	3/5	2/5	5/5	2/5	4/5	2/5	1/5	19/35
Thermal feedback	4/5	4/5	4/5	5/5	1/5	1/5	1/5	20/35

Weights for SRL applications	System portability	Actuators size	System average cost	Comfort	Temporal resolution	Feedback richness	Spatial resolution
	4X	2X	1X	5X	3X	3X	2X

Table 2 – Characteristics comparison of different feedback techniques.

2.3 Encoding strategy

2.3.1 General encoding

As presented in Feedback technology, it has been decided to adopt an encoding strategy that relies on hybrid feedback to provide the contact and proprioceptive information: the firsts are communicated to the user using a vibrator, which is capable of notifying events very effectively, while the seconds using pressure feedback, which can provide a less "invasive" continuous feedback. It has been demonstrated in (Huang et al. 2017) and (Jimenez and Fishel 2014) how vibrators and pressure actuators can be implemented together for restoring different feedback modalities in upper limb amputees without performances loss. Nevertheless, the combined use of pressure and vibrotactile actuators allows us to avoid providing information relying on

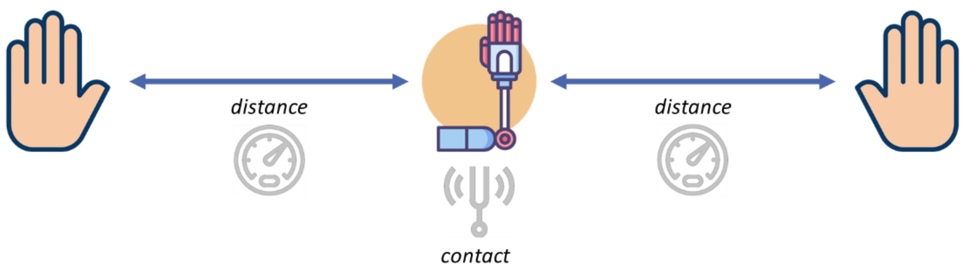


Figure 14 - Encoding strategy concept.

continuous vibrations only, that could be perceived as annoying by the user (Hussain et al. 2015). The original encoding strategy presented in this section was intended as an example of how it is possible to provide very complex proprioceptive and contact information relying on this kind of actuators. In *figure 14* is shown the core idea of the strategy, that aims to allow the user to determine the positioning of the third hand in the space, providing information about the relative distances with the natural hands, and contact events. These last are encoded thanks to a vibrator that could, for example, provide short vibration bursts when an object is touched. In contrast, distances information are encoded with pressure actuators, that could provide a continuous pressure stimulus with intensity proportional to the relative distances, for example. The basic setup showed in *figure 14* is not able to encode very complex movements, as 3-Dimensional ones. To do so is necessary to use a larger number of pressure actuators and to split the feedback system in two: one for encoding the anteroposterior movements and one for encoding movements happening on the frontal plane. In *figure 15* is shown a possible approach to encode the anteroposterior distance between a natural hand and the XL one. It is possible to do so using two pressure actuators, placed on the pectoral and the posterior shoulder, that are respectively activated when the XL hand is ahead of the natural one (positive distance) or when the artificial hand is behind the natural one (negative distance). Using this approach for both the natural arms is possible to determine the third-hand position along the anteroposterior axis, knowing the position of the two natural hands. To encode information about movements that happen on the frontal plane is instead possible to use a set of tactors placed on the abdomen as shown in *figure 16,* in which every actuator provide distance information only when a natural

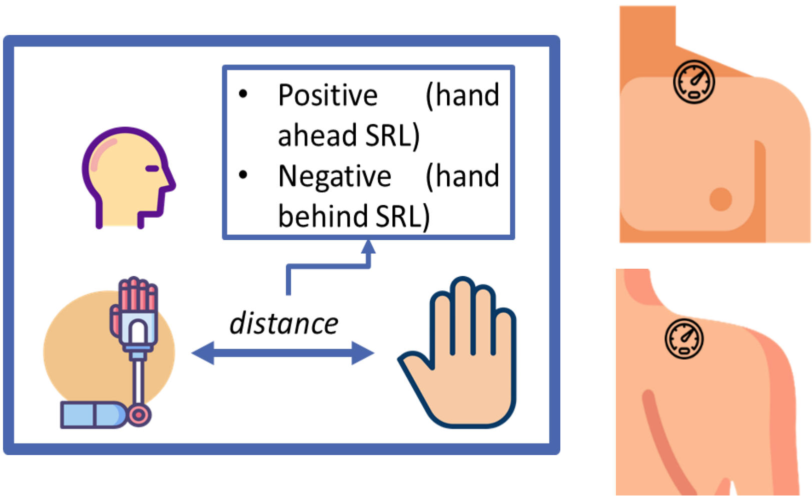


Figure 15 - Part of the strategy that encodes the anteroposterior movements.

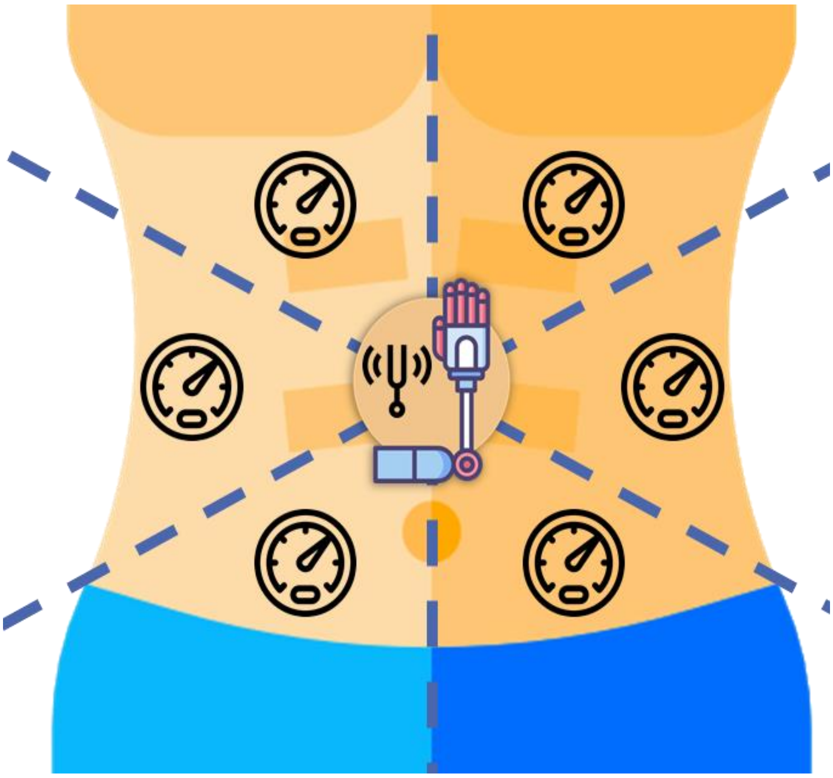


Figure 16 - Part of the strategy that encodes the frontal plane movements.

hand is in its region of competence. It is important to precise that the number of motors placed on the abdomen and consequently the number of competence regions can vary: the larger the number of the areas, the higher the precision in determining the position of the natural arm and the encumbrance of the system. In both the abdomen and shoulders approaches the core idea of the strategy remains unchanged, using a continuous pressure stimulus to encode distance information and vibrations to communicate contact events, but as it was shown that modifying the placement and the number of the motors is possible to encode different and complex behaviours in a detailed way, as determining the third arm position in a 3D environment.

2.3.2 One-dimensional encoding

During the experiments the user will be asked to perform different bimanual or unimanual tasks, in all of these the extra arm end effector start from an area called rest-zone and, when requested, the user has to reach a target zone and stop inside it. Since the task involves mono-dimensional movements (that happen along the connecting line between these two zones) and it was necessary to test the core idea of the strategy, it has been decided to do not use the encoding presented in General encoding, but to proceed to implement a version that relies on one pressure actuator and vibrator only, and that would satisfy the design specific presented in Design specifications. As previously said, the SS display must provide Contact feedback and Proximity feedback to the user, encoding respectively the contact event between the third hand and the target and the relative distance between them (instead of the relative distance between the XL and the two natural hands). The core idea of the strategy is to provide information about the relative distance using a pressure actuator, that is capable of delivering a continuous stimulus changing its intensity accordingly to the target and artificial hand proximity. The closer they are, the higher is the exercised pressure by the actuator, for example. Instead, the vibrotactile motor has the purpose of delivering information about the contact, providing a vibration burst on contact and separation events of the extra hand with an external object. Regardless, since in the virtual reality experiment the target is not physical, but it is an area that can be crossed, the vibrator will be used to provide information about the entry and the exit in this area rather than actual contact information. The concept idea of the encoding is shown in *figure 17*, where the case of a physical target is considered. Since the movements are allowed only along the connecting line between the target and the start position of the supernumerary hand, is necessary only to encode information related to one distance and contact, respectively with a pressure actuator and a vibrator.

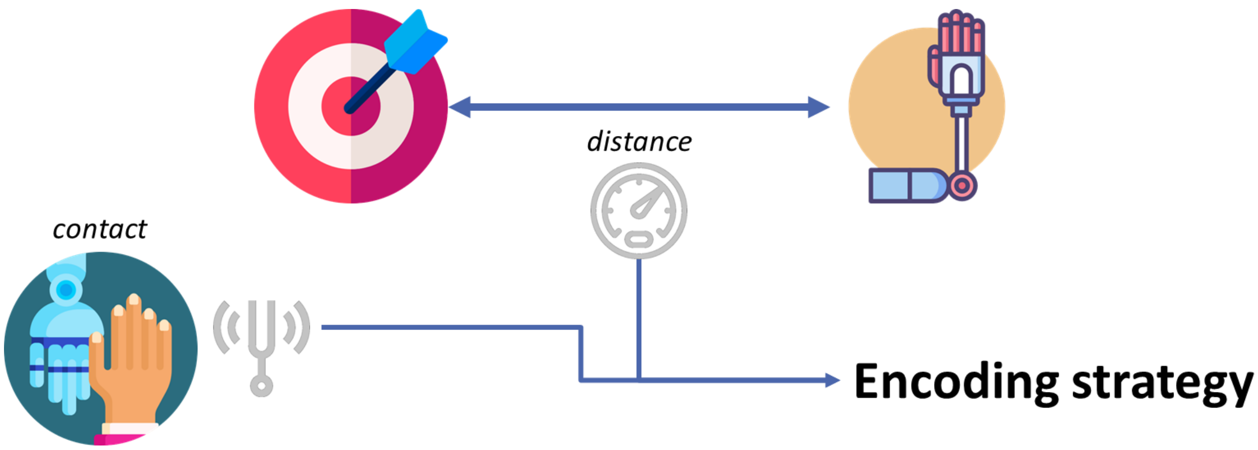


Figure 17 - Encoding strategy concept, in case of a physical target.

2.4 Hardware

2.4.1 Actuators

For the proposed SS display, two kinds of actuators are needed: vibrotactile motors and pressure actuators. Of the first kind, only one actuator is needed. Since it has to provide short vibration bursts only, to communicate contact and separation events, the choice of the motor typology is not critical. Regardless, to promote portability, we opted for one with a compact and flat design. The choice of pressure actuator is more complex instead: these have to be compact, reactive and powerful enough to provide useful feedback; compactness is essential because of the wearable nature of the device, reactivity is necessary to promote the embodiment of the third arm, accordingly to (Ismail and Shimada 2016) is necessary to have a feedback delay smaller than 200 ms to promote it, and actuators must be powerful enough to exercise 10 N of force at least on the skin to provide useful feedback (see (Schoepp et al. 2018), (Antfolk et al. 2010) and (Abd et al. 2018)). Three types of pressure actuators have been considered: balloon actuators, linear voice coil motors and servomotors (*Table 3*). The firsts are currently widely used in research for their ability to produce great forces (up to 20 N in (Abd et al. 2018)) and to adapt their shape to the skin surface. However, the fact that they are pneumatic systems represents the main drawback since the system would necessitate of a pump and valves to work,

Pressure feedback actuators comparison		
ACTUATORS	PRO	CONS
Balloon actuators	• Great output force (up to 20 N). • They adapt to skin surface. • Customizable.	• Bulky. • Less responsive. • Non-commercial technology.
Linear voice coil motors	• Very responsive • Drivable with PWM technique	• Bulky. • Expensive. • Small average skin displacement (~6 mm).
Servomotors	• Cheap. • Compact. • Good skin displacement. • Good responsiveness (~100 ms). • Drivable with PWM technique.	• Noisy.

Table 3 - Pressure actuators comparison for sensory substitution applications.

making it bulkier and less responsive if compared to other options. Moreover, these kind of actuators are currently a non-commercial technology; this implies that they have to be custom-built, increasing the cost and the complexity of the project. Linear voice coil motors are more responsive and easy to control (they can be driven with the pulse wave modulation (PWM) technique) if compared to balloon actuators instead. However, the displacement-size ratio represents the main limitation of these: as shown in (Antfolk et al. 2010), to elicit forces up to 9 N on the forearm is necessary to produce a skin displacement of the order of 2 cm, while commons linear voice coil actuators capable of exercising the desired amount of force have an average stroke of 6 mm and a housing height of 5 cm, resulting very cumbersome and ineffective. Servomotors turned out to be the right choice: they are capable of providing a skin displacement up to 2 cm and of exercising a sufficient force (up to 15 N in (Schoepp et al. 2018)) without giving up compactness and ease to use (they are drivable with the PWM technique). Moreover, the average response time of a feedback system based on servos is below 200 ms, as shown in (Schoepp et al. 2018). The main disadvantage of employing this kind of motors is the acoustic noise they can emit, that make necessary the use of noise cancelling phones in certain typologies of experiments. To selct the right servomotor for our XL application we evaluated three characteristics: motor torque, that has to be at least 30 N/cm to exercise a 15 N force on the skin usin a 2 cm lever; resolution time, that has to be less than 0.2 s/60° to allow a 2 cm skin displacement in less than 200 ms; and size, as the system must be less cumbersome possible. After different evaluations the DES 448 BBMG produced by Graupner (*figure 18*) has

Figure 18 - Graupner DES 448 BBMG servomotor.

been chosen, a digital servo with a 69 N/cm torque, 0.1 s/60° resolution time and a vertical profile of 9.5 mm only (the motor lays flat on the subject skin).

