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# Closing the Loop: Brain Processes underlying Control and Embodiment of Supernumerary Robotic Limbs

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# Abstract

Embodiment, i.e. the feeling of possessing and being in charge of a body, is a multifaced concept that requires complex estimations, achieved through multisensory integration, and deals with a settled knowledge according to a Bayesian statistical approach. Embodiment is intimately related to the body schema: a sensorimotor representation of the body that guides actions. Thus, motor output and sensory feedback are inscribed in a closed loop, known as sensorimotor loop, which is considered of paramount importance in the genesis of embodiment itself. However, the relative contributions of multisensory cues and motor planning remain to be assessed. This issue is addressed in the present work by combining the Moving Hand Illusion and the Tendon Vibration Illusion paradigms. Results demonstrated that, in order to feel embodiment of an artificial limb, the congruency between two integrated sources of information is required, be it an inter-sensory or a sensorimotor congruency. Furthermore, it is suggested that the efference copy could be exploited as a sensory modality to doublecheck for the embodiment of an artificial limb. Successively, by delving into the theory of Internal Models and showing that it is possible to induce low-level kinematics adjustment through artificial proprioceptive feedback during a lifting task, it is argued that a similar double role can be played by sensory afference as well. Notions and results expressed up to this point are finally framed in the context of human augmentation, and Supernumerary Robotic Limbs (SRL) in particular. The present work addresses the open question of how to establish a bi-directional communication through the addition of a robot-related proprioceptive sensory feedback, in order to close the sensorimotor loop and achieve a better human-robot interaction. Results suggested that position feedback seems to be a valid option for conveying supplementary proprioceptive feedback. Lastly, the present thesis tackles with another open issue in the field of human augmentation: to really benefit from an SRL, the user needs to receive feedbacks from the SRL seamlessly. By investigating the feasibility of a real-time supplementary feedback processing, the present preliminary work suggests that proprioceptive information regarding the SRL, such as the cartesian space position, could be conveyed and understood by the user with high precision and low delay.

# Author's publications

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2. Pinardi M., Raiano L., Formica D. and Di Pino G. "Altered Proprioceptive Feedback Influences Movement Kinematics in a Lifting Task." *42nd Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC) IEEE* (2020).
3. A. Noccaro, L. Raiano, M. Pinardi, D. Formica and G. D. Pino. "A Novel Proprioceptive Feedback System for Supernumerary Robotic Limb" *8th IEEE RAS/EMBS International Conference for Biomedical Robotics and Biomechatronics (BioRob)* (2020): 1024-1029.
4. Pinardi M., Raiano L., Noccaro A., Formica D. and G. Di Pino. "Cartesian space feedback for real time tracking of a supernumerary robotic limb: a pilot study" *10th International IEEE EMBS Conference on Neural Engineering* (2020, in press).
5. Noccaro A., Pinardi M., Formica D., Di Pino G. "A virtual reality platform for multisensory integration studies." *2020 42nd Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC)*. IEEE, 2020.
6. Pellegrino G., Pinardi M., Kobayashi E., Masiero S., Marioni G., di Lazzaro V., Keller F., Arcara G., Piccione F., Di Pino G. "When noise becomes unexpectedly salient" *Human Brain Mapping* (under review).
7. Bassolino M., Franza M., Bello Ruiz M., Pinardi M., Schmidlin T., Stephan M.A., Solcà M., Serino A., Blanke O. "Non-invasive brain stimulation of motor cortex induces embodiment when integrated with virtual reality feedback." *European Journal of Neuroscience* 47.7 (2018): 790-799.
8. Noccaro, A., Mioli, A., D'Alonzo, M., Pinardi, M., Di Pino, G., & Formica, D. "Development and validation of a novel calibration methodology and control approach for robot-aided Transcranial Magnetic Stimulation (TMS)". *IEEE Transactions on Biomedical Engineering* (2021)

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# Contents

# Chapter 1

# Introduction

## 1.1 Motivation and Objective

Embodiment, the impression that our body belongs to us, is a fascinating concept which attracted the interest of neuroscientific literature for many years. Despite seeming simple and immediate, embodiment hides a complex and multi-componential nature (Medina, Khurana, and Coslett 2015; Tsakiris 2017), whose main components can be identified in ownership (i.e. possession of the body) and agency (i.e. sense of control over the body). The complexity of embodiment is testified by the many definitions that can be found in literature, but most of all, by the complex mechanism embodiment is born from. Indeed, scientific evidence strongly points toward the idea that Embodiment is generated thanks to *multisensory integration* (Blanke 2012). Multisensory integration consists in the combination of cues coming from different sensory modalities to form percepts, and to sustain other cognitive activities, such as establishing causal relations between events in the world. Multisensory integration is of paramount importance for action as well: it allows our motor system to perform better by merging visual and proprioceptive information, thus guiding limb movements and preparing our body to deal with unexpected perturbations (Cluff, Crevecoeur, and Scott 2015; Sabes 2011). The wide range of influence of multisensory integration highlights not only the extreme importance it has for our interaction with the world, but also how it intimately permeates our everyday life, along our entire existence. Multisensory information, integrated through a Bayesian approach, is then employed to create a simulation of our body, primarily at a cortical level, which heavily influences the embodiment. Indeed, in order to perceive our body as our own, i.e. to embody it, we first need to know how it is made, its proportions, the relationships between one body segment and another, and what it can do and how. In other words, we need to build a body representation and, in particular, a *Body schema:* a sensorimotor representation of the body that guides actions (de Vignemont 2010). The link between embodiment, body representation and action informs us about the reciprocal influence that sensory feedback and motor command exert on each other. This closed circle is often referred to as the *sensorimotor loop*, meaning a closed loop connecting input and output information, that finds wide confirmation in the neurophysiology of the brain. Information inside the sensorimotor loop contributes to build the representation of the body through an inferential process that starts from spatiotemporal congruency (von Holst and Mittelstaedt 1950; Bays, Wolpert, and Flanagan 2005; Crapse and Sommer 2008), but the relative contributions of the involved actors remain to be assessed. Hence, the first objective this thesis aims to achieve is determining the specific role and contribution of afferent (i.e. sensory feedbacks) and efferent information (i.e. motor command) in closing the loop, i.e. determining embodiment. By exploiting the Moving Hand Illusion paradigm (Dummer et al. 2009) and the Tendon Vibration Illusion (Goodwin, McCloskey, and Matthews 1972), the present work suggests that ownership and agency of a robotic hand may be independently processed by the human brain and the presence or absence of the efferent component can modulate the salience of visual/proprioceptive integration. Results demonstrate that, in order to feel embodiment of an artificial limb, the congruency between two integrated sources of information is required, be it an inter-sensory or a sensorimotor congruency. Moreover, this thesis suggests an additional novel speculation: it is known that our brain uses a copy of the motor command, called efference copy, to predict the sensory consequences of the action we are going to execute (D. Wolpert, Ghahramani, and Jordan 1995; Shadmehr and Krakauer 2008). We strongly suggest that the prediction generated from the efference copy could be used as a source of information to "double check" for the embodiment of an artificial limb, exploiting motor instructions as an additional sensory modality. After shedding light on the mechanisms of the sensorimotor loop, the present work considers the theory of Internal Models (D. Wolpert, Ghahramani, and Jordan 1995) to clarify the contribution of sensory afference to motor control, showing that it is possible to induce low-level kinematics adjustment by artificially altering proprioceptive feedback during a lifting task. Results obtained so far showed how efferent information can be used as a sensory modality and sensory afference can influence kinematic behaviour, contributing to motor command, fortifying the idea of a constant and seamless flow of information inside a closed sensorimotor loop.