2.4.2 Sensors

2.4.2.1 Sensor typology choice

To measure the output force of the pressure actuators is essential for the success of the preliminary psychometric experiments and the possibility of creating a closed-loop control for the final version of the SS display. To accomplish such measures a sensor capable of being mounted on the tactors heads (around 1 cm diameter), without changing how the pressure is perceived, is needed. Therefore, the sensor must be thin, small and have a sensing range between 10 N and 20 N; thin-film force sensors (*figure 19 (left)*) or miniaturized load cells (*figure 19 (right)*) can be valid options. The thickness of the firsts is below the 0.5 mm, they can have a sensitivity range above 20 N and they are flexible. However, they present the drawback of poor repeatability and precision of the measurements for on-body applications, mainly due to hysteresis problems (it can be the 10% of the full range) and dependence of the output on the skin-sensor interface. Instead, miniaturized load cells present high measurement performances and large measurement range sacrificing vertical compactness. The general height of them is around 5 mm against the 0.5 mm of the thin-film ones but could be easily used in our application adapting the tactor head and the placement technique. Regardless, it has been decided to do not use this kind of solution for the cost (400 € per unit), that is too high for a proof of concept project. To work around the problem, it has been decided to measure the current absorbed by

Figure 19 - Example of a thin-film force sensor (left) and miniaturized load cells (right).

the servo motor to obtain an indicator of the force exercised. Although this is a common approach for driving DC motors, the “spike” behaviour of the control of servos makes necessary some precaution and adaptations, both in the tests and circuit design. The basic concept of this approach is to use a shunt placed in series to the actuator to generate a voltage proportional to the current absorbed and amplify it before the measurement. To do so, a 250 mΩ resistor, an AD8210 bidirectional current shunt monitor by AnalogDevices with an amplification factor of 20 and an Arduino Mega 2560 have been used. The resistor value has been chosen considering the maximum current absorption of the motor at 6 V (1 A), the maximum voltage drop allowed and the full-scale of the board used for the measurements (5 V); 250 mΩ turned out to be the optimal value since permits to make measurements using the whole 5 V range of the board causing a maximum voltage drop of 250 mV, acceptable if we power the servo at 5.5 V. By the way, to make an accurate measurement is also essential to know the motor behaviour when subjected to an external force: digital servos are controlled by impulses of the duration of 0.5 ms – 2 ms provided every 20 ms to the control pin, the length of the impulse determines the angular position while the frequency of it determines the force the motor is applying to get to the desired position or to resist an external force; this spike control reflects on the current consumption of the motor visible at the power pin, where we could observe a spike at 50 Hz in

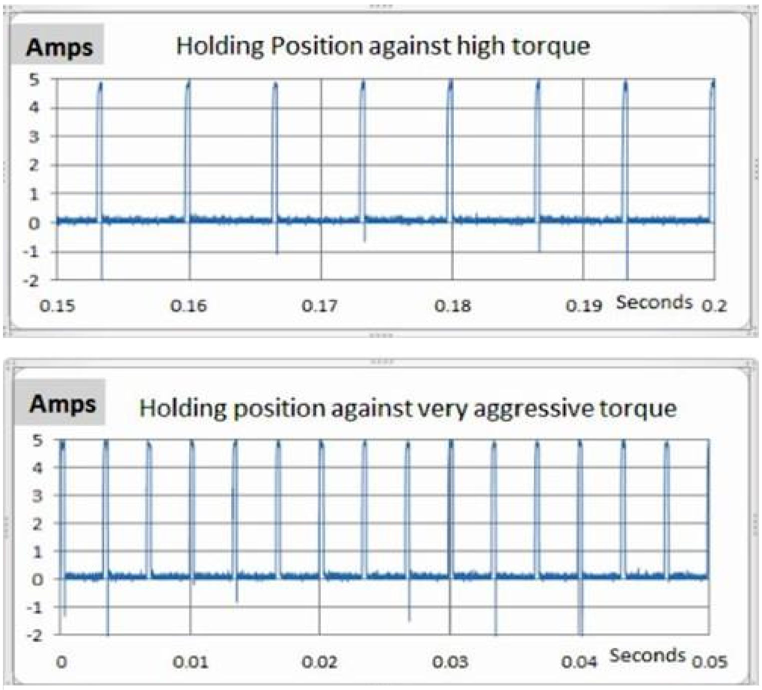


Figure 20 - Servo motor current consumption when holding position against an high torque (up) or a very high torque (low) (Buxton 2014).

a stationary case or at an higher frequency in case of an applied external torque as shown in *figure 20* and explained in (Buxton 2014). It is important to note that the behaviour showed in *figure 20* is realistic only when the motor is holding the desired position against an external force and not when it is moving against a torque, or it is stalled. Consequently, in our setup, we will be able to measure forces correctly only when the skin reaction force is not causing the motor to stall and with a steady motor. Therefore, is possible to acquire samples over a 20 ms period (at least) and to calculate the average current consumption and the applied force consequently, after having done a calibration process to compute the current-force relation of the servo motor.

2.4.2.2 Determination of the motor current-force relation

The current-force relation is necessary to have a non-invasive and reliable method to measure the force exercised on the body by the servomotors and to be capable of providing the same feedback level among different users and positions. To do so, it is necessary to build a fast and precise current measuring tool and to calibrate it correctly. The “tool” is composed by an Arduino Mega 2560 communicating with the MATLAB environment through a serial port

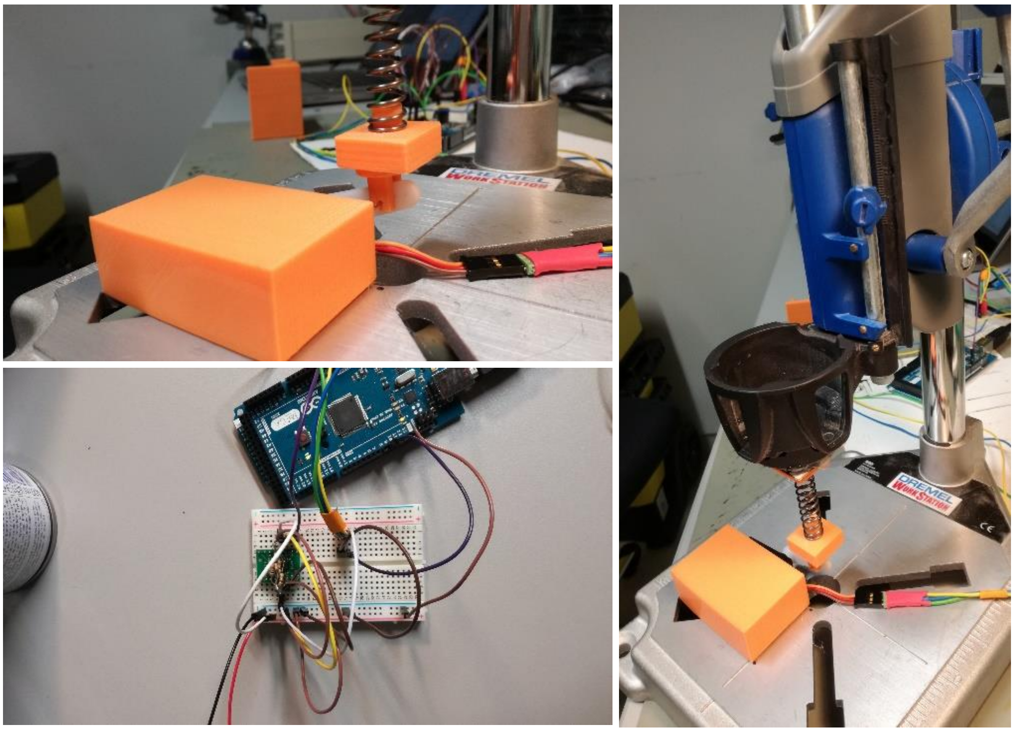


Figure 21 - Current-force calibration setup.

connection, by an AD8210 current amplifier and a 250 mΩ shunt resistor; while the calibration setup is composed by a spring of known elastic constant (3.16 N/mm), by drill support and by a graduated ruler (see *figure 21*). Thanks to the setup, is possible to compress the spring of a known quantity and consequently exercise a known force on the tactor head. Instead, to obtain the current data is necessary to amplify the shunt voltage, acquire samples with the board for a sufficient amount of time (at least 20 ms due to the characteristics of the motor) and to average them to obtain the average current consumption over the acquisition period. During the calibration procedure the tactor head was solicited compressing the spring of a known quantity, starting from a 1 mm compression and arriving at a 9 mm one, with 1 mm steps; after having applied the force and having measured the average current the spring was unloaded. To obtain more reliable data, each force has been applied five times, and the current output has been averaged. The outcome of the calibration and relative curve fitting is shown in *figure 22*. It is possible to notice than the maximum absorbed current is mostly lower than the 800 mA stall current (typical value with a 5.5 V power supply) of the servo datasheet. This happens because the motor is resisting to an external force and it is not stalled; consequently, the current

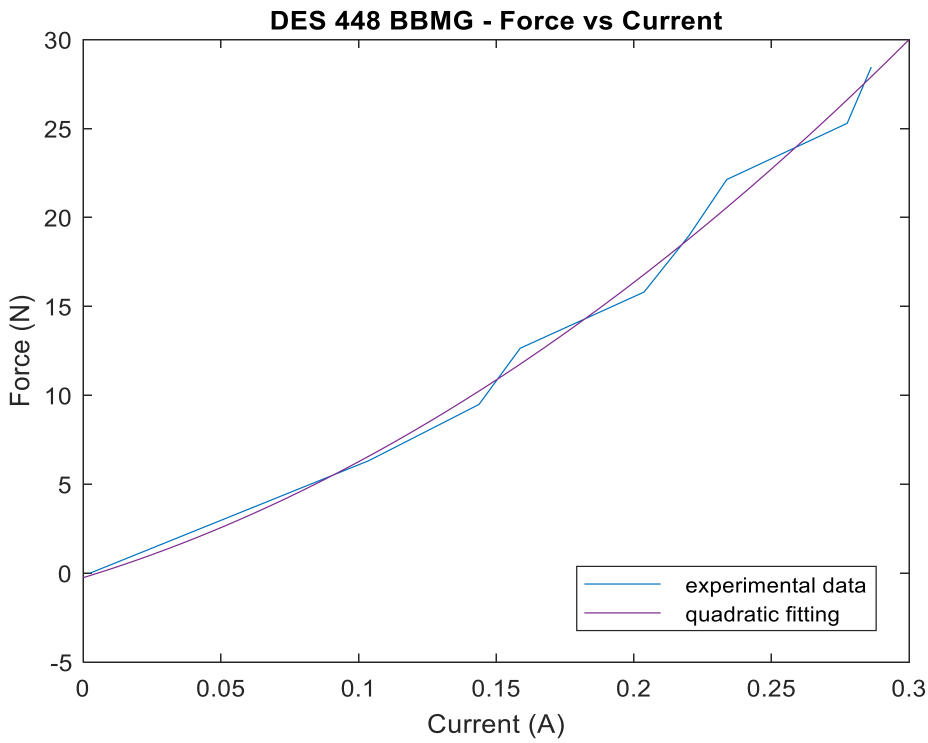


Figure 22 - Current-force relation of the DES 448 BBMG servo motor.

consumption behaviour is different (see Sensor typology choice). This is an acceptable approximation since we only measure the current after the motor has moved.

2.4.3 Placement garments and technique

The placement of the haptic actuators is a crucial component in every sensory feedback application, providing useful feedback in the right body area, comfortably and stably is as much as important as having a suitable encoding. For the majority of feedback technologies (vibrotactile or temperature ones, for example) is pretty easy to obtain a stable contact within the actuators and the skin surface since they have not external moving parts. However, in case of pressure feedback actuators, it could be more difficult because they are exercising a force thanks to membranes as in (Abd et al. 2018), shafts as in (Schoepp et al. 2018) or levers as in (Antfolk et al. 2010). In general, we want our placement garments to be adjustable, to fit different body sizes and shapes; thin and elastic, to slightly compress the body area avoiding actuator displacement and excessive preloads; and comfortable. Also, it is essential to consider that this XL is designed for healthy subjects and that to avoid performance losses and user's annoyance it is better to place the SS display in a location that avoids interferences between the artificial sensory pathways and the natural arms ones. Considering all this aspect and that the virtual third arm is placed on the abdomen, the most suitable positioning for the feedback system results to be the subject's trunk. In particular, we decided to test which one is the best

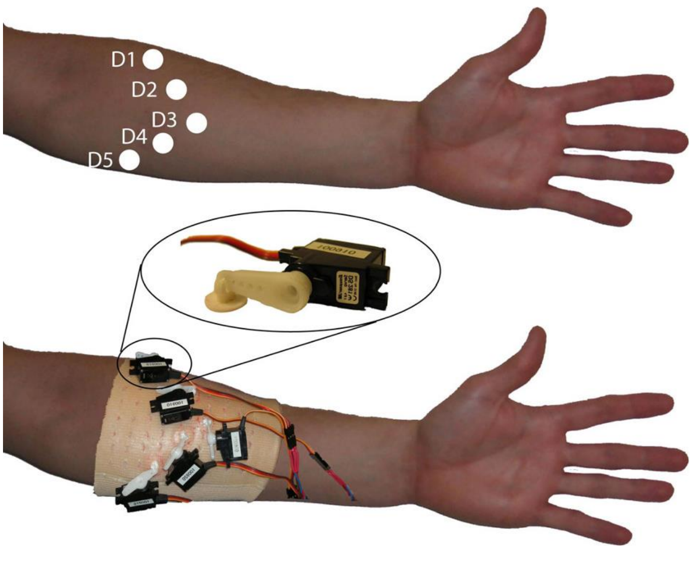


Figure 23 - Figure showing the placement technique in (Antfolk et al. 2010).

between three possible placements: the abdomen, the pectorals and the posterior part of the shoulders (see PSYCHOMETRIC ASSESSMENTS). Since we are implementing the lever system, using servos to provide the haptic sensations, we took inspiration from the placement technique showed in (Antfolk et al. 2010), in which the motors bodies are fixed on top of an elastic band on the subject's forearm, while the tactors heads are placed below it and connected to the lever through a cut in the tissue (see *figure 23*). To adapt it to our system location, it has been decided to use elastic belts or a post-operation belt for the abdominal location and a modified posture corrector for the shoulder location. The first is both adjustable and elastic to guarantee adhesion and comfort, while the second is a universal adjustable size (see *figure 24*). In the final version, it has been made a change to the posture corrector adding a velcro stripe between the two shoulder straps as shown in *figure 25 (left)*, to provide the feedback closer to the upper pectorals rather than the frontal shoulders and to allow the user to move the arms more freely, in the optic of using the SS display in experiments involving the ALEx exoskeleton. Moreover, to allow more stable feedback and to avoid undesired torsions the servo motors have been fixed below the garments, instead of above as shown in (Antfolk et al. 2010), using cable straps and, for the

Figure 24 - Example of postoperative elastic belt (left) and shoulder posture corrector (right).

Figure 25 - Motor position on the pectorals (left), shoulders (center) and abdomen (right).

abdomen and the chest, 3D printed structures (see *picture 26*). In the final version of the device, the actuators could be sewed or glued to the tissue for further improved stability, and the velcro strap on the chest could be made of a slightly elastic material to improve comfort.

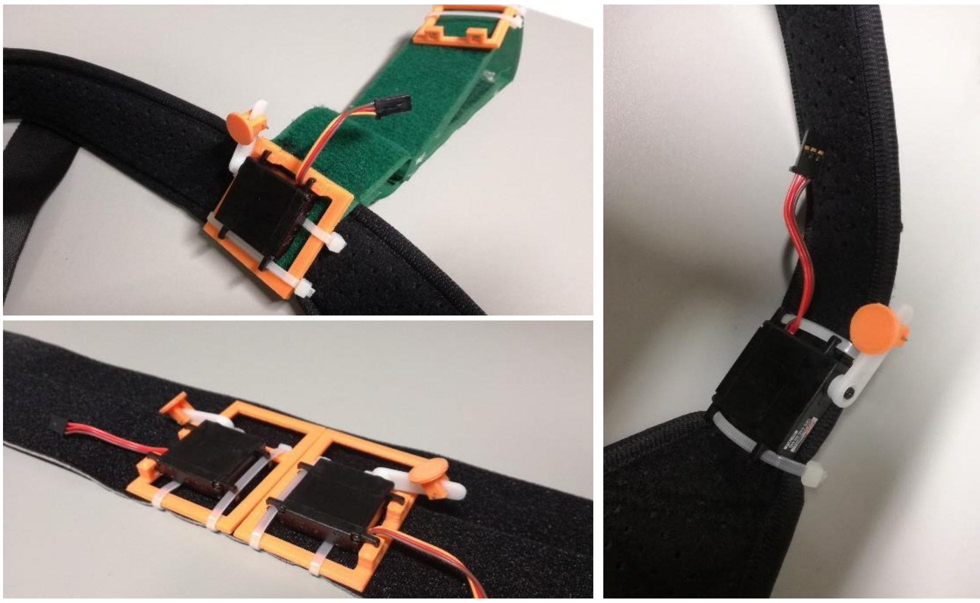


Figure 26 - Attachments of the motors to the garments in the pectoral (upper left), abdomenn (lower left) and shoulder (right) positions.

2.4.4 Hardware for device control

The whole SS system, composed by the actual display and by the driving hardware, must be both portable, to be carried by the user in future applications, and fast, to promote embodiment and usability. As explained in (Schoepp et al. 2018) and (Ismail and Shimada 2016), the sensory feedback delay has to be lower than 200 ms to elicit a sense of ownership and agency, considering the motors, the communication and the control hardware speed. Since the chosen servomotors present a resolution time of 0.1 s/60°, the control hardware must be able to process all the information received by the ALEx exoskeleton and to start the movement of the motors in less than 100 ms. To do so we opted for using an Arduino Mega 2560 connected to a portable computer through a serial port connection, this board model revelated to be the optimal choice if compared to the entry-level Arduino UNO because of the higher number of digital pins, necessary for driving up to 10 servo motors (in the most complex encoding) and 1 vibrator, and for its higher baud rate (115200 baud against the 9600 baud of the UNO board), that allows the system to have smaller delays when communicating with the MATLAB environment through the serial port. To test the impact of the baud rate on the system speed we made a simple experiment: it has been hypotized to send to the board a string composed by 8 integers of three digits, representing distances and contact information in the virtual environment, and by start, end and separation markers, used to correctly encode the data, for a total of 33 characters; then the time necessary to read and manage the data has been measured. For the UNO board 34 ms were necessary to ultimate the task, while for the Mega 2560 one 4 ms were sufficient. This performance difference allows the system to be more responsive and leaves more room for possible delays caused by the exoskeleton or the MATLAB environment.

3 PSYCHOMETRIC ASSESSMENTS

In the field of sensory substitution technologies, psychometric tests are aimed to investigate the sensorial perception, through the evaluation of the subject response to a various range of stimuli such as vibration (Hussain et al. 2015), force, pressure (Weber 1834), temperature and skin stretch ones for example, but also proprioception and body representation, as shown in (Klein et al. 2018) and (Crowe 1987) for proprioceptive accuracy in arm movements and by (Bassolino et al. 2014) for body and space representation. In our specific case, we are interested in these studies to optimize the design of the SS display for an extra arm, that must provide information as much similar to the natural ones as possible and in an efficient way, and decide the most suitable position for providing the feedback in our experimental setup. From (WEINSTEIN and S 1968) is possible to estimate that the distance between two tactors heads must not be smaller than 4 cm since the two-point discrimination distance for the abdomen is around 40 mm. In (Klein et al. 2018) has been determined that proprioception sensitivity of the arms is around 3 cm and depends on the arm position and configuration in space, from this is possible to have a rough idea of the spatial resolution that the SS system must achieve. Moreover, is possible to determine the possible optimal number of classes for a classification task since many papers show that it is possible to obtain a high classification accuracy with 5 or 6 classes, using pressure actuators such as servo motors (Antfolk et al. 2010) or balloon actuators (Abd et al. 2018). Despite pressure actuators are widely used to provide haptic information there are no examples in the literature of system providing the stimuli in the locations of our interest: posterior shoulder, pectoral and abdomen; it has been therefore necessary to carry on some psychometric tests by our own, to determine quantities such the maximum forces exercisable, the just noticeable difference (JND), the optimal number of classes for our specific system and placement.

3.1 Experimental protocol

3.1.1 Introduction

The objective of the tests was to perform psychometric evaluations of tactile perception in different body areas, in the optics of finding the most suitable positioning to provide haptic feedback for a supernumerary robotic arm application. The pressure feedback has been provided using servo motors mounted on readapted garments, an elastic belt and a shoulders posture corrector, to test three different body areas: pectoral, posterior shoulder and abdomen.

Three psychometric assessments have been carried out:

1) the determination of the relation between the servo motor angle and exercised force. The objective was to measure this relation to determine the optimal motor movement range and reference stimuli for the next assessments.
2) the just noticeable difference (JND) assessment. The objective was to estimate the minimum difference of pressure perceivable by the user, using different reference stimuli.
3) the assessment of the number of recognizable pressure levels on the abdomen. The purpose was to evaluate the performances of the user in classifying different pressure levels. The test has been repeated with 2 number of classes: 6 and 5.

Each assessment has been repeated for each possible placement. At the end of the experiment is asked to the subject to report which position was the most comfortable and in which position the feedback was clearer.

3.1.2 Materials

The experiment has been carried out with the subject sitting, wearing headphones to avoid auditory clues from the moving motors. The feedback has been provided using Graupner DES 448BB MG servo motors, kept in position on the user's body thanks to an elastic belt, for the abdomen placements, and a shoulders posture corrector, for the shoulder placements. The motors were attached to the internal part of the garments using Velcro straps and hot glue to guarantee stability. The motors were driven by an Arduino Mega 2560 and powered by an external power supply. The force exercised on the subjects' skin has been measured using a 250 mΩ shunt resistor, the AD8210 integrated circuit and the Arduino Mega 2560 to measure the current absorbed by the motor. The experimental data have been collected using a personal computer and MATLAB R2019b.

3.1.3 Experimental design

Healthy subjects have been involved in three sessions for each tested body area; all of them must have been accomplished before removing the equipment and test the next body area. Before each session, the procedure was explained to the subject and the equipment was adjusted to be comfortable and stable.

1) In the first session, psychometric assessment 1) has been performed six times for each subject to collect and average data among the subject's trials and population. A single servo has been used for this session, placed using velcro straps on one of the following body parts: pectoral, posterior shoulder and abdomen; the chosen position has been maintained for the next two sessions. The motor lever was moved step by step, from the rest position to the end position, increasing the pressure on the skin, then was moved step by step to the rest position, decreasing the pressure on the skin. After each step was

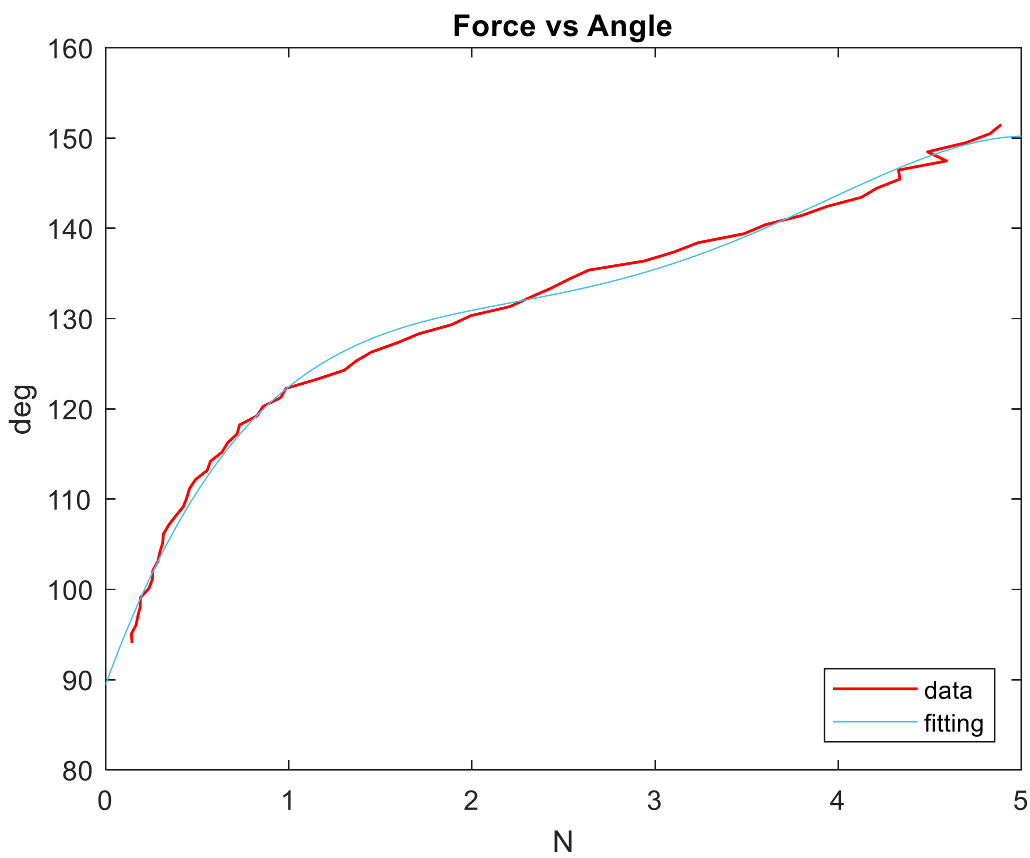


Figure 27 - Force angle relation example.

taken, the force outcome has been measured using the system described in Sensor typology choice. At the end of the 6th trial, the forces have been averaged to obtain the average force angle relation for the current subject and placement (*figure 27*). In the case of the user's discomfort or of too low force output, the positioning needed to be adjusted, and the test repeated. To extract an excellent force-angle relation was necessary sometimes to remove the lasts and the firsts samples of the tests, respectively due to the motor stall (see *figure 28*) or of the poor initial contact of the tactor head.

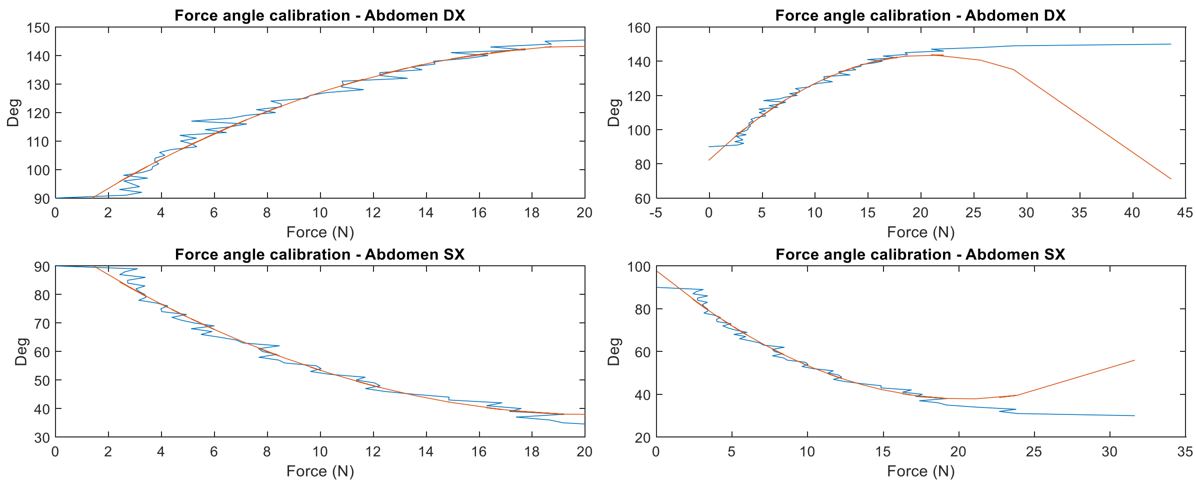


Figure 28 - Example of the effect of the motors stall on the right and the final relation on the left (approximized relation in red).

2) In the second session, assessment 2) has been performed one time for each subject and reference stimulus to collect and average data among the subject's trials and population. Two servos have been used for this session, placed on the left and right tested body part in a mirror way, one provided the reference stimulus while the other changed the exercised pressure following the classic staircase method (*figure 29*). The reference stimulus and the initial gap between the reference and active stimuli were decided by the operator, accordingly to the operational range defined for the placement with assessment 1). The best option was individuating at least four reference forces possibly equally spaced and with a starting gap of 2N at least; nevertheless, sometimes, for higher force reference values could have been necessary to increment the initial gap value to 3N or 4N. To determine the active stimulus intensity, the gap was randomly subtracted or added to the reference stimulus. During the test, the subject was questioned to determine if the active stimulus was bigger or smaller than the reference one. After three

correct responses, the gap was halved; after each error, the gap was increased to the midpoint between the last occurred error and the last correct answer before the first error. After three correct responses, the trial ended, the JND was considered equal to the last gap value.