Notions and results expressed up to this point are finally framed in the context of human augmentation. Human augmentation refers to the use of methodologies, tools and devices originally designed to compensate the loss of function, to improve the abilities of healthy individual beyond the limitations typical of the human being (Di Pino, Maravita, et al. 2014). An important role in human augmentation is played by Supernumerary Robotic Limbs (SRLs), to the point of becoming a new research area in the field of human robotics. SRL are additional robotic limbs, ideally wearable, which are employed by users, together with their natural limbs, to reach a higher level of performance. It was demonstrated that integrating non-corporeal objects into the existing body schema increases the intuitiveness in their control (Manoharan and Park 2019) and even the proficiency with tools has been theorized to emerge from the integration of that specific tool into the body schema (Arbib et al. 2009; Farnè, Serino, and Làdavas 2007; Cardinali et al. 2012). Hence, in the present work, we studied how to establish a bi-directional communication through the addition of a sensory feedback relying proprioceptive information about the robot position to the user, in order to close the sensorimotor loop and achieve a better human-robot interaction. Lastly, the present thesis tackles with another open issue in the field of human augmentation. To really benefit from an SRL, the user needs to be able to send command, and most of all, receive feedbacks from the SRL seamlessly, as it happens with his own body. Despite the relevance of this feature, the possibility of real-time processing of sensory feedback coming from an SRL has never been addressed. Results from a preliminary study prove the feasibility of a real-time processing of proprioceptive feedback regarding the cartesian space position of the SRL.

## 1.2 Thesis Outline

**Chapter 2** introduces the reader to the fundamental concepts of Embodiment, Multisensory Integration and Sensorimotor Loop. These topics shall lay the foundation for the integration of Supernumerary Robotic Limb (SRL) into the body schema, possibly improving their control.

**Chapter 3** presents an experimental setup used to systematically investigate the specific contributions of sensory afferences and motor output in determining the embodiment of a robotic hand. Results are framed in the Bayesian approach, suggesting a novel role of efferent information in multisensory integration.

**Chapter 4** explores the role of artificial sensory feedback in determining low-level kinematics adjustments. Considering together the results from Chapter 3 and 4, the idea of a sensorimotor loop in which afferent and efferent information flow seamlessly with reciprocal influence is further confirmed.

**Chapter 5** starts by introducing another pivotal topic of the present thesis: human augmentation. Particular attention is paid to SRLs, and current knowledge about the embodiment of tools is discussed. Furthermore, an experimental setup for conveying proprioceptive feedback from the SRL to the user is presented, and two different feedback types (i.e. position and torque) are compared.

**Chapter 6** tackles with the issue of real time processing of supplementary sensory feedback. Results from the previous chapter are used to select the most appropriate sensory feedback type and the feasibility of real time processing of proprioceptive information coming from the SRL is tested.

**Chapter 7** finally sums up the major achievements of the present thesis and its main results. Additionally, the chapter discusses some open issues and lays the foundations for future works addressing those issues. As a last contribution, ethical issues relevant for the present topic are considered and discussed.

# Chapter 2

# Embodiment, Multisensory Integration and Sensorimotor Loop

## 2.1 Embodiment

During our everyday life we perceive our body as our own: it moves when we command it and whatever stimulus interacts with it, we feel it too. But it is not just that. We have the clear impression that our body belongs to us, in contrast with everything else around us. This sharp feeling of possession of our body has often been called *Embodiment*. A seemingly simple and immediate concept, Embodiment hides a complex and multi-componential nature, which has been a focus of neuroscientific literature for many years (Medina, Khurana, and Coslett 2015; Tsakiris 2017). Researchers nowadays agree on considering Embodiment as the combination of at least two main aspects: ownership and agency (Braun et al. 2018; Longo et al. 2008).

### 2.1.1 Ownership

Ownership is defined as the feeling that the body belongs to us, and it can be referred to the whole body (body ownership) or even to a single body part (limb ownership). The latter case is depicted in the paradigm of the Rubber Hand Illusion (Botvinick and Cohen 1998). In the classic version of this famous experimental paradigm, the real participant's hand lies out of view, on a surface next to a rubber hand, which can clearly be seen by the participant. An experimenter strikes both hands synchronously with a brush (Figure 1). Aften a brief period of repeated synchronous stroking, most participants report a feeling of ownership of the rubber hand, assessed through specific questionnaires (Longo et al. 2008). In addition to explicit measures of ownership, some other tools, more implicit and objective, have been developed. Participants who feel ownership of the rubber hand tend to mislocalize their real hand toward the rubber one, a phenomenon known as proprioceptive drift (Botvinick and Cohen 1998). Moreover, a threatening stimulus, like a needle, approaching the rubber hand can produce a physiological response in the form of a skin conductance alteration as measured on the participant's hand, and this has been considered as a proof of ownership of the rubber hand (Armel and Ramachandran 2003; H Henrik Ehrsson et al. 2007). To testify the complexity of Embodiment and its components, ownership has been assessed in a great variety of paradigms stemming from the classic RHI: ownership of an artificial hand has been successfully produced using different combination of multimodal stimulations, e.g. tactile-proprioceptive instead of visuo-tactile (H H Ehrsson, Holmes, and Passingham 2005), or exploiting a virtual environment to alter features which could not be easily manipulated in reality. Finally, ownership could be referred to the entire body, as stated before. This scenario is investigated in the Full Body Illusion (H Henrik Ehrsson et al. 2007), in which a gentle struck is applied to the participants' back, and they can see, through and HMD, their own body being struck. This third person perspective allows participants to feel the tactile stimulation on their own body, and to see it on the back a virtual, displaced body. This paradigm is known to induce self-identification with the displaced body and referral of touch (Lenggenhager et al. 2007), similarly to what happens with the RHI.

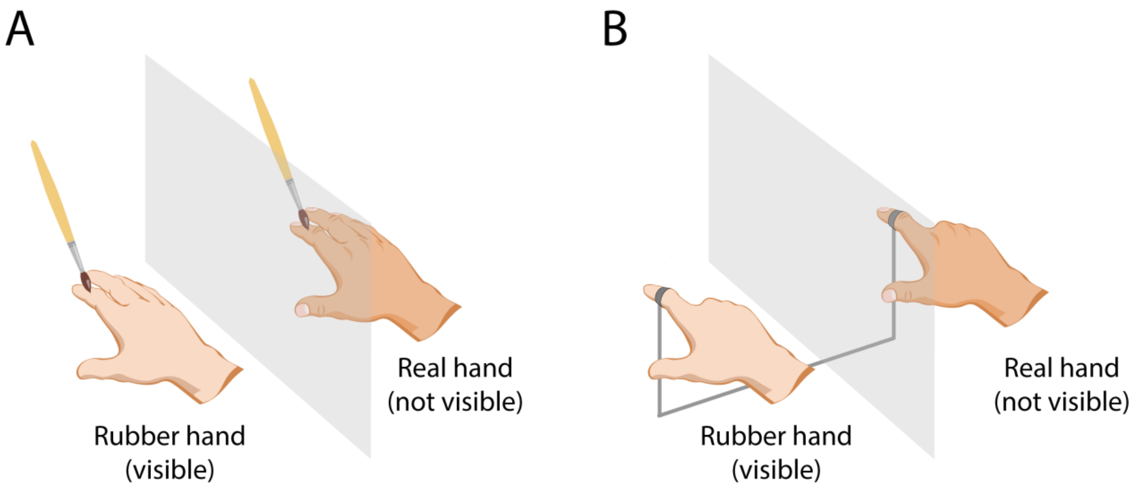


*Figure 1 – **Rubber Hand experimental setups.** Panel A shows the classic setup for Rubber Hand Illusion Experiment. Real and rubber hands are both struck with a brush synchronously. Visuotactile integration induces embodiment of the artificial hand. Panel B shows the variant called Moving Hand Illusion. Real and rubber hand are mechanically coupled and participants have to move their hand (typically their finger), which in turn causes the artificial hand to move. In both setups participants can only see the rubber hand, while the real hand is kept out of view.*