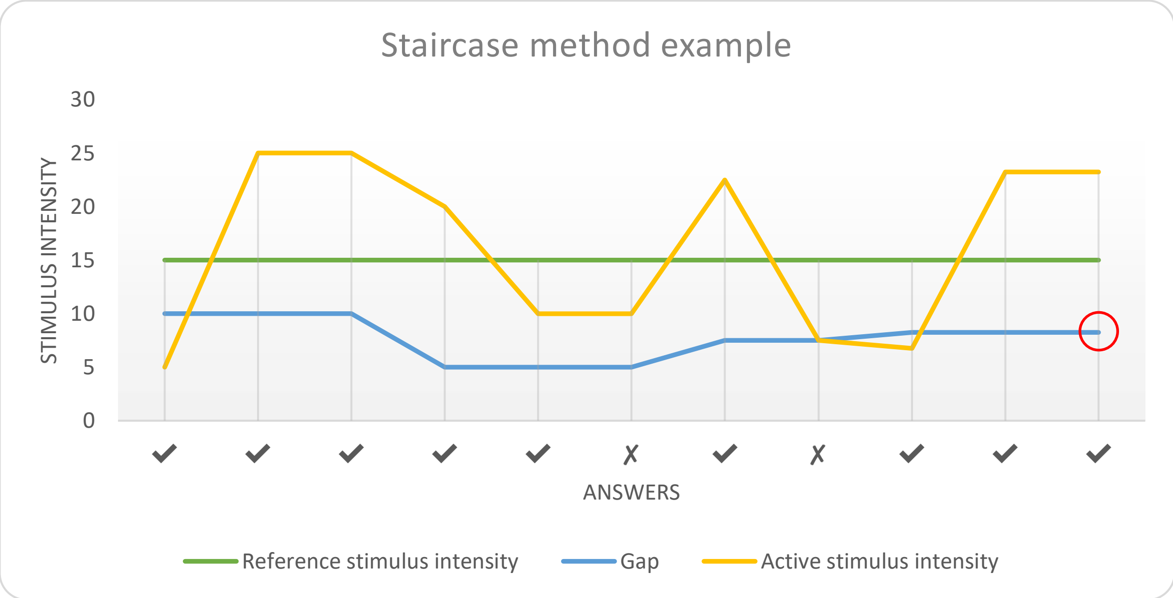


Figure 29 - Staircase procedure example.

3) In the third session, assessment 3) has been performed two times for each subject, one for each number of classes (6 and 5). To allow performance comparison between subjects, it has been decided to fix a force interval and to generate 6 and 5 classes suitable for all the users. The extremes of the interval were fixed taking as reference the ones found with assessment 1) and taking enough big margins (~2N) to guarantee the classes to be used on every subject. To determine each force level knowing the extremes of the interval, we imposed a simple relation between subsequent classes: $C_n = C_{n-1}(1 + \Delta C)$; in this way was possible to determine the maximum value of ΔC capable of generating 6 or 5 classes in the given interval. A single servo has been used for this session, placed using velcro straps on the tested body part. Before each trial, two minutes were given to the subject to become acquainted with the different pressure levels and the procedure. During the test, pressure levels were provided to the subject in a pseudo-random way, after the movement of the servo, the user had as many time as he wants to input the class number on the computer; among the whole trial, each

pressure level hs been provided six times. At the end of the trial performances and errors were shown to the subject.

3.2 Results

The experiment has been performed on 8 subjects, 3 females and 5 males, aged between 23 to 28 years old. The duration of the whole test was 1.45 hours on average, including the positioning of the servos and the garments. From assessment 1) was possible to obtain information about the maximum force exercisable given a placement position and the relative force-angle relation of the servo, both measuring the current absorbed by the motor. The average maximum forces (*figure 30*) turned out to be little variable among the population: for the abdomen was always

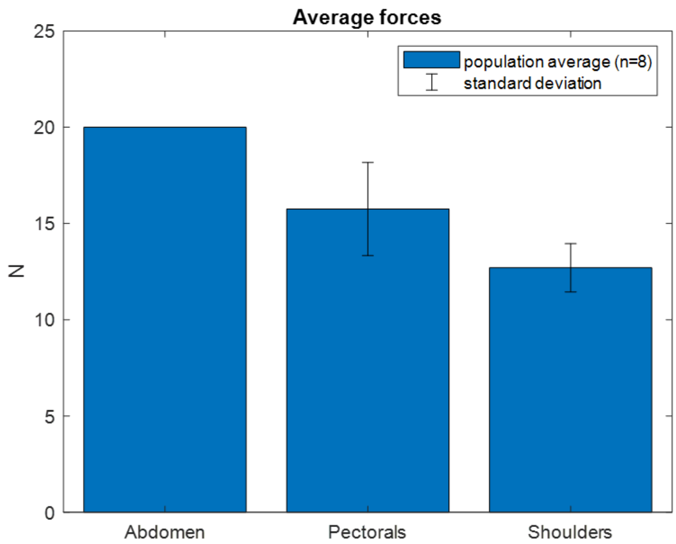


Figure 30 - Average maximum force for each placement.

possible to reach 20 N, sometimes even before the maximum rotation was accomplished by the motor, the average force for the pectoral was of 15.75 N with a standard deviation of 2.43 N, making this position the one with maximum variability, while for the shoulder the average force was 12.7 N with a standard deviation of 1.25 N. In assessment 2), after collecting data, a linear fitting has been done to find out the relation between JND and reference force for every subject; in both the pectoral and the abdomen position the relationship between the two variables was the one expected, with an increase in the JND linked to an increase of the reference force, while the JND for the shoulder positioning showed an unexpected behaviour instead, with an increase in the JND linked to a decrease of the reference force, probably due to the positioning technique

	Abdomen		Pectoral		Shoulder	
Subject n°	mean WF	R-squared	mean WF	R-squared	mean WF	R-squared
1	20.47	0.45	30.06	0.86	11.02	0.12
2	22.77	0.55	11.86	0.42	9.26	0.73
3	12.92	0.23	18.50	0.28	19.49	0.16
4	14.70	0.28	18.33	0.77	19.89	0.49
5	13.02	0.39	25.72	0.81	26.02	0.16
6	19.18	0.70	23.76	0.68	30.44	0.09
7	22.16	0.07	13.05	0.02	13.52	0.16
8	24.59	0.49	18.05	0.03	16.09	0.34
Average	18.73	0.39	19.92	0.48	18.22	0.28

Table 4 - Weber fraction for every position and every subject.

and the less compliance of the skin and muscle in this body area. In both the pectoral and shoulder positioning the relation inverted for at least one subject, with a decreasing JND for the pectoral and an increasing one for the shoulder. Computing the R-squared value for each fitting revelated a not so strong relation between these two quantities, as shown in *table 4*. For every subject the Weber fraction has also been computed (averaged among the trials), as the fraction of the JND on the reference force, and then averaged among the population; as shown in *figure 31*, the values are slightly higher than the literature ones (18.73% for the abdomen, 19.92% for the pectoral and 18.22% for the shoulder). The differences are not statistically significant concerning the positioning (Friedman test, p=0.88). The variability between subjects for the same positioning is of the order of tens of percentage points, and this is probably linked to the physical differences of the subjects and to the fact that the garment used for the pectoral and

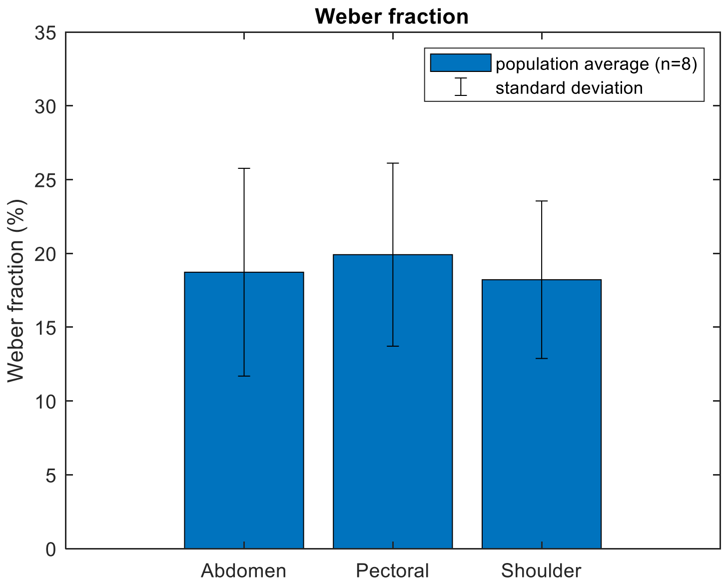


Figure 31 - Average Weber fraction for each placement among the population.

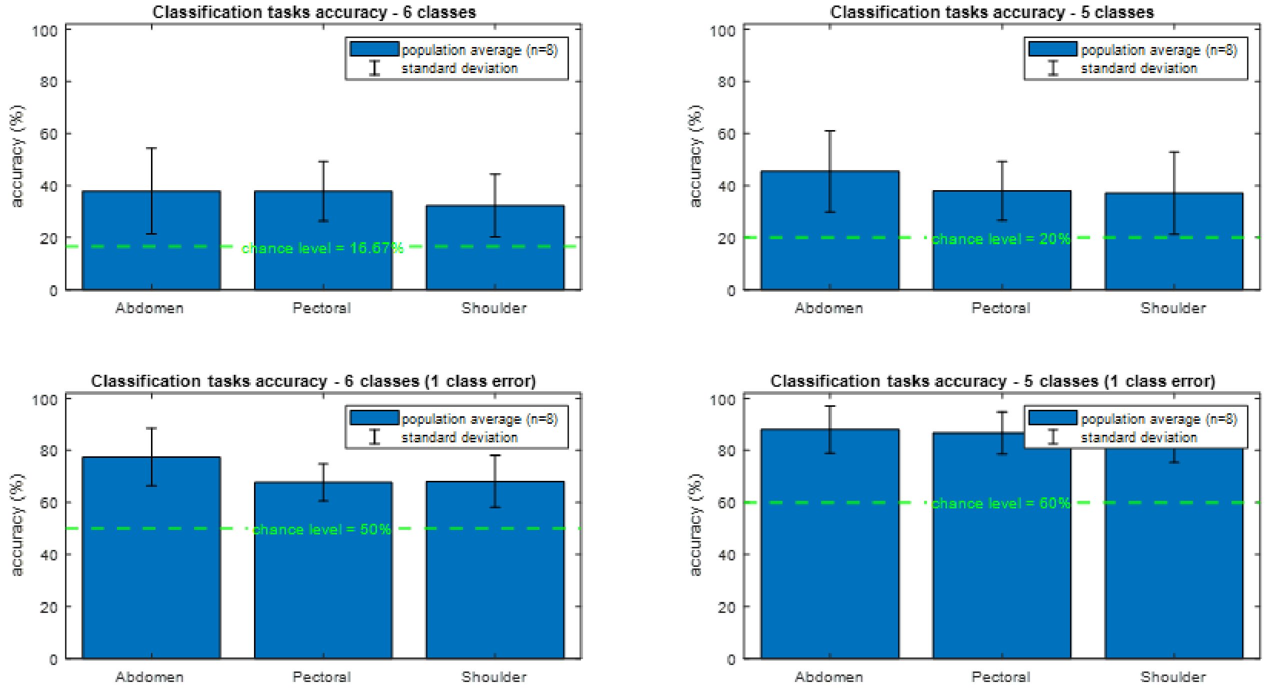


Figure 32 – Classification task accuracy.

shoulder positioning was not precisely adjustable on every body size and shape. In assessment 3) the ability of the subjects in classifying different pressure levels was tested and to allow a comparison between different subjects everyone has been tested with the same force levels, independently by the performances of the previous tasks. As shown in *figure 32*, two performances indicators are considered for each possible placement and number of classes: the classic percentage of correctly classified and the percentage of correctly classified allowing an error of one class as in (Antfolk et al. 2010). The last parameter has been introduced since some subjects were able to differentiate between the different pressure levels correctly. However, they were biased in perceiving all the stimuli stronger or weaker. To assess if the positioning has any impact on the classification task accuracy the Friedman test has been performed, the outcome confirmed that the body area tested has not a relevant impact as expected, due the small differences and the high standard deviation. Furthermore, it has been investigated if there was a preference among the population for specific stimulus intensities by dividing the classes into two subgroups: the high-pressure stimuli one, that contains classes 4,5 and 6 for the 6 classes task and 3,4 and 5 for the 5 classes task; and the low-pressure stimuli one, that contains the remaining 3 or 2 classes. As shown in *figure 33*, there is a clear preference in classifying more potent stimuli rather than weaker ones; the result has been validated using the Wilcoxon

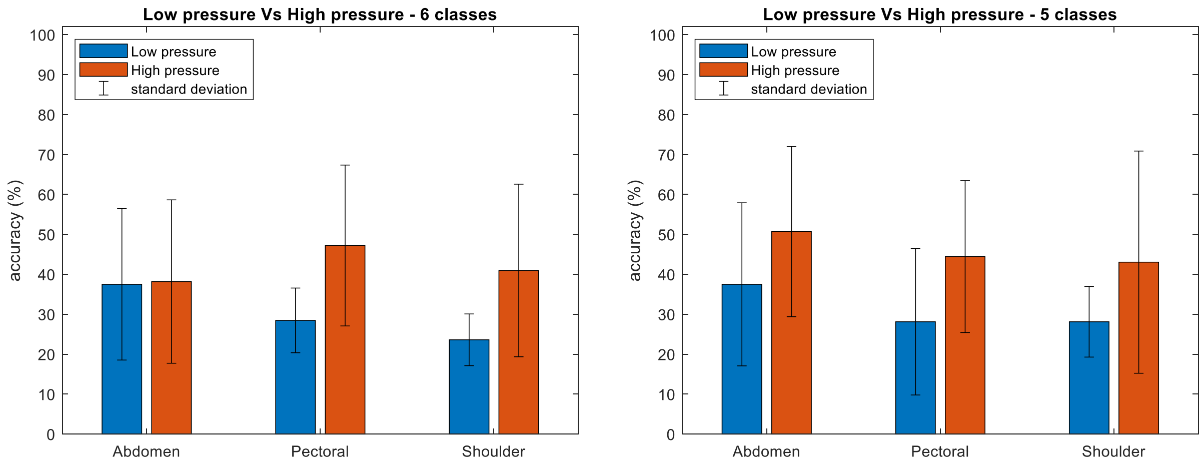


Figure 33 - Accuracy differencies in classifying low-pressure stimuli and high-pressure stimuli.

signed-rank test. The performance improvement obtained passing from the task with 6 classes to the one with 5 has also been investigated (*figure 34*) and it revelated to be dependent by the body area tested. In particular, while for the abdomen no noticeable improvements are visible reducing the number of classes, for the other two positions is possible to appreciate a clear one if a 1 class error is allowed, meaning that the average classification error was reduced among the whole population ($p < 0.05$, Wilcoxon signed-rank test). At the end of the experiment was asked to every subject to tell which one of the three positions was their favourite in terms of