### 2.1.2 Agency

Agency is defined as the sense of authorship over our action, the sensation that we are in charge whenever our body moves voluntarily. Just like Ownership, Agency has been investigated in several experimental paradigm, the most known of which is a variation of the RHI, called Moving Hand Illusion (Dummer et al. 2009; Kalckert and Ehrsson 2012; Walsh et al. 2011). During this paradigm, participants actively move their real hand, out of view, while seeing the rubber hand replicating the same movement (Figure 1). In this case, a visuo-motor integration tricks the brain into thinking that the fake hand belongs to the participant, raising the feeling of embodiment, and agency specifically (Blanke 2012; Blanke, Slater, and Serino 2015). Once again, several measures of agency exist, both implicit and explicit. The most widespread implicit measure of Agency is the intentional binding effect, consisting in the distorted perception of time interval between a voluntary action and its sensory consequences: time distance between action and consequence seems to be shorten when the action is considered voluntary, and longer when it is considered involuntary (Haggard, Clark, and Kalogeras 2002;

Haggard, Taylor-Clarke, and Kennett 2003). Despite not being completely unchallenged, it is generally accepted that temporal binding is caused by a prediction mechanism that binds together the will to act with the corresponding sensory outcome, thus strongly connecting intentional binding and Agency (Moore and Obhi 2012). On the other hand, explicit measures of Agency have been used as well, generally relying on the use of specific questionnaire that investigates how much participants feel they contributed to the action considered. Indeed, Agency appears to be intimately linked to motor control, to the point of being sometimes considered reliant on the presence of efferent motor component.

## 2.2 Multisensory Integration

Defining Embodiment and its main components is just a part of the equation. Another important aspect is understanding how Embodiment happens. Scientific evidence strongly points toward the idea that Embodiment is generated thanks to *multisensory integration* (for a review see Blanke 2012). Multisensory integration consists in combining cues coming from different sensory modalities, leading not only to what we call perception, but also to the creation of causal relations between events in the world and to better behavioural performances. Indeed, it has been shown that some perceptual phenomena, like flavour, intrinsically rely on the integration of multiple senses, i.e. gustatory and olfactory cues (Spence 2015; Maier et al. 2015). Moreover, multisensory integration improves our discriminatory ability, helping us understanding the events around us in a noisy environment (Marc O. Ernst and Bülthoff 2004; Alais, Newell, and Mamassian 2010; Chandrasekaran et al. 2009). Multisensory integration is of paramount importance not only for perception, but for action as well: it allows our motor system to perform better by merging visual and proprioceptive information, thus guiding limb movements and preparing our body to deal with unexpected perturbations (Cluff, Crevecoeur, and Scott 2015; Sabes 2011). Finally, multisensory integration has been shown to improve task and information learning compared to unisensory exposure (Shams and Seitz 2008).

The wide range of influence of multisensory integration highlights not only the extreme importance it has for our interaction with the world, but also how it intimately permeates our everyday life, along our entire existence. Indeed, it is interesting to speculate that we do not perceive our body as our own the moment we are born, as if it were an innate sensation, but we learn to classify our body as our own thanks to a lifetime of congruent multisensory integration. But how does it work? Before delving deeper into how multisensory integration is achieved, it is important to note that the effortless nature of multisensory integration hides an extremely complex process which follows strict computational rules.

### 2.2.1 Principles of Multisensory Integration

*Neuronal responses to multisensory stimuli.* To better understand what multisensory integration is from a neurophysiological point of view, we need to consider the activity elicited by multisensory stimuli on neurons able to respond to different sensory modality, i.e. multisensory neurons. Indeed, if we consider a Visual and Auditory cue, a multisensory neuron will produce an activity, i.e. alter its firing rate, in response to both cues alone, but will also be able to produce a brand new pattern of neuronal activity if those cues are present, approximately, at the same time (Schwarz 1994; Drugowitsch et al. 2014). The way those cues can be integrated to produce a new activity pattern can follow three principles: i) *superadditivity*, if the integrated multisensory response is stronger than the response produced by summing single unisensory cues; ii) *subadditivity*, if the integrated response is weaker than the summed unisensory ones; iii) *additivity*, if the integrated response is similar to the sum of the single unisensory cues. It is interesting to note that most of the neuronal responses follow the *additivity* mechanism, while *super-* or *subadditivity* characterize mainly very weak or very intense stimuli. This observation leads to the next principle of multisensory integration.

*Inverse effectiveness*. Multisensory stimuli are integrated more efficiently if the unisensory cues are weak in intensity (Chandrasekaran 2017). It is easy to understand the functional relevance of this principle if we consider a practical situation: the need for multisensory integration, and the benefits it leads to, is lower when we observe a ball bouncing on a tennis field in broad daylight, with perfect visibility conditions. On the other side, if the day was an extremely foggy one (weak visual stimulus), integrating the weak visual cue with the sound of the bouncing ball might indeed help us in locating the ball.

*Temporal window of integration.* For reasons that can be intuitively understood, one cannot integrate every multisensory cue received from the environment, as it would simply not be efficient nor helpful. Thus, the most effective criterion to decide which cues must be integrated is time: multisensory integration is maximal, or more likely to happen, when unisensory stimuli occur approximately at the same time, as a direct result of the limited time window in which neurons can integrate sensory inputs (Chandrasekaran 2017).

These computational principles, established over the years thanks to several experiments on different animal species (Stein and Stanford 2008), can help us understand which rules multisensory integration must strictly adhere to, but they are not formal computational model, and can only describe the mechanism of multisensory integration from a qualitative point of view. Nevertheless, a qualitative description of these principles can be considered sufficient for the aim of the present work, as they help in determining important factors when designing experimental setups, e.g. stimuli onset time or duration of a stimulation. Neuroscientific research has then focused on describing how these principles are employed by our brain to integrate multisensory stimuli. In other words, what is the best strategy we use to perform multisensory integration?

### 2.2.2 Bayesian Integration

When talking about multisensory integration, the great issue that we face whenever we deal with sensorimotor information is the uncertainty of the sensory input that we receive. Indeed, our sensorimotor system is incapable of recording and producing afferent and efferent information respectively, with perfect precision: the reliability of sensory inputs will depend on the sensory modality (e.g. vision can considered more precise than proprioception, generally speaking), but even the most accurate of our sensory system is plagued by noise (Barlow et al. 1987; Scott and Loeb 1994) and our muscles produce noisy output as well (Clamann 1969; Matthews 1996). In order to deal with this intrinsic sensorimotor uncertainty and produce an optimal multisensory integration, our brain has to frame this issue within a statistical framework. As a matter of fact, in the absence of absolute truth about sensorimotor information, estimating the state of the world becomes a matter of statistical probability: in other words, if we have to judge where a tennis ball will land on the field or if a certain body part belongs to us, our brain has to determine how likely that outcome is. Neuroscientific research nowadays vastly agrees that the tool our brain employs to do so is Bayesian statistics.

Bayesian statistics revolves around the assignation of probabilities about what happens in the environment. Performing multisensory integration to make optimal decisions within a Bayesian framework means considering both the experience we had in the past and the sensory information we receive in real time. Bayesian estimation dictates how this information must be combined: sensory inputs coming from different sensory modalities are weighted in relation to the reliability of each one of them, and the more reliable source of information will contribute greatly to the integrated multisensory feedback, called *likelihood* (e.g. proprioceptive input, a usually noisy source of information, is considered less reliable than visual cues, thus multisensory feedback will verge toward the information carried by vision). Additionally, the likelihood shall be combined with our previous experience, called *prior*, to formulate an optimal estimate of the variable we are considering. The resulting optimal estimate consists in the judgment we make about the considered aspect of the world and is formally called *posterior judgment*. An important aspect to consider is that Bayesian estimation is a highly adaptive process: a weighted temporal estimation is applied in order to account for any variations in the relative uncertainties of sensory cues (Drugowitsch et al. 2014; Chandrasekaran 2017). This means that if a single sensory cue decreases its reliability, the other sensory cue will gain weight, and if all of them become too noisy (i.e. the likelihood loses reliability) the posterior judgement will shift toward the prior. This mechanism is illustrated in Figure 2.

As anticipated before, several works demonstrated how Bayesian estimation can account for multisensory behaviour (Ma 2012; Chandrasekaran 2017; Bizley, Jones, and Town 2016; Shangari et al. 2015), and the strong role it plays in determining Embodiment of a fake limb (Samad, Chung, and Shams 2015).