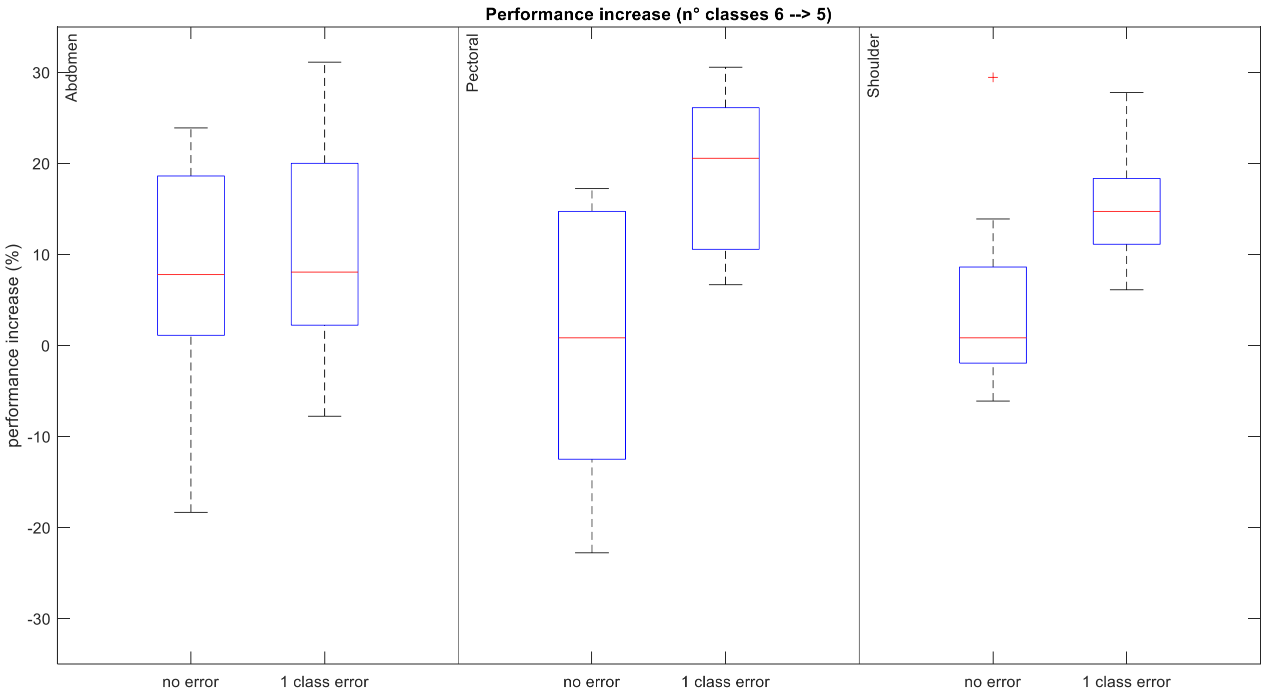


Figure 34 - Performances increase for the classification task when reducing the number of classes from 6 to 5.

comfort and clarity of the feedback. On a total of 8 subjects, 6 rated the pectoral and 2 the abdomen as the most comfortable position and 5 rated the pectoral and 3 the abdomen as the positions with the clearest feedback perception.

3.3 Discussion

The aim of these assessments was both investigating the perception of pressure stimuli on these body areas and selecting the most suitable one for placing a SS display for a third arm application. About the first objective, it is clear that the typology of setup has played a fundamental role in increasing the variability of the results since both the classification accuracy and the average Weber fraction values are different from the ones of the literature and present a high inter-subject variability. Indeed, with some body sizes and shapes revelated difficult to efficiently adapt the garments for obtaining a good adhesion between the tactor head and the skin without compromising users comfort. In particular, the most challenging position resulted to be the shoulder one since it was often necessary to replace or adjust the posture corrector used for holding the servos. Moreover, the average population accuracy in the classification task is sensibly lower than the literature one (60% of correctly classified with 6 levels of pressure) and only three subjects have been capable of reaching such performances. A plausible explanation could be found in the differences between the experimental protocols since we used a larger number of subjects and positions and a shorter training, while in (Antfolk et al. 2010) and (Fan et al. 2009) less than two subjects were involved, maintaining a fixed position for the whole duration of the experiment and performing longer training sessions. About the choice of the most suitable position for placing a SS display, we could not rely on the percentage of correctly classified pressure levels or the Weber fraction values due to the lack of statistically significant differences. Regardless, the pectoral placement has been selected mainly for two reasons: the first and most important is that it was the users favourite concerning both the comfort and the feedback clarity, the second reason is that it is the only placement with which no subject performed below the chance level in the classification task. Another aspect that confirmed our choice and that we considered was the setup used for the XL experiments, in which the arm is controlled using an eye-tracking system integrated into a VR display and by a respiration belt, worn on the abdomen at the height of the diaphragm muscle. In particular, placing the actuators on the abdomen using elastic belts could have hindered the subjects when performing the respiration tasks by limiting the abdomen expansion or making it more difficult.

4 TESTING THE SENSORY SUBSTITUTION STRATEGY IN A REAL WORLD 1D TASK

Selecting the right encoding strategy is a crucial factor to reap the maximum benefits from the implementation of haptic feedback in any extra limb application. Strategies with different characteristics have different strengths and weaknesses that can be acceptable or represent an excluding factor depending on the purpose of the feedback. In the specific case of our setup, the main objective is to find a way to communicate to the user the needed information for avoiding constantly relying on visual feedback while using the XL, without annoying him excessively. Consequently, the encoding must be discrete enough not to distract the operator when he can rely on vision but also strong enough to be perceived when he is focused on another task or when disturbing factors are present in the environment. These are the reasons behind the creation of the hybrid feedback strategy presented in One-dimensional encoding and its variations presented in Adaptation of the sensory substitution strategy to the experimental setup. Testing these last, to select the most suitable for the final implementation, is necessary since in literature there are no examples of pressure actuators used in combination with vibration motors to provide distance information without using simple linear encodings.

4.1 Adaptation of the sensory substitution strategy to the experimental setup

In our experimental setup, a virtual XL is used, and the tasks performed by the subject involve non-physical targets. In particular, during the experiments the user will be asked to perform different bimanual or unimanual exercises, in all of these the extra arm end effector will start from an area called rest-zone and, when requested, the user will have to reach a spherical zone and stop inside it. The use of non-physical targets introduces two main issues: the contact information no longer needs to be provided to the user during the task execution and the overshoot condition must be encoded since it is possible to pass through the target. Consequently, it has been decided to maintain unchanged the distance encoding characteristics, providing the pressure feedback accordingly to the extra hand position in respect to the target one, while using vibrations to encode new pieces of information: the entry and exit from the

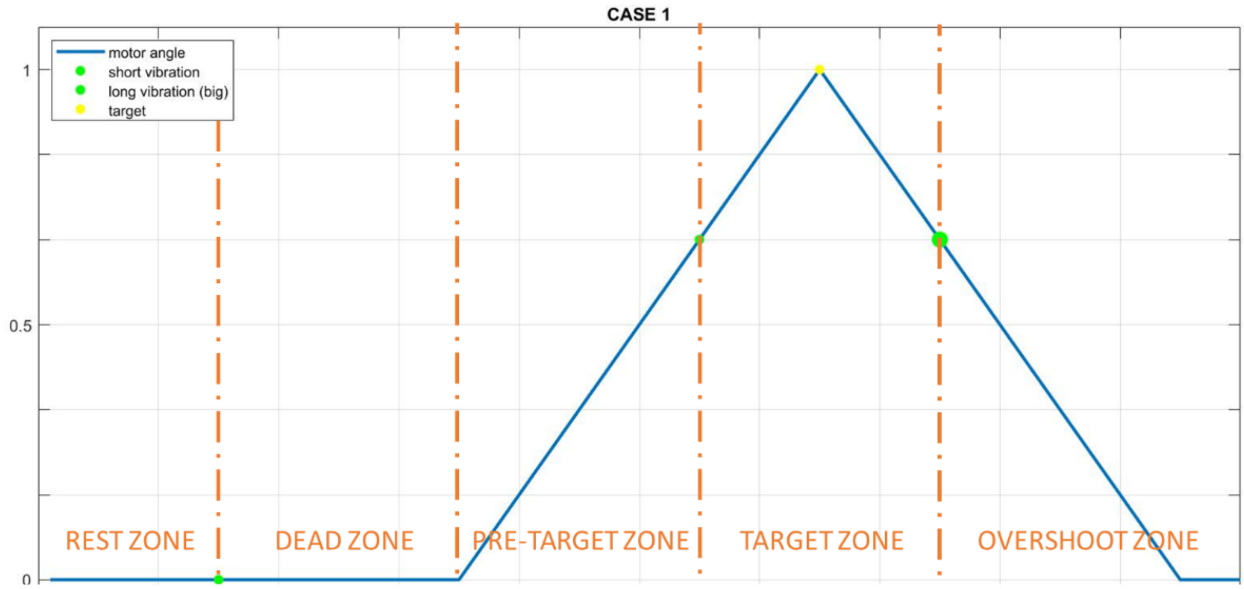
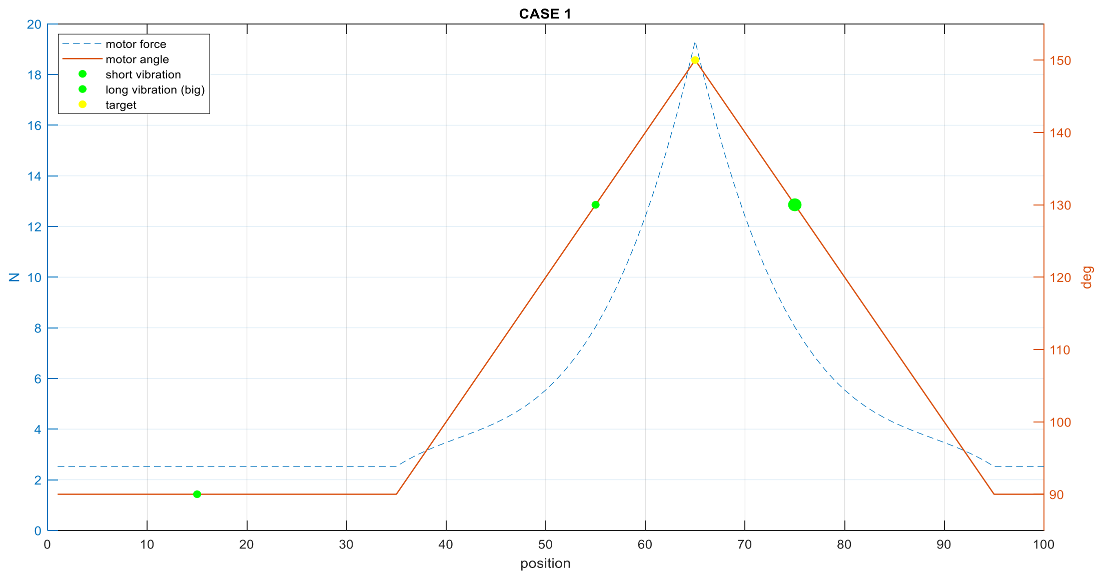
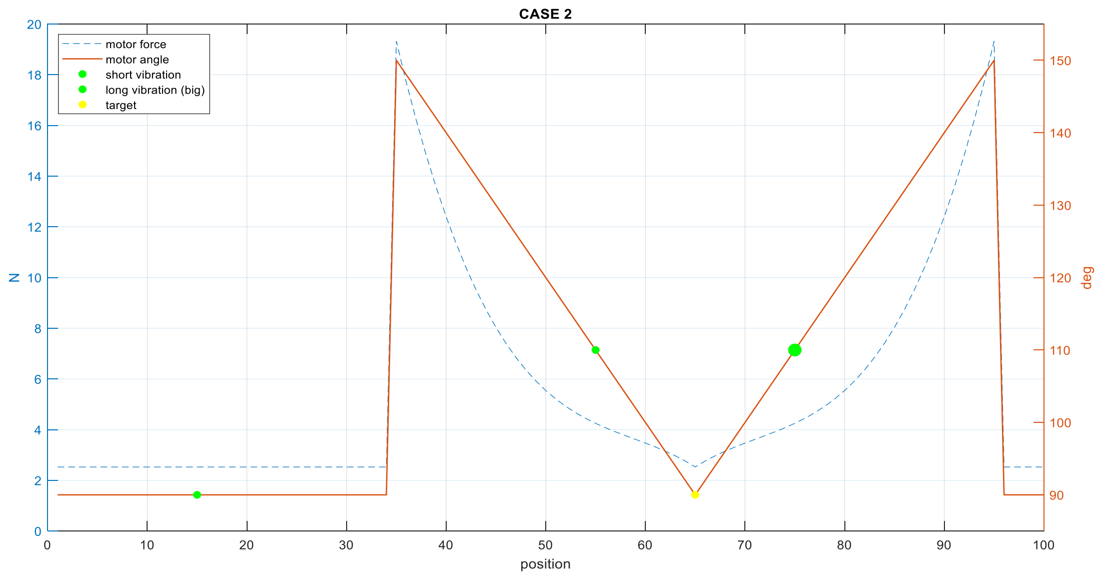
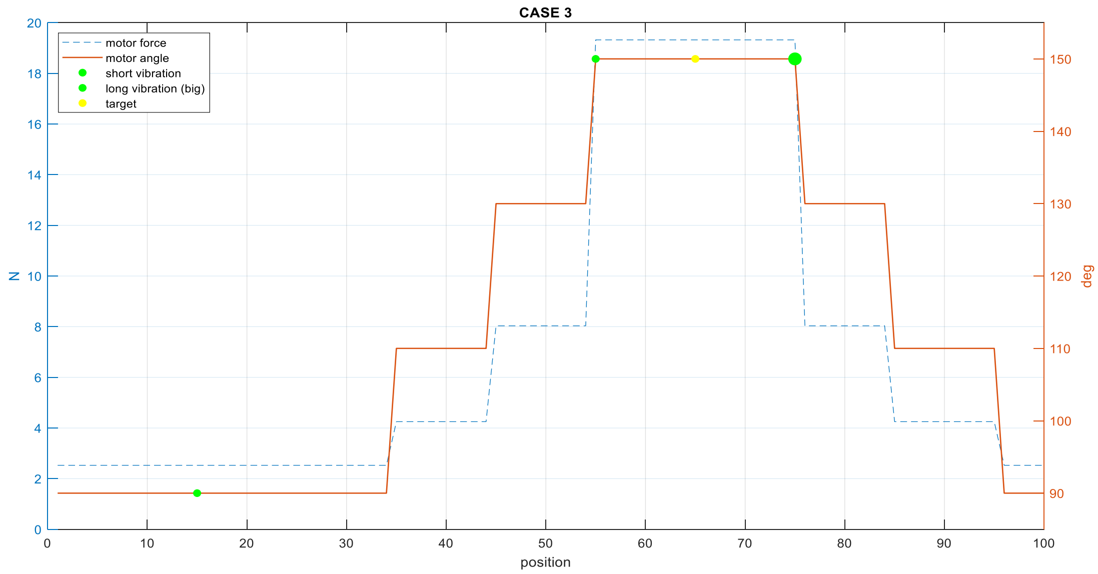


Figure 35 - Division of the distance between the XL starting point and the target-zone in 5 sub-zones.

target and rest zones and the overshoot condition. Accordingly to these needs, the distance between the XL starting point and the target has been divided into different sub-zones, shown in *figure 35*; using the vibration to communicate the entry and exit events (from the target and rest zones) and the overshoot condition (with a long vibration). Also, it has been decided to provide Proximity feedback only when the third hand and target are close enough, to avoid distracting the subject when not needed. Consequently, accordingly to the target position, a dead-zone in which no feedback is provided could be present. The proportions between the different subzones have been kept as similar as possible to the ones of the pre-existing third arm experiment. In particular, the pre-target zone is always as large as the target and rest ones, and these dimensions remain constant during the experiments; the only subzone with a variable size is the dead zone one. In *figure 36* are presented five different adaptations of the original encoding, all of them follow the same principles and aim to encode the entry and exit from the rest and target zones and the overshoot condition relying on vibrations or different profiles of pressures. The objective is to allow the user to be able to determine if he is getting closer or moving away from the target and from which side he is approaching it, relying on additional marker events (the vibrations) to determine more effectively when he is in a specific subzone. The differences of each strategy are presented in *Table 5*. It is possible to divide them into two sub-categories: the symmetrical ones (cases 1 to 3), that rely on a long vibration to communicate to the user when he is surpassing the target, and the asymmetrical ones (cases 4 and 5), that rely on their asymmetry to do so. The different strategies are compared in ***Errore. L'origine riferimento non è stata trovata.*** to select the best one to be implemented in the final setup.