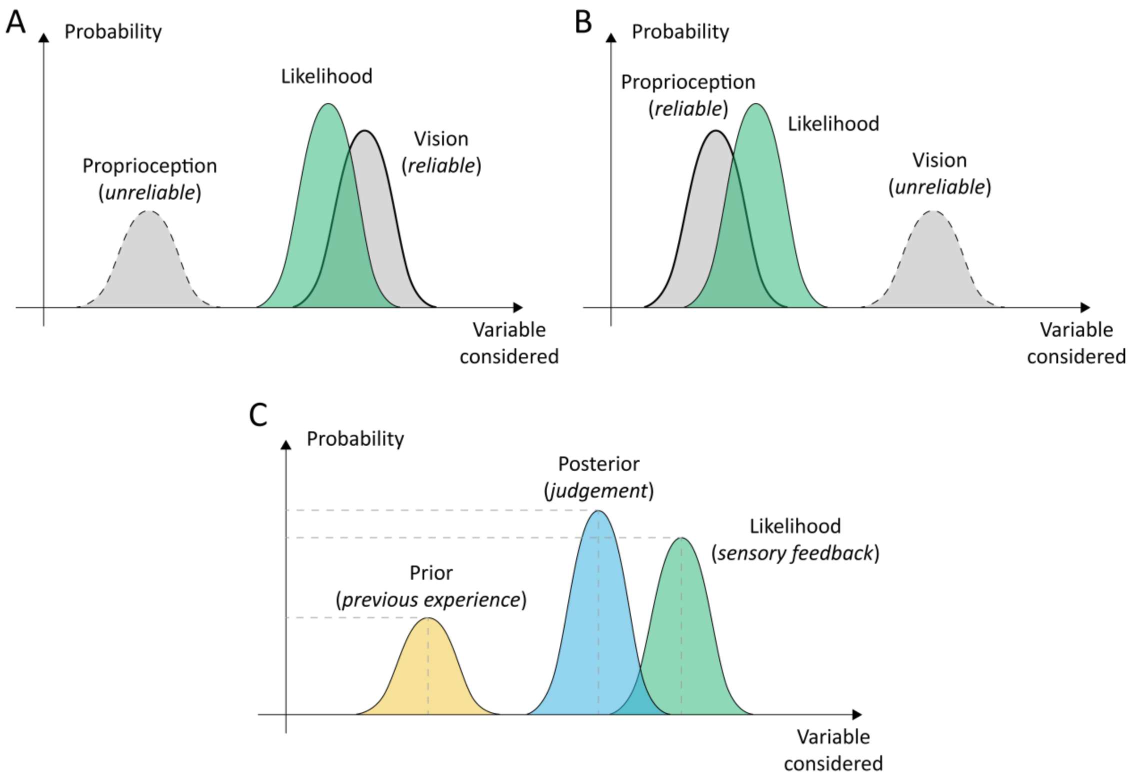


*Figure 2 – **Bayesian estimation approach**. **Panel A** and **B** show how visual and proprioceptive cues are combined, in relation to the relative reliability, to form the Likelihood. Panel A shows the case in which Vision is considered reliable and Proprioception unreliable, while Panel B shows the opposite scenario. In both cases, the Likelihood will shift toward the more reliable cue. **Panel C** shows how Likelihood and Prior are integrated into a Posterior Judgement. The Likelihood usually carries information deemed more reliable than the Prior, since it is the result of our real time experience, but in the event of a poor quality of sensory feedback (unreliable Likelihood) the Posterior would shift toward the Prior.*

## 2.3 Body Representations

Multisensory information, integrated through a Bayesian approach, is then employed to create a simulation of our body, primarily at a cortical level. This simulation is of paramount importance for embodiment. Indeed, in order to perceive our body as our own, i.e. to embody it, we first need to know how it is made, its proportions, the relationships between one body segment and another, and what it can do and how. In other words, we need to build a body representation. The idea of a body representation, first referred to as *body schema*, dates back to the beginning of the XXth century (Bonnier 1905), and focused on the spatial organization of internal bodily sensation. The principle of spatial organization is nowadays widely accepted, and the figure of the *homunculus* has become famous as well: a plastic somatic representation whose proportions are determined by the density of sensorimotor innervation of each specific body part, and are subjected to change in response to a modification of the innervation density. The concept of homunculus does not perfectly overlap with that of body schema, but it is an effective way to understand what a body representation consists of. The variety of ways we have to relate to our body (i.e. different sensory modalities) and the different clinical scenarios which emerged along the years, led to the consensus that there are at least two different body representation, with distinct functions and characteristics: the *body image* and the *body schema*.

### 2.3.1 Body Image

The *body image* is the representation with the most shaded definition, and it is surrounded by a certain degree of controversy. Generally speaking, body image groups several types of body representation that are not strictly related to action: perceptual, conception or emotional (Gallagher 1995). It is considered a conscious representation, but it's dynamics can vary from short term body concepts to long term body concepts (de Vignemont 2010). Its heterogeneity led some researcher to further split body image into two separate levels: a visuo-spatial level and a semantic level (Schwoebel and Coslett 2005; Sirigu et al. 1991). The *visuo-spatial body image* focuses on the relationship between body parts and their structural description. The *semantic body image* is a conceptual, linguistic representation, focused on the functional purpose of body parts and the "meaning" they have for us. To sum up its role, body image, be it visuo-spatial or semantic, is charged with the perceptual identification and recognition of our body (de Vignemont 2010).

### 2.3.2 Body Schema

Contrarily to body image, neuroscientific research vastly agrees on the definition of *body schema.* Body schema is a sensorimotor representation of the body that guides actions (de Vignemont 2010). Observations on neuropsychological patients, especially those with apraxia, led to the idea of the body schema as a paramount, if not fundamental, factor in determining a correct motor control (Buxbaum, Giovannetti, and Libon 2000; Schwoebel and Coslett 2005; Romano et al. 2021). The strong relation between the way we represent our body and a motor action makes perfect sense if we consider that no successful or effective action can be done without a correct representation of the characteristics and parameters of each body segment, the relationship they have with each other, and ultimately, our body as a whole. Taking into account that the majority of movement dynamics and kinematics are unconscious and automatically regulated, and given its role in supporting motor actions, body schema is generally considered unconscious as well, even though it might become conscious during specific task, for example during motor imagery (Schwoebel and Coslett 2005). What is most interesting, especially in the perspective of the present work, is the role of body schema in motor hierarchy. Indeed, it covers a pivotal role in the Internal Models theory. Internal models are hypothetical flowcharts that our brain uses to plan motor commands, to predict the sensory consequences of movements and to adjust and fine-tune commands in order to interact efficiently with the environment, accounting for any possible perturbation (D. Wolpert, Ghahramani, and Jordan 1995). The topic of internal models, their features and links with the body schema shall be discussed more in depth in successive chapters.

## 2.4 Sensorimotor Loop

The link between embodiment, body representation and action highlighted so far is further supported by a recent study which demonstrated that reducing the excitability of M1 through low frequency rTMS, increases the susceptibility to RHI, thus increasing the embodiment over the rubber hand (Fossataro et al. 2018). Additionally, healthy participant whose arm was mechanically immobilized, showed a weaker sense of ownership for the immobilized limb, and an higher susceptibility to the RHI (Burin et al. 2017). What can be inferred from this scientific evidence is the reciprocal influence that sensory feedback and motor command exert on each other. Indeed, it was discussed how embodiment depends on a coherent multisensory integration and how this combination of sensory feedbacks is the primary tool our brain uses to build a body representation. Body representation is then pivotal for correct planning and execution of motor commands. Furthermore, contrarily to what common sense could suggest, motor commands are not a mere physical execution of our brain's will but are actively used to predict the sensory consequence of our actions (a concept that will be discussed more in depth in the following chapters) (D. Wolpert, Ghahramani, and Jordan 1995). What emerges here is a connection between the afferent information (sensory feedback) and the efferent information (motor command), which are involved in a continuous, closed circle. This closed circle is often referred to as the *sensorimotor loop*.

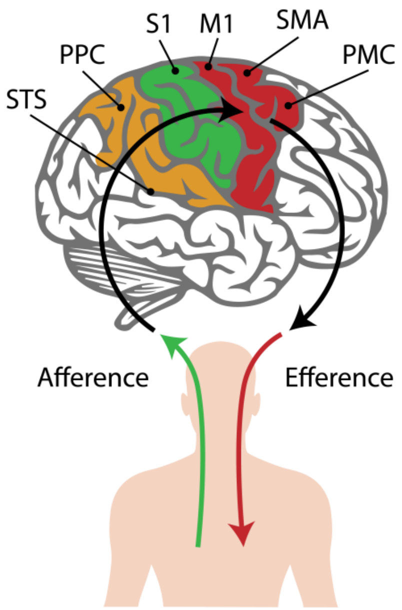


*Figure 3 – **Example of the neurophysiological basis of the sensorimotor loop**. Afferent information coming from the body (e.g. somatosensory feedback) and related sensory cortex in shown in green (S1: primary somatosensory cortex). Efferent information and main motor areas area shown in red (M1: primary motor cortex; SMA: supplementary motor area; PMC: premotor cortex). Main multisensory and associative areas are shown in orange (STS: superior temporal sulcus; PPC: posterior parietal cortex).*
*The idea of a closed loop connecting input and output information is not new and finds wide confirmation in the neurophysiology of the brain (*

Figure 3). Indeed, brain cortices, thalamus and cerebellum are the major actors involved in an extended and complex network, or loop, ultimately responsible of multisensory integration and sensorimotor coordination. To be more specific, cortical loops connect frontal motor neurons with basal ganglia, cerebellum, thalamus, parietal cortex and brain stem leading to the formation of spatiotemporal patterns of activity for the spinal cord (Bizzi and Ajemian 2020). Frontoparietal cortical loops, between parietal and premotor cortex, have been extensively studied in animals, and have been shown to play a role in the integration of multisensory information, including gaze direction and limb proprioception, to achieve a successful and accurate reaching movement (Pandya and Kuypers 1969; Wise and Kurata 1989). Another observation suggesting an intimate connection between action and sensory feedback, is the fact that the primary motor cortex (M1) and dorsal premotor cortex (dPMC) are the main point of convergence of several brain networks. Indeed, signals coming from cerebellum, basal ganglia, thalamus and sensory cortices converge on M1 and dPMC, and involve the supplemental motor area (SMA) and the cingulate motor area as well (Rathelot and Strick 2006, 2009). To conclude, despite the lack of a definitive and global theory regarding the sensorimotor loops, it seems now clear that a neat separation between afferent and efferent information would be artificial and inappropriate. Thus, to understand how our sensorimotor system works in relation to embodiment, it is mandatory to adopt an experimental approach able to consider and study both afference and efference by keeping the sensorimotor loop intact.

# Chapter 3

# Sensory Confirmation and Motor Commands for Ownership and Agency

## 3.1 Introduction

A proficient interaction with the environment requires a continuous and harmonic flow of motor commands and incoming sensory feedbacks. This sensorimotor loop is constitutive for movement planning and control (Kawato 1999; Shadmehr and Krakauer 2008), yet it has crucial implication beyond it. Whenever an action is performed, a certain level of spatial and temporal congruency links the planned motor command and its effect (Chandrasekaran 2017), thus the integrated multisensory feedbacks well match the anticipated sensory consequence of the movement. Over a lifetime, the knowledge of having a body, and being in charge of it, is built upon such congruent integration of multiple senses and motor planning, determining what we call *embodiment* (Medina, Khurana, and Coslett 2015; Tsakiris 2017).

As discussed in the previous chapter, embodiment is a complex, multi-componential process which presents at least two main aspects: i) ownership, i.e. the feeling that a body part belongs to us; ii) agency, i.e. the feeling of initiating and controlling actions of a body part (Braun et al.

2018; Longo et al. 2008). The process of embodiment leads to the creation of the body representation, which is a transitory internal construct representing our body and the relationship between its parts (Armel and Ramachandran 2003). Besides our body, ownership and agency can be related to external objects not originally belonging to the self (Giummarra et al. 2008; Dummer et al. 2009; Kalckert and Ehrsson 2012; Walsh et al. 2011; Di Pino et al. 2020): the synchronous brush stroking of both a visible fake hand and the real hidden one elicits ownership of the former. In the late Nineties, this experimental paradigm, namely the Rubber Hand Illusion (Botvinick and Cohen 1998), has revived the interest in the study of the representation of the body in human, and it is still the most widespread tool to test the impact of factors on embodiment. The overlap between the mechanisms involved in motor control and the ones building the representation of the body suggests the speculation that the effective embodiment of a limb or a tool would positively impact the ability to proficiently control it (van den Heiligenberg et al. 2018; Makin, de Vignemont, and Faisal 2017). The implications for amputees are just beyond the corner: a prosthesis able to restore the lost sensorimotor functions can aspire to achieve better control performance also through an induction of a more effective embodiment. Better embodiment, in turn, may also help to restore the perceived integrity of the body, altered since the amputation (Crea et al. 2015; Alonzo, Clemente, and Cipriani 2015; Murray 2008; Di Pino, Pellegrino, et al. 2014).

Different senses and motor planning together contribute to build the representation of the body through an inferential process that starts from spatiotemporal congruency (von Holst and Mittelstaedt 1950; Bays, Wolpert, and Flanagan 2005; Crapse and Sommer 2008). Once established this, their relative contributions remain to be assessed. *Proprioception*, the ability to sense the position and forces of one's own body, is particularly relevant among the different senses that take part in the spatiotemporal congruency (Tuthill and Azim 2018). Typically, the movement of the hand in the space gives back, and it is controlled through, visual and proprioceptive information, being the touch less informative in the absence of interaction with objects (U. Proske and Gandevia 2012).

To investigate how much the establishing of the body schema is robust against the rupture of congruency of the sensorimotor loop, we selectively manipulated in healthy subjects the binds between sight and proprioception and the efferent motor command. The embodiment of the hand was measured while the link between who was controlling its movement, and the hand itself, was weakened in a three-step process to the point of having theoretically no connection.

The loss of incoming connections was achieved by modulating the sensory information given back to the users, in order to make it incongruent with the efferent command they sent. The absence of the efferent component was also tested while the user could still receive meaningful afferent information.

To have a testbed of the sensorimotor loop controlling the hand, which allowed us to modulate afferences and efferences, we employed the following technologies and already existing experimental paradigms:

- A modified version of the well-known Rubber Hand Illusion, called Moving Hand Illusion (Dummer et al. 2009; Kalckert and Ehrsson 2012; Walsh et al. 2011). During the Moving Hand Illusion, participants actively moved their real hand, kept out of view, while seeing the rubber hand replicating the same movement. Visuo-motor integration tricks the brain into thinking that the fake hand belongs to the participant, raising the feeling of embodiment (Blanke 2012; Blanke, Slater, and Serino 2015).
- A robotic hand was employed to perform complex multifingered movements with the introduction of a delay between the movement executed by the real hand and the one observed, which was performed by the robot (i.e. modulation of visual information).
- The Tendon Vibration Illusion (TVI) (Goodwin, McCloskey, and Matthews 1972) was employed to manipulate proprioception (U. Proske and Gandevia 2012). In the TVI, a vibration delivered above a muscle tendon simulates the afferent information of an elongation of the muscle and evokes an illusion of movement (IoM). TVI can be used to provide the movement sensation for a completely relaxed limb (Roll and Vedel 1982; Albert et al. 2006; Ferrari, Clemente, and Cipriani 2019) and to alter its perceived position (Goodwin, McCloskey, and Matthews 1972; Capaday and Cooke 1983).