CASE 1
motor force
motor angle
short vibration
long vibration (big)
target
N
deg
position


CASE 2
motor force
motor angle
short vibration
long vibration (big)
target
N
deg
position


CASE 3
motor force
motor angle
short vibration
long vibration (big)
target
N
deg
position

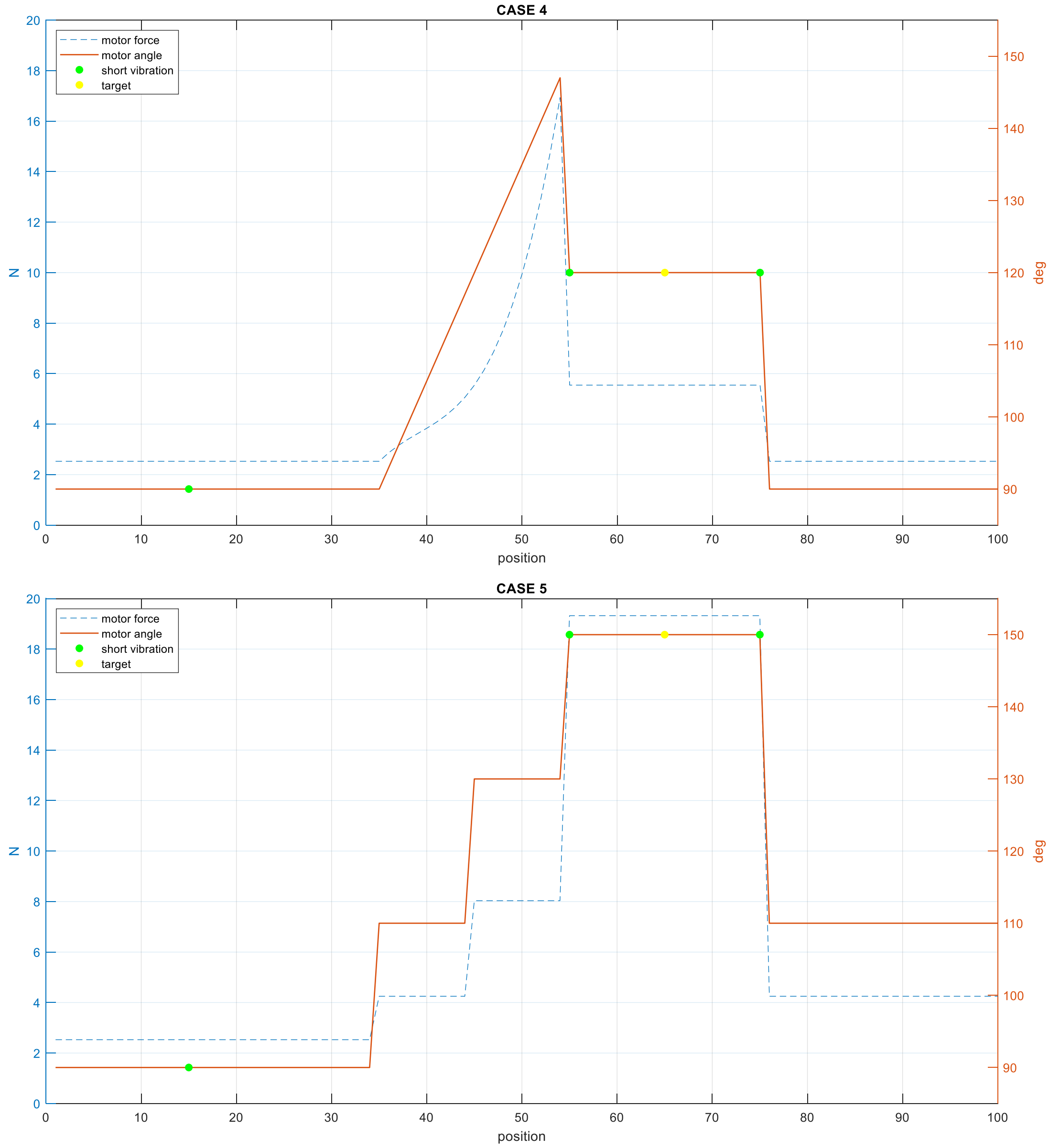


Figure 36 - The 5 encoding strategy tested. Each one test a different approach changing how the distance and position information are provided to the user, employing steps rather then smooth pressure changes or modulating the length of the vibration. For every strategy are shown the angle of the servo, the position and duration of the vibrations (0.15 s the short one and 0.3 s the long one) and an example of the resulting force on the skin.

Encoding strategy	Characteristics
Case 1	• Not annoying for the user. • Vibration is essential for the user to understand when he is entering/exiting the target zone. • Long vibration needed for the overshoot encoding.
Case 2	• The big step could be annoying for the user. • More precision close to the target due to small force levels. • Vibration is essential for the user to understand when he is entering/exiting the target zone. • Long vibration needed for the overshoot encoding.
Case 3	• It is easier to perceive the motor movements due to the steps (Zheng and Morrell 2012). • Between one step and another we do not have movement information. • Vibration is useful for the user to understand when he is entering/exiting the target zone.

	• Long vibration needed for the overshoot encoding.
Case 4	• Equal to CASE 1 until we enter in the target zone. • Vibration is NOT essential for the user to understand when he is entering/exiting the target zone. • The overshoot encoding is done thanks to a big step movement.
Case 5	• Equal to CASE 3 until we overshoot. • Vibration is useful for the user to understand when he is entering/exiting the target zone. • The overshoot encoding is done thanks to a big step movement.

Table 5 – Characteristics of the different encoding strategy adaptations.

4.2 Experimental protocol

4.2.1 Introduction

The objective of the experiment was to determine which one between 5 encoding strategies was the most suitable for providing proprioceptive feedback for a supernumerary robotic limb (XL) application. The strategies tested are shown in *figure 35*. The primary purpose of each one is to provide information about the relative position and distance between the supernumerary end effector and the target zone using a pressure actuator and a vibrator. The first, composed by a servo motor and a lever, is used to encode the distance, while the vibrator is used to provide information about the entry and the going out in the target or rest zones. Since the final goal was to implement the best strategy in a pre-existing XL setup, the proportions of the distances have been kept identical to the ones in the third arm experiment.

The test was divided into two parts:

1) the determination of the precision of the subject in following a random movement along the position axis without relying on visual feedback, but only on the servo-vibrator system, and in determining his final position.
2) the assessment of how the user perceived the strategy.

The test has been repeated for every encoding strategy. The order with which the strategies have been presented was randomized.

4.2.2 Materials

The experiment has been carried out with the subject sitting, wearing headphones playing white noise to avoid auditory clues from the moving motors. The feedback has been provided using one Graupner DES 448BB MG servo motor, kept in position on the user's left pectoral thanks to a shoulders posture corrector, and coin-shaped vibrator, kept in position on the user's right pectoral thanks to an adhesive bandage. The servomotor was attached to the internal part of the garment using Velcro straps, hot glue and a 3D printed plastic frame to guarantee stability.

The motors were driven by an Arduino Mega 2560 and powered by an external power supply. The experimental data have been collected using a personal computer and MATLAB R2019b.

4.2.3 Experimental design

Healthy subjects have been involved in two sessions for each tested encoding strategy, all the strategies must have been tested before removing the equipment. Before each session, the procedure and encoding strategy have been explained to the subject and the equipment has been adjusted to be comfortable and stable.

1) In the first part of the experiment, the subject was sitting comfortably on the chair in a way that allowed him to reach the mouse and keyboard to enter the answers quickly. Before the start, the encoding strategy has been explained to the subject in detail, and the initial angle of the motor was adjusted to guarantee a good start adhesion between the tactor head and the skin. During the experiment, the subject was completely autonomous and could use the keyboard to proceed from the training to the test section and the mouse to insert the answer or start the trial. A high pitch sound notified that the system was ready and it was waiting for the user click to start the trial, after the click, the computer simulated a linear and continuous movement that the subject had to follow

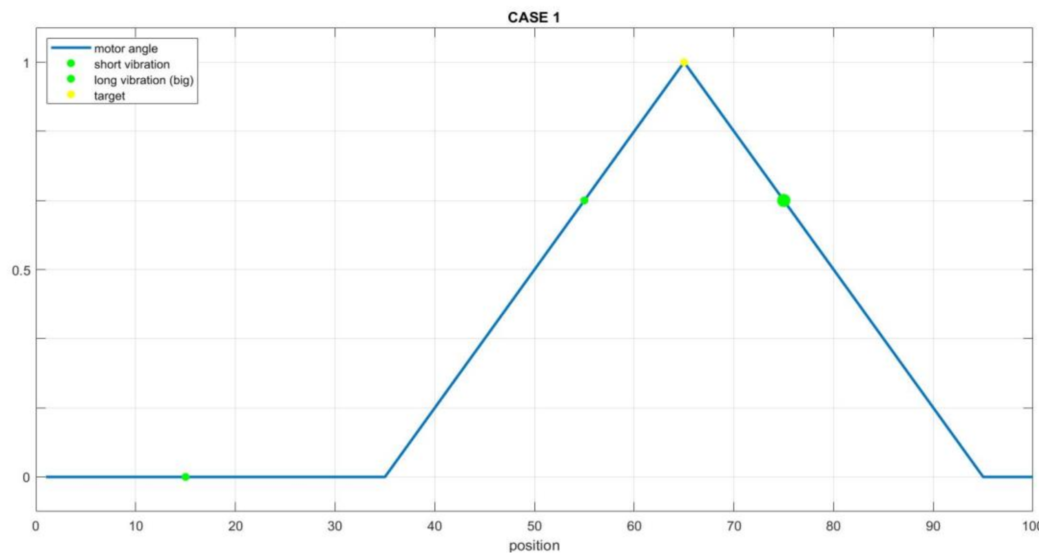
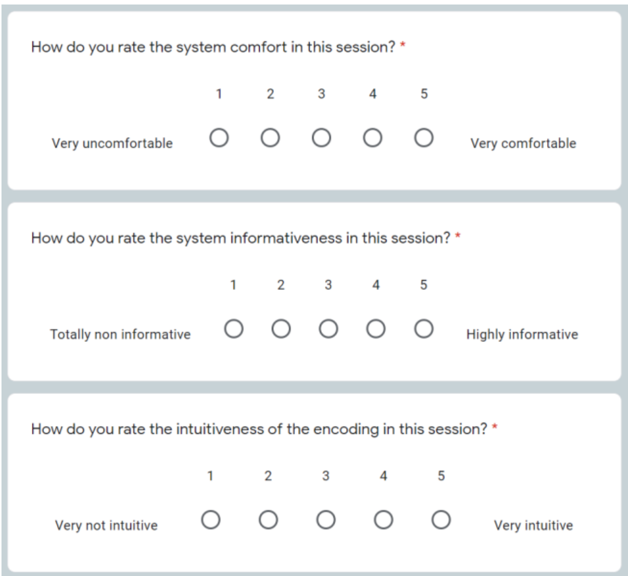


Figure 37 - Example of the image that's showed to the user during the test. The answer is inserted by clicking on the spot where the user thinks the system stopped.

relying on the tactile feedback only; during the trial the speed was constant, but before reaching the final position the system could pass through a random one to avoid the user to use the movement time as a clue. When the final position was reached another high pitch sound notified that it was possible to insert the answer (the final position guessed) by clicking on the image presented (*figure 37*). After the input, the user had 3 seconds before it was possible to start with the new trial. This scheme has been used for both the training and the test parts; the only differences were that during the training the initial and final positions were showed to the user and that every trial start position was the final of the previous one. In contrast, for the test, the trial always started at position 1. The whole test was composed of 7 training trials, with predefined stop positions, and 34 test trials, 2 in the rest zone, 2 in the dead zone, 10 in the pre-target zone, 10 in the target zone and 10 in the overshoot zone. The area covered by each zone is shown in *figure 18*.

2) In this part, the user had to self-evaluate himself by communicating to the operator how good his performance was, on a scale between 0 and 10, and to complete a brief questionnaire (*figure 38*), where he was asked to evaluate three aspects of the encoding on a 5 point scale: comfort, informativeness and intuitiveness.


How do you rate the system comfort in this session? *

	1	2	3	4	5	
Very uncomfortable	○	○	○	○	○	Very comfortable

How do you rate the system informativeness in this session? *

	1	2	3	4	5	
Totally non informative	○	○	○	○	○	Highly informative

How do you rate the intuitiveness of the encoding in this session? *

	1	2	3	4	5	
Very not intuitive	○	○	○	○	○	Very intuitive

Figure 38 - Questionnaire compiled by the subject after every encoding test.