The impact on embodiment of a three-step loss of congruency between streams of information constituting the sensorimotor loop was tested in two different experiments. The first experiment (Exp A) featured a self-generated movement, with participants actively controlling a robotic hand, while in the second experiment (Exp B) participants had to keep their hand still, while observing the robotic hand moving. Both experiments were designed to mirror each other conditions, being the presence of movement the only changing variable. In both experiments, conditions were designed to have three (motor command, vision and proprioception), two or no congruent streams of information.

Embodiment was assessed through questionnaires, rating specifically ownership and agency, and by measuring proprioceptive drift and skin conductance.

## 3.2 Methods

43 healthy participants, naive for the employed protocols, took part in the study. 21 participants were enrolled in the first experiment (Exp A) (11 females, 18 right-handed, aged 30±3) and 22 different participants in the second experiment (Exp B) (16 females, 20 right-handed, aged 29±2 years). All participants declared to have normal vision and hand sensations. All participants provided written informed consent in accordance with the declaration of Helsinki and following amendments. The study was approved by the Ethics Committees of the Scuola Superiore Sant'Anna, Pisa (request no. 6/2017) and of the Università Campus Bio Medico, Rome (protocol EMBODY, ver. 2018.04.06).

### 3.2.1 Experimental apparatus

An instrumented robotic platform was set to modulate motor command, visual and proprioceptive sensory feedback in a modified version of the Moving Hand Illusion. Participants had to move the fingers of their own hidden hand in order to command a visible robotic hand (*Experiment A*) or just lay still while observing the robotic hand moving (*Experiment B*). Participants' real hand was hidden from view and the visual feedback was given by the visible robotic hand.

Robotic hand movement could be artificially delayed, making the visual feedback incongruent with the participants' intention to move. Proprioceptive feedback could be made incongruent with the participants' intention to move as well, by exploiting a randomly-delayed vibrotactile stimulation delivered above distal tendons on the back of the participants' right hand. The delay induced during incongruent conditions, albeit random, always caused the IoM (flexion) to be generated during an extension phase of the participant's movement. Finally, the causal-effect relation between participants' motor command and movement of the robotic hand could be broken as well, by independently controlling the robotic hand movement with position commands sent over a serial bus from a PC. The IoM generated by the vibrotactile stimulation was assessed before starting the experiment to find optimal responders to the illusion. This led to the exclusion of 3 out of 43 participants.

During the experiment, each participant sat comfortably on a chair in front of a table, with the right arm lying in a prone position over a 6 cm high wooden support. The arm was hidden by a screen ensuring that it was out of sight throughout the entire experiment. A life-sized right-handed prosthetic hand (IH2 Azzurra, Prensilia SRL, Italy), was placed parallel, and medially to the participant's real right hand (center-to-center distance of 15 cm). The robotic hand was kept in the same prone position, at the same height of the real hand, by a wooden support. The wooden support and the right shoulder of the participant were both covered by a blanket (Figure 4). Both experiments had four conditions, whose order was randomized across participants and each condition lasted 90s. Experiment A and Experiment B shared a common experimental condition (MRHI) (Kalckert and Ehrsson 2012): participants actively controlled the movements of the robotic hand and they were asked to make complex finger movements by randomly flexing and extending the index, middle or ring and little fingers in a tapping fashion with a smooth speed profile. Participants were told to move the little and ring fingers together because the robotic hand implemented their movement with a single motor and because their independent use is not comfortable and not relevant in the execution of an extensive repertoire of daily manipulative tasks (Aoki, Tsuda, and Kinoshita 2019) such as tool-handles grasps (Kapandji 2007). A brief training was carried out to teach participants how to move their fingers correctly and each complete flexion-extension of one finger lasted about 2 seconds.

In the conditions where the robotic hand was controlled by the participant (whole Experiment A and the MRHI condition of Experiment B), the movements of the participant's real right hand were tracked by a motion capture system (Leap Motion Controller in Experiment A and Cyber Glove in the MRHI condition of Experiment B) and translated into similar movements of the robotic hand. Conversely, in the remaining conditions of Experiment B, the artificial robotic hand was externally activated by a PC through a custom software (C# code) independently from the participant, who had to lay still without making any movement. The movements involved in the experimental setup were executed only one at a time (e.g. participants never flexed the index finger while extending the middle finger) and this, together with the slow tapping pace, made the movement tracking quite easy to achieve. To further improved the tracking performance of the Leap Motion, we placed a black sheet of paper under the participant's hand in order to have a dark matt background, which can help the correct detection of movements. Finally, in conditions where the robotic hand had to move congruently with respect to participants' movement, the intrinsic delay between participants' hand movement and robotic hand movement was approximately 50ms.

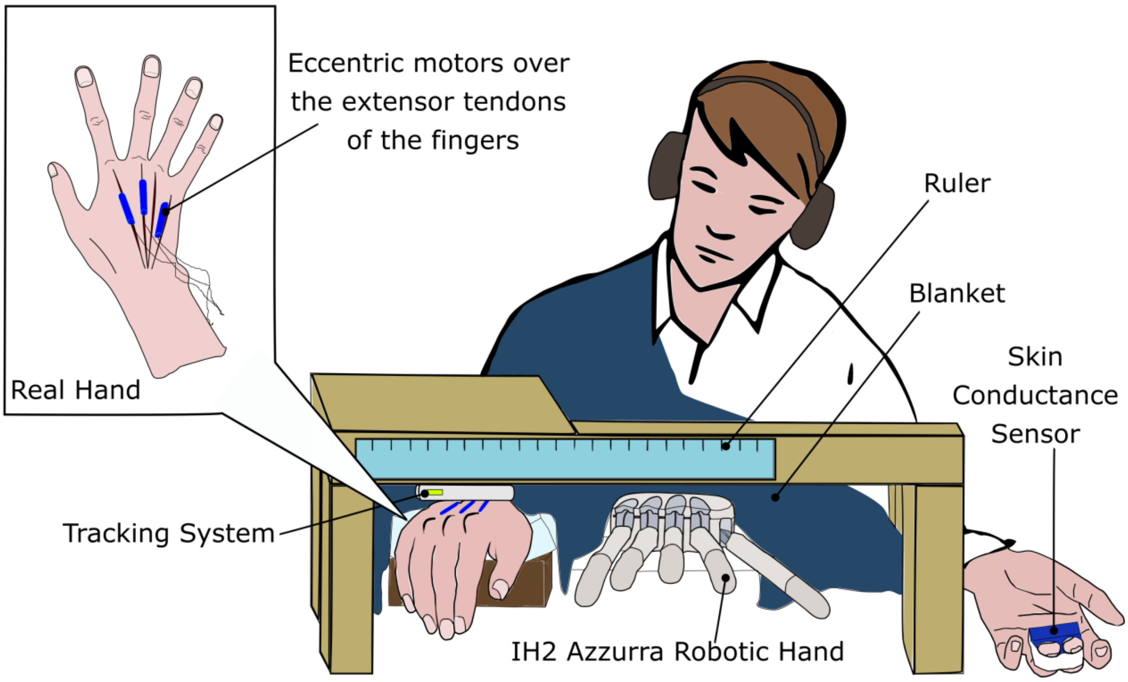


*Figure 4 - **Experimental Setup**. A tracking system (Leap Motion Controller or Cyber Glove) recorded the movements of the real hand fingers that were simultaneously converted into movements of the robotic hand. The hand of the participant was equipped with three eccentric motor over the tendons of the extensor indices, extensor digitorum communis and extensor digiti minimi muscles to induce an illusion of movement (IoM).*

To modulate the visual feedback, the robotic hand moved after the actual movement of the real hidden right hand, with a delay ranging randomly from 0.5 s to 1 s (steps of 0.25s).

To modulate the proprioceptive feedback, an Illusion of Movement (IoM) was elicited exploiting the TVI. The IoM consisted in an illusion of finger flexion. The TVI was always induced on the participant's finger that he/she was moving, in Experiment A, or on the participant's finger that matched the moving robotic finger, in Experiment B.

A distinct sensation for each finger movement was obtained by means of three eccentric rotating mass vibration motors (Model 307-100, Precision Microdrives Limited) taped over the skin on the back of the hand where distal tendons could be easily identified through palpation and where they were not detached by flexion-extension movement. Index finger IoM was produced by stimulating the distal tendons of the extensor indicis, middle finger IoM by stimulating the distal tendons of extensor digitorum communis and ring and little fingers IoM was obtained by stimulating the distal tendons of the extensor digitorum communis and of the extensor digiti minimi (Figure 4, left). The tendons conduced the vibration to proprioceptors in the muscle belly and their superficial position granted an efficient and easy stimulation, able to generate three distinct IoM (Tuthill and Azim 2018; Gay et al. 2007).

A pilot experiment was run before the study to determine optimal frequency and duration to achieve IoM. Strongest illusion was achieved by vibrating motors at a frequency of 70-90 Hz (Roll and Vedel 1982) and for a duration set to 1.1 s, thanks to a custom microcontroller board. Additionally, whenever an incongruent artificial proprioception was delivered, the vibration was delayed of an interval ranging randomly from 0,5 s to 1 s, with steps of 0,25 s, with respect to the controlling motor command.

To help participants familiarize with the IoM and to evaluate its vividness, a pre-test was conducted before both experiments, and, if needed, participants were hinted about the expected illusion to facilitate its detection, and vibrators placement was adjusted until a stable and clearly perceived IoM was achieved (M.W. Taylor , J.L. Taylor 2017). Once the vibrators were set, consecutive short vibrotactile stimulations towards the index, the middle and the ring fingers were delivered in random order over 1 min. Immediately after the stimulation we employed a 6 statements illusion survey to find optimal responders to the illusion and determine which participant could be tested in experimental conditions during Exp A and Exp B. Participants were asked to answer using a 7-point Likert scale where -3 meant ‘‘strongly disagree’’, 0 meant ‘‘neither agree or disagree’’, and +3 meant ‘‘strongly agree’’. The purpose of the questionnaire was to: i) check if the IoMs was clear and consistent with the expected movement sensation (Q1: During the vibrotactile stimulation I perceived an extension of my fingers, Q2: During the vibrotactile stimulation I perceived a flexion of my fingers); ii) quantify the vividness of the IoM for each finger (Q3-5 The perceived movement is clear/vivid as the natural movement of my finger); iii) assess the presence of any aftereffect (Q6: At the end of the vibration, I feel as my finger was moving in the opposite direction coming back to the starting position). Inclusion criteria consisted in (i) reporting a rating above -1 for questions Q3, Q4 and Q5 and (ii) reporting a movement coherent with the one justified by the neurophysiological substrate in Q1 and Q2 (i.e. illusory flexion of fingers). Failing to meet these criteria resulted in the exclusion of the participant from the study. As a result, one participant was excluded from Experiment A and two participants from Experiment B. For both experiments, the number of participants that took part to the following phase was 20.

### 3.2.2 Experiment A

The first experiment investigated the effect on embodiment of modulating the congruency between sensory feedback (afferences) and the motor command (efference). More specifically, the *Moving Robotic Hand Illusion* (MRHI) where visual and proprioceptive feedbacks were congruent with the motor command, was compared with three additional experimental conditions (Figure 5A): i) Vision congruent Proprioception incongruent (VcPi), ii) Vision incongruent and Proprioception congruent (ViPc) and iii) both Vision and Proprioception incongruent with the motor command and between them (ViPi). In all conditions, the participants directly controlled the movements of the robotic hand by moving their own real hand, thus the causal-effect relation between motor volition and hand movements was present.

In the *Vision congruent Proprioception incongruent* (VcPi) condition, the seen movement of the robotic hand (i.e. the visual feedback) was congruent with the actual movement of the real hand, as in the MRHI condition. However, in this case, proprioceptive feedback felt by the participants was incongruent because of the combination of the delayed IoM and the natural proprioceptive feedback.

In the *Vision incongruent Proprioception congruent* (ViPc) condition, participants flexed and extended their own fingers, while the corresponding robotic fingers were belatedly activated. Proprioception was congruent because participants did not receive any vibrotactile stimulation.

Finally, in the *Vision incongruent Proprioception incongruent* (ViPi) condition, both the additional artificial proprioceptive feedback and the visual feedback were incongruent with respect to the actual movement of the participant's hand, as well as between them. Indeed, the artificial proprioceptive feedback was also randomly delayed with respect to the movement of the robotic hand.

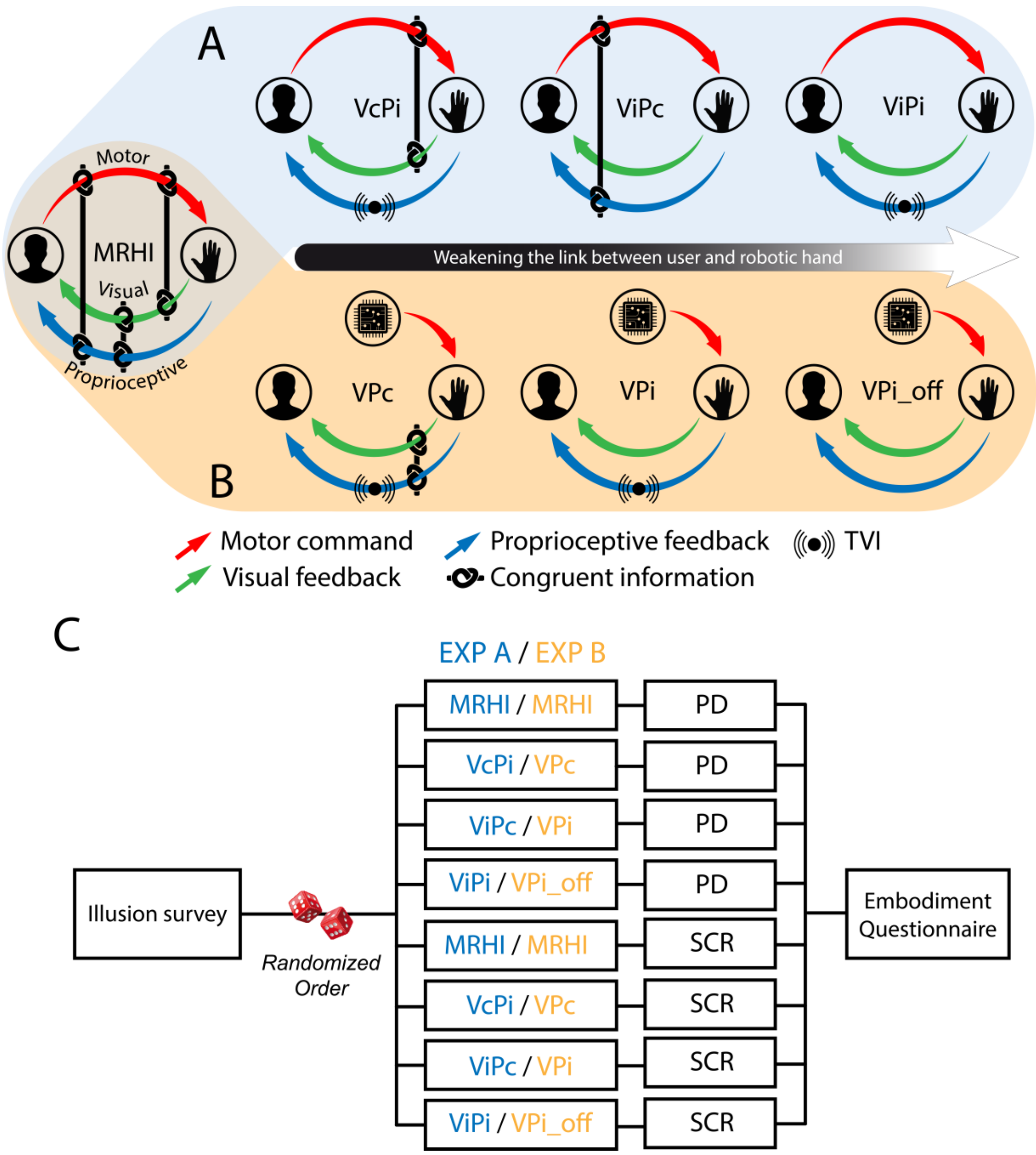


*Figure 5 –* ***Experimental conditions and protocol****. The figure shows the weakening of the link between the participant and the robotic hand of both experiments A (Panel A) and B (Panel B). The red arrows indicate motor command, which can be generated by participants (Experiment A) or by the computer (Experiment B), while green and blue arrows indicate visual and proprioceptive feedbacks, respectively. Congruent streams of information are tied together by black knots. Vibration icons show proprioceptive feedback altered through TVI. MRHI was a common condition of both experiments in which motor commands and sensory feedbacks were congruent. In the other conditions motor command, visual or proprioceptive feedback were modulated. Vc and Vi indicates congruent and incongruent visual feedback respectively, while Pc and Pi refer to congruent and incongruent proprioceptive feedback. Finally, VPi_off indicates the absence of any vibration-induced proprioceptive feedback.*