4.3 Results

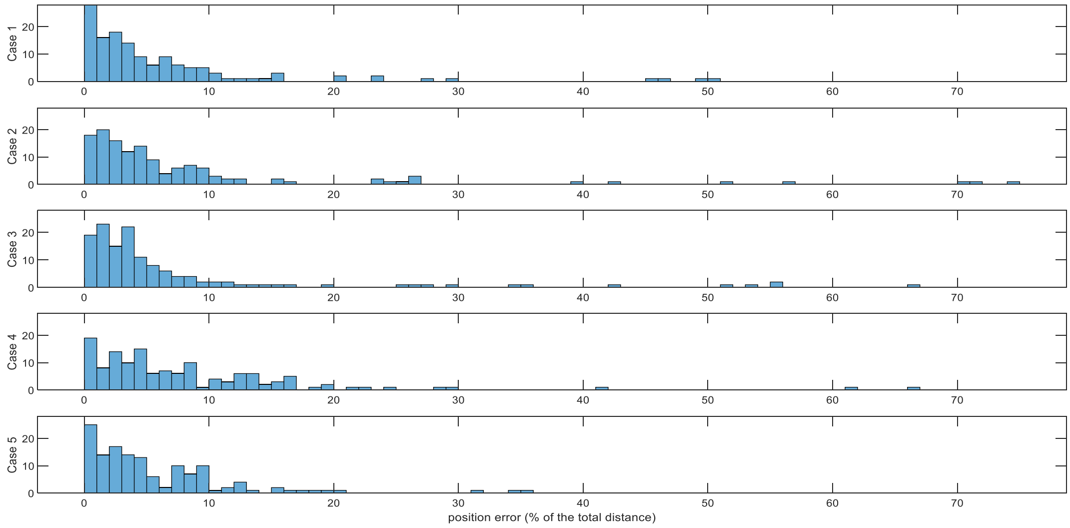


Figure 39 - Errors distribution of the different encoding strategies (Cases) for the whole population.

The experiment was performed on 4 subjects, 1 female and 3 males, aged between 23 to 26 years old. The duration of the whole test was 1 hour on average, including the positioning of the servos and the garments. After a preliminary data inspection and the visualization of the error distributions (*figure 39*), several performance indicators have been selected to evaluate differences between the strategies: the number of large errors, average error, classification accuracy in the different sub-zones (pre-target, target and overshoot) and self-evaluation statistics. The number of large errors has been selected as an indicator to measure how often the subjects got completely lost during the task. The threshold has been set to 20 % of the total

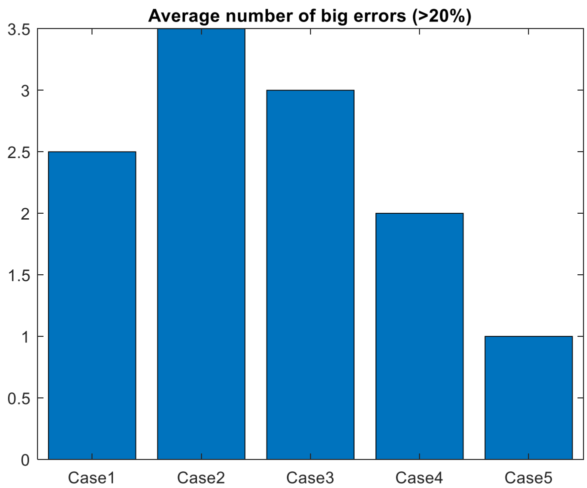


Figure 40 - Average number of big errors (> 20 % of the total distance) for the whole population.

Strategy	Comfort	Informativeness	Intuitiveness
Case 1	4.25	4.25	4.25
Case 2	4.25	4.50	4.00
Case 3	4.25	4.50	3.75
Case 4	4.25	4.00	4.50
Case 5	4.25	4.00	4.50

Table 6 – Average results of the surveys for the population.

distance looking at the sub-zones division (*figure 35*); this value was reasonable since for errors bigger than the 20 % the user is thinking of being in a sub-zone that's not even adjacent to the correct one. Moreover, it has been decided to remove these outliers from the calculation of the average error parameter to have an idea of the precision when the user can follow the movement simulated by the computer. As shown in *figure 40*, subjects tend to get lost less frequently while using strategies that do not involve the use of a long vibration to encode the overshoot situation; in particular, the 5th case results to be the best regarding this parameter. The average error and classification accuracy are shown in *figure 41* and *figure 42,* respectively. For these two parameters, it has been decided to compare the performances in the Encoding-zone only, composed by the pre-target, target and overshoot zones since the encoding was identical in both the rest and dead ones. Overall, the ability of the users in discerning in which area the movement ended revelated to be excellent, with an average accuracy always above the 80 %, with the only exception of case 2 in the overshoot-zone. It is possible to appreciate more marked differences in *figure 41* instead, where, as expected, subjects committed more significant errors in the target and encoding zones while using strategy 4 or 5, in which are

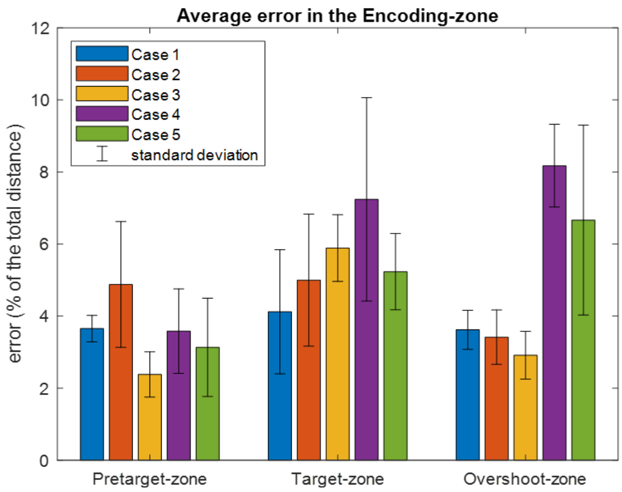


Figure 41 - Average error in the encoding zones (pre-target, target and overshoot).

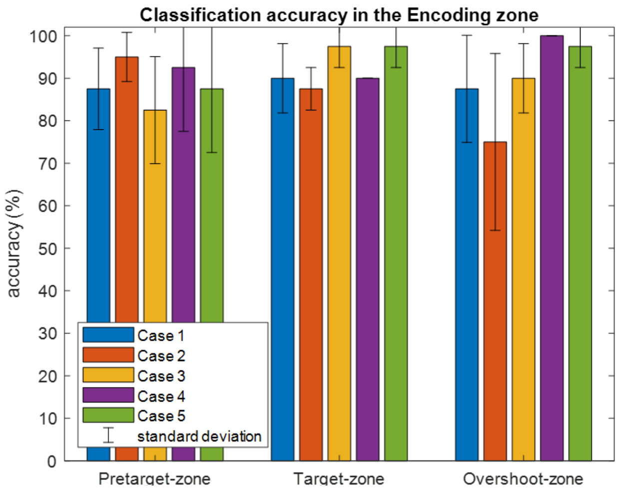


Figure 42 - Average accuracy in the encoding zones (pre-target, target and overshoot).

provided only "binary" information in such areas. Instead, in the pre-target region, all the strategies brought to similar performances while a smaller error was expected for strategies with gradual pressure changes (Case 1,2 and 4) if compared to the ones with a "step behaviour" (Case 3 and 5). The results of the surveys and the self-evaluation part are shown in *table 6* and *figure 43* respectively; as it is possible to notice from the first, the subjects perceived all the strategies as comfortable, and there are no differences between one case and another, but they tended to rate as less informative and more intuitive Case 4 and 5, that do not rely on long vibrations to encode overshooting situations. As visible in *figure 43* instead, users perceived they performed better when using encoding number 5 or 4. This also emerged when after the experiment they were communicating their sensation and opinions informally, and the majority of them reported to feel more sure in providing the answers when there was no need to focus on the vibration length.

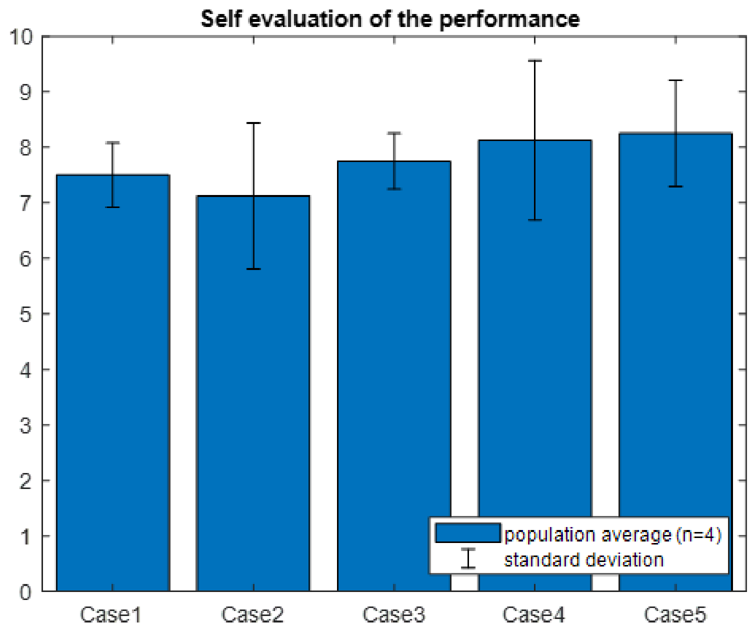


Figure 43 - Performance self-evaluation, averaged among all the subjects.

4.4 Discussion

The experiment aimed to compare performances obtained while using different encoding strategies and to select the most suitable one for further investigations. To do so, we based the choice on four decision criteria: the number of big errors, the target-zone classification accuracy, the average error in the pre-target zone and the outcome of self-evaluations and surveys. The first parameter has been chosen as an index of usability of the different cases since we wanted the movement to be easy to follow and to minimize the number of times the user gets completely lost. As shown in *figure 40*, Case 5 revelated to be the best option with only 1 big error on average, followed by Case 4 with 2. The accuracy in the target-zone has been selected because the essential feature of the strategy is supposed to be to effectively communicate to the subject when he is inside the target; as shown in *figure 42*, there are no large differences between cases, and it was possible to reach accuracies above the 85 % with all of them. However, strategy 3 and 5 generally led to better performances with an average accuracy of 95 % in this sub-zone. Instead, the pre-target zone error has been selected to evaluate the precision in discerning the distance to the target during the approach phase, essential to succeed in stopping inside the target and not passing through it. As it is visible from *figure 41*, the average error is of the order of a few percentage points for all the strategies tested, and no significant differences emerged (Friedman test, $p=0.21$). Therefore, this parameter did not result suitable to choose the best encoding strategy, even considering the small population and the variability due to the kind of application. The last parameter that has been selected is the outcome of self-evaluations and surveys, essential to have an insight into how the subjects perceived the different encodings. Regarding the self-evaluation of the performances, the subject tended to prefer Case 4 and 5 that do not rely on long vibration for the overshoot encoding. At the same time, the surveys revelated they were considering these two as the most intuitive, but the least informative. Considering all the parameter, the 5th encoding results to be the most suitable solution for further investigation: movements are easy to follow without getting lost, it is intuitive and perceived as useful by the user and is very effective when the subject needs to understand if he is in the target zone or not. Moreover, the classification accuracy is among the bests in the other sub-zones also. In general, it is possible to notice that the preference of the subjects is shifted toward cases that do not implement different vibration lengths and that these led to fewer large errors; two factors that could explain this circumstance are the overall complexity of the strategy used and the fact that the user could get used to repeated stimuli. About the first, it is possible that providing simpler input when in the target or the overshoot zones and no more distance information could have led to a decreasing in the perceived complexity of the encoding, that permitted to the user to focus more on specific events as the entry or exit in these sub-zones and consequently in higher classification accuracy. About the second factor, only one subject verbally reported after the experiment that he was getting used to the vibration stimuli, but in the light of the results, other subjects may have experienced the same sensation. This could be because the vibration stimuli were less variable and more repetitive if compared to the pressure ones. Consequently, it was easier to get used to them, leading to an increase in the number of large errors.

5 INTEGRATION TEST

To evaluate the impact that an encoding strategy has on performances and usability of an XL effectively is necessary to test it in the most realistic possible environment, using the final setup and subjects belonging to the target population. It is necessary to assess if the feedback is useful and what aspects of it must be tuned, but also if the hardware and software choices made during the design process integrate adequately with the extra limb without causing any delay in providing the feedback or discomfort for the user. In our specific case, these assessments have been made using the encoding strategy selected in Discussion(Case 5) and a pre-existing setup used for carrying on parts of the third arm experiment in which the final SS device need to be integrated, thus managing to keep a high fidelity to the characteristics of the final setup. During the experiments the user was asked to perform different bimanual or unimanual exercises, in all of these the third hand will started from an area called rest-zone and, when requested, the user had to reach a spherical zone and stop inside it.

5.1 Experimental protocol

5.1.1 Introduction

The objective of the experiment was to test the validity of the previously selected (see Discussion for the selection criteria) encoding strategy when used in combination with a virtual supernumerary third arm. The primary purpose of the haptic feedback system was to provide information about the relative position and distance between the XL end effector and the target zone using a pressure actuator and a vibrator. The first, composed by a servo motor and a lever, was used to encode the distance, while the vibrator was used to provide info about the entry and the exit in the target or rest zones. The third arm position was controlled with an eye-tracking system and respiration belt. The first allowed the user to lock a target by only looking at it, while the second permitted to control the movement: a deep inspiration made the third arm moving toward the target and a deep expiration made it move toward the body. During the experiment, it has been asked to the subject to perform the task described in Adaptation of the sensory substitution strategy to the experimental setup under three feedback conditions: feedback (*figure 44 (top)*), no feedback and feedback with additional dead-zone encoding (*figure*

44 (bottom)). The latter implements a distance encoding in the dead-zone (see *figure 27* for the division in zones of Case 5), providing information about the degree of extension of the third arm: as soon as the hand exit the rest-zone the pressure is maximum, while when the arm is fully extended the pressure is null. The control and feedback systems communicate with each other thanks to an ethernet connection.

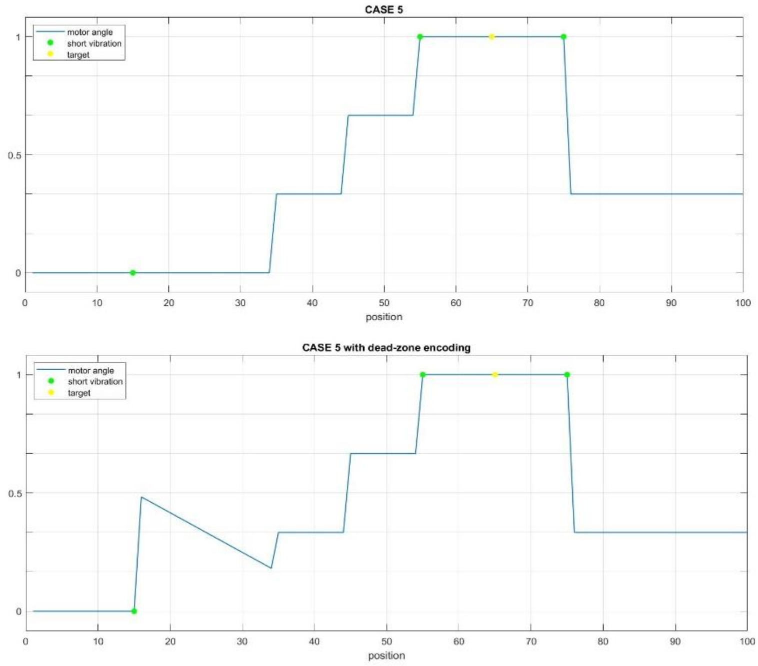


Figure 44 - feedback condition (top) and feedback condition with dead-zone encoding (bottom).

The experiment was divided into three blocks:

1) In block 1) the three conditions (feedback, no feedback and feedback with dead-zone encoding) have been tested consecutively. Before each test condition, a familiarization phase was done, in which the user performed the same tasks but with the third arm visible.
2) Block 2) was equal to block 1), but there were no familiarization phases, and the three conditions have been tested in a different order than in block 1).
3) Block 3) was equal to block 2), but the three conditions have been tested in a different order than in block 1) and 2).

At the end of the experiment was asked to the subject to report sensations and comments on the use of feedback during the task.

5.1.2 Materials

The experiment has been carried out with the subject seated, wearing HTC Vive Pro Eye Head Mounted Display (HMD) and a respiration belt on the abdomen for controlling the extra arm, measuring the thoracic expansion during expiration and inspiration phases. The feedback has been provided using one Graupner DES 448BB MG servo motor, kept in position on the user's left pectoral thanks to a shoulders posture corrector, and coin-shaped vibrator, kept in position on the user's right pectoral thanks to an adhesive bandage. The servomotor was attached to the internal part of the garment using Velcro straps, hot glue and a 3D printed plastic frame to guarantee stability. The motors were driven by an Arduino Mega 2560 and powered by an external power supply and MATLAB R2019b. The experimental data have been collected using a personal computer and LabRecorder. See APPENDIX: INTEGRATION TEST SETUP PICTURES for setup figures.

5.1.3 Experimental design

Healthy subjects have been involved in one session composed of 3 blocks. For this test, the target had a 5 cm diameter and the pre-target zone had an extension of 5 cm. Before the start, the procedure and encoding strategy have been explained to the subject and the equipment has been adjusted to be comfortable and stable; the eye-tracking system of the headset and the respiration belt were calibrated and the adhesion between the tactor head and the skin has been checked.

1) In block 1) the three conditions (feedback, no feedback and feedback with dead-zone encoding) have been tested consecutively, performing 18 randomized trials with three different target positions for each test condition. The subject's objective was to start from a known rest position, reach the target and stop inside for 500 ms without seeing the third arm and before the trial ended, after 5 s. Before each test condition, a familiarization phase has been done, in which the user performed the same tasks but with the third arm visible; this phase ended when he performed successfully two trials in a row. In both the familiarization and test phases the user received an acoustic hint at

the end of each trial, the sound was low pitch if the trial failed (the subject could not complete the task in 5 s) or high pitch if the trial was successful.

2) In block 2) the 3 test conditions have been tested as in block 1), but without doing a familiarization process before and changing their order.
3) In block 3) the 3 test conditions have been tested as in block 1), but without doing a familiarization process before and changing their order, so that it was different from block 1) and 2).

5.2 Results

The experiment has been performed on a 25 years old male subject only, and the duration of the whole test was 1 hour, including the positioning of the feedback and the XL control systems and the garments. To evaluate the impact of each condition on the subject performances, several indicators have been extracted from the raw data; in particular, from the 17 streams made available by the system only six have been used: the “trial ID”, the “success”, the “respiration”, the “distance”, the “feedback typology” and the “target ID” ones. From the “success” stream has been possible to calculate the percentage of successful trials in total (*figure 45*) and per block (*figure 46*); a trial is considered successful if the subject was able to stop inside the target area and stay still for 500 ms before surpassing the time limit of 5 s. The figures show an improvement in performances when the “Feedback + dead-zone encoding” condition is used, with the only exception of the third block, in which the subject performed

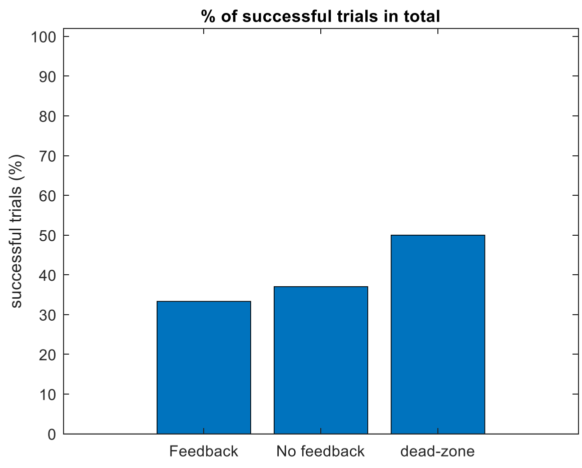


Figure 45 - Percentage of total successful trials.

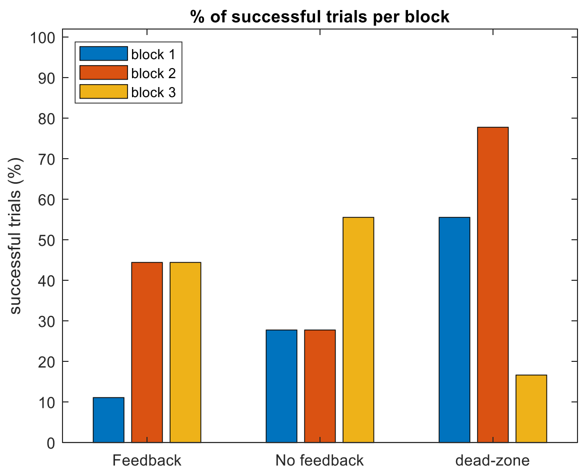


Figure 46 - Percentage of successful trials per block.

very poorly. A possible explanation to this could be that this specific condition was the last one of the third block to be tested and that the fatigue could have had a role in the performances drop. The differences between the "Feedback" and "No feedback" conditions are minimal instead, contrary to what was expected the percentage of total successful trials was slightly higher without any feedback. Merging the information derived by the "target ID" (for target positions), "distance" (for third-hand positions), "success" (for the end of the trials) and "trial ID" (for the start of the trials) streams, it has been possible to make considerations about the errors committed by the user at the end of the trial, intended as the distance between the extra hand and the target. *Figure 47* shows how this error tends to decrease continuously in all the conditions, as for the percentage of successful trials the only exception is the third block of the "Feedback + dead-zone encoding" condition, in which we can observe an abnormal behaviour. Also, the distributions of the errors in the three conditions revelated to have not statistically significant differences (*figure 48*), in both the successful and unsuccessful trials. Since the subject at the end of the experiment reported to be aware of the position error but that he failed in correcting it before surpassing the limit time, further analysis has been performed considering both the position at the end of the trial in respect to the target and the information of the "respiration" stream used to control the third arm movement. In particular, it has been checked if the user was giving the right input to correct the end-effector position or stop the movement actively. Three types of correct inputs were possible: the subject was in an overshoot condition and was exhaling, the subject was in an undershoot condition and it was inspiring, or

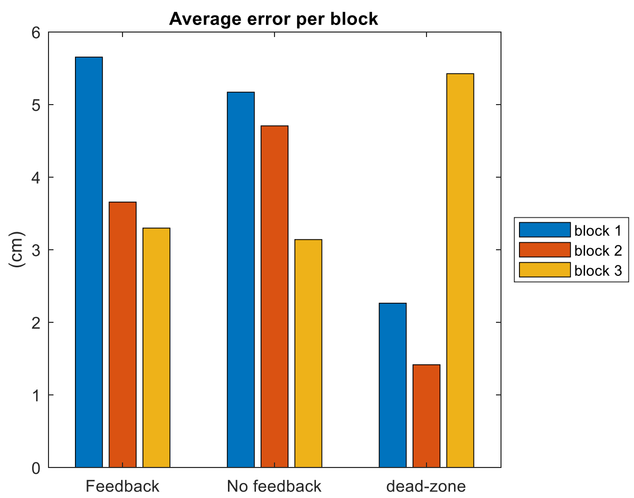


Figure 47 - Average error per block.

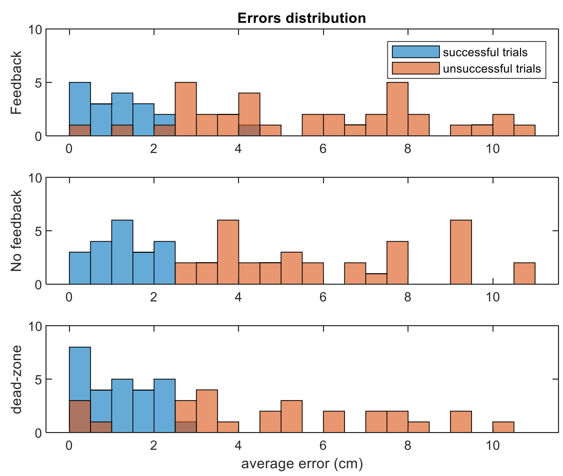


Figure 48 - Distribution of the errors in both successful and unsuccessful trials.

the subject was inside the target area and it was not giving movement inputs. As shown in *figure 49*, during the "No feedback condition" the user was giving the right input only when he wanted to stop and was inside the target already, while he was not able to effectively try to correct the position in undershoot or overshoot situations. With the two feedback conditions instead, the user was able to correct the error effectively giving the right input more often.

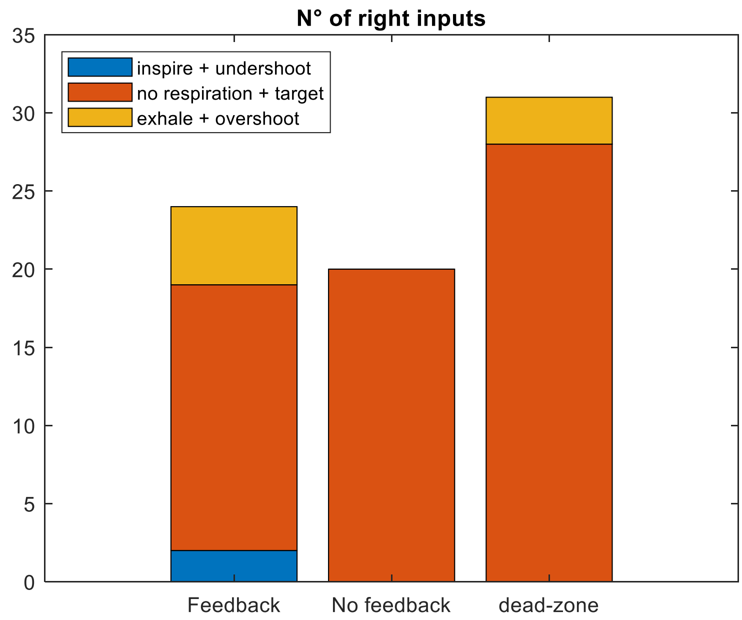


Figure 49 - Number of correct inputs at the trials end.

5.3 Discussion

Considering the results presented, it is possible to assert that the introduction of feedback has increased the spatial awareness of the subject regarding the relative position of the third hand in respect of a target. Nevertheless, it is clear that performances improvements have manifested only in the "Feedback + dead-zone encoding" condition, while for the "Feedback" one the task success rate was the same as the condition of "No feedback". This could be due to the lack of tuning of the encoding for the specific experimental setup and to the fact that only one subject has been tested. Since it was reported that the feedback was provided too late to stop inside the target comfortably, a possible solution could be incrementing the pre-target area in which the feedback is provided, bringing it from 5 cm to 10 cm for example, and giving the subject more time to modulate the respiration correctly. The user also reported that he was not able to correct overshoot and undershoot situations fast enough, so it could also be useful to increase the limit time for the task in further experiments to appreciate more the possible differences between the two feedback conditions and the one without. Regarding the impact of the different conditions on the learning of the task, it is impossible to appreciate any difference between the two feedback conditions and the one without. Regardless, it could be interesting to investigate further involving more subjects and dividing them into different subgroups to compare the evolution of the performances. In conclusion, the implementation of a SS display is promising for this application, and there is evidence that suggests improved usability and spatial awareness when using the third arm without vision help. Further improvements must be made to make the best of it, both in the feedback device display and experimental protocol fields. Regarding the first, a good starting point could be to tune the pre-target zone size to be sure the feedback is provided sufficiently before the target; regarding the second, increasing the trial limit time could provide a more precise understanding on the actual impact of the feedback system in simpler conditions.

6 CONCLUSION AND FUTURE WORK

The goal of this project was to provide the groundwork to get, in the long term, better integration between the user and extra arms by developing a SS display prototype capable of providing clear and reliable proprioceptive and contact feedback. The core idea was to develop a non-invasive and hybrid haptic display, that relies on both pressure and vibration feedback to provide the desired information. During the project, both system performances and sensory perception of the subjects have been investigated, highlighting the limits and strengths of the device and suggesting the needed improvements for overcoming these limits. The psychometric assessments showed a preference of the subjects toward the pectoral position for receiving pressure feedback, both from the point of view of stimuli clarity and comfort. However, the performances were in line with the other two placements: abdomen and posterior shoulder. The encoding strategies comparison test demonstrated how following a movement passively using such encodings is possible, obtaining excellent performances in terms of accuracy and position error; but adapting the selected strategy to the pre-existing extra arm simulation brought its limits to light, in particular regarding movement speed and pre-target zone dimension: a too fast movement or too small pre-target area can limit feedback effectiveness, not giving to the user enough time to modulate the breath to stop inside the desired target. Since the third arm speed cannot vary, a possible solution could be increasing the pre-target zone size to communicate distance information in advance and give enough time to the subject to effectively adapt his respiration pattern. Integration test outcomes suggest that the spatial awareness of the subject is increased despite the lack of performances improvement and that changing test parameters, such as the task difficulty (i.e., the time, could make differences between feedback and non-feedback conditions clearer. Once reached the maximum efficiency in providing proprioceptive and contact information could be possible to implement other feedback typologies also, like temperature or force ones, to promote XL embodiment or usability in specific situations. It will be necessary also to provide proprioceptive information about the end effector configuration and the grasping force once the user will be able to control it.

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8 APPENDIX: INTEGRATION TEST SETUP PICTURES

Figure 50 - Setup pictures of the Integration test setup during the carry-on of the experiment.

Figure 51 - Close-up of the feedback system used during the Integration test (top) and close-up of the placed vibrotactile motor (bottom).