*Panel C shows the experimental protocol shared by both Exp A and Exp B. After the Illusion survey, participants performed every experimental condition of Exp A (blu, left) or Exp B (yellow, right) twice (once of PD and once for SCR measure) in randomized order. After each condition, they answered the Embodiment Questionnaire. A more detailed description of the experimental protocol can be found in the Apparatus Section of Supplementary Materials.*

### 3.2.3 Experiment B

The second experiment investigated if, and how much, the congruency between different sensory feedbacks (vision and proprioception) impacts on the induction of embodiment of a robotic hand, in the absence of an outgoing motor command, thus when the causal-effect relation between motor command and sensory feedback is broken. More specifically, the *Moving Robotic Hand Illusion* (MRHI) was compared to three additional experimental conditions (Figure 5B): one having congruency between visual and artificial proprioceptive feedback (VPc), another with incongruency between visual and vibration-induced proprioceptive feedback (VPi), and control condition without any vibration-induced proprioceptive feedback (VPi_off).

The *Vision-Proprioception congruency* (VPc) and *Vision-Proprioception incongruency* (VPi) conditions were characterized by the addition of the vibration-induced proprioceptive sensory feedback which was added to the natural proprioception of the participant's hand, kept steady and relaxed over the support.

In the *Vision-Proprioception congruency* (VPc) condition, each vibrator was activated only during the flexion of the robotic finger in order to induce an illusion of flexion of the participant's corresponding finger, which matched the movements reproduced by the robotic hand (controlled through the PC). Hence, in this condition, the visual and the vibration-induced proprioceptive feedback were congruent with each other.

Conversely, in the *Vision-Proprioception incongruency* (VPi) condition, a delay was introduced between the flexion movement of the robotic hand and the beginning of the vibration. Hence, the delayed vibration evoked an IoM which was incongruent with the visual feedback.

*Vision-Proprioception incongruency_off* condition (VPi_off) was conducted as a control condition to exclude any direct effect of vibratory stimulation on the feeling of embodiment.

### 3.2.4 Embodiment and Movement Illusion evaluation

Embodiment was assessed through explicit Ownership and Agency measures (self-evaluation questionnaire), and implicit measures (proprioceptive drift (PD) and skin conductance response (SCR)) collected after each condition. Each experimental condition was repeated twice, to allow the collection of PD and SCR data without mutual interference, in a pseudo-randomized order. The overall experimental session, including both experiments, lasted about 60 minutes and lead to the collection of four PD and SCR ratings (one per each condition) and eight self-evaluation questionnaires (two per condition). For each experimental condition separately, the eight ratings (4 questions * 2 repetitions) obtained for each questionnaire condition (ownership, ownership control, agency and agency control) were pooled together by computing their mean. Questionnaire data were processed to obtain Ownership and Agency Indexes. In both experiments, the questionnaire was always performed after the PD or the SCR test. Each embodiment and movement illusion evaluation techniques are described in detail below.

*Proprioceptive Drift.* At the beginning of each condition, participants were asked to close their eyes and to indicate with their left index finger the felt position of their right index finger. In order not to give cues on the post-stimulation measure, that could be either PD or SCR, the pre-stimulation pointing was conducted also when the trial was performed to acquire the SCR. A ruler mounted on the screen (and not visible by the participant) was used to measure the end point of the movement (Figure 4). A new pointing test was performed after the stimulation. The proprioceptive drift was calculated as the difference between the pre-stimulation and post-stimulation pointing task measurements. Positive values represented a mislocalization of the participant's right hand toward the robotic hand, which is considered a sign of embodiment (Botvinick and Cohen 1998).

*Skin Conductance Response*. It has been described an increase in the skin conductance response (SCR) to a threat stimulus against the rubber hand when the illusion occurs (Armel and Ramachandran 2003). The SCR (sampling rate 2000 Hz) was recorded using MP160 Biopac



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(Biopac Systems, Inc.). The sensor was worn five minutes before the experiments began in order to achieve a stable hand-electrode contact impedance. All the participants were informed that a needle could suddenly approach the fake hand but that they would not experience any painful sensation. After the experimental condition, the robotic hand was suddenly stabbed with the needle (threatening stimulus) attached to a syringe (20 ml) (D'Alonzo and Cipriani 2012). Order randomization of the implicit tests was done to prevent participants from predicting the stabbing. SCR was calculated by high-pass (10Hz) filtering the signal and identifying a peak value within 1–10 s from the onset of the threat stimuli. The magnitude of the SCR was used to measure the extent of the illusion (Armel and Ramachandran 2003; D'Alonzo and Cipriani 2012).

*Questionnaire*. After every experimental condition, participants filled in an Italian translation of the Moving Hand Illusion self-evaluation questionnaire (Kalckert and Ehrsson 2012), readapted to take into account the use of a robotic hand. It required participants to rate the strength of their agreement with sixteen statements (Table 1) presented in a randomized order. Four illusion statements (S1-S4) referred to the sensation that the artificial robotic hand belongs to the participants' body, i.e. the feeling of ownership. Other four illusion statements (S9-S12) were used to evaluate the sense of active control over the robotic hand, i.e. the feeling of agency. The remaining eight statements were used as control statements for the ownership (S5-S8) and for the agency (S13-S16). These statements served as controls for compliance, suggestibility, and ''placebo effect''. As in the IoM pre-test questionnaire, participants were asked to rate each statement using a 7-point Likert scale where -3 meant ''strongly disagree'', 0 meant ''neither agree or disagree'', and +3 meant ''strongly agree'' (Kalckert and Ehrsson 2012). The Ownership and Agency Indexes were defined as the difference between the mean of ratings of the pooled illusion statements and of the control statements, and they were calculated for each condition and employed as the illusion measures for ownership and agency in the following analyses (Abdulkarim and Ehrsson 2016).

Four further statements (S17-S20) were added to the questionnaire in all experimental conditions involving vibrotactile stimulation (Vision congruent Proprioception incongruent, Vision incongruent Proprioception incongruent, Vision-Proprioception congruency and Vision-Proprioception incongruency conditions) to qualitatively evaluate the IoM that the participants perceived (IoM assessment statements). In particular, S17 tested the vividness of the illusion, i.e. how much the IoM was similar to a real finger movement; S18 attested if participants perceived a delay in the incongruent artificial proprioceptive condition; S19 and S20 were used to verify whether the perceived movement had similar velocity and range of motion of the one reproduced by the robotic hand, respectively.

| CATEGORY | STATEMENTS |
|---|---|
| **Ownership** | S1. I felt as if I was looking at my own hand |
| | S2. I felt as if the robotic hand was part of my body |
| | S3. It seemed as if I were sensing the movements of my fingers in the location where the robotic fingers moved |
| | S4. I felt as if the robotic hand was my hand |
| **Ownership control** | S5. I felt as if my real hand were turning robotic |
| | S6. It seems as if I had more than one right hand |
| | S7. It appeared as if the robotic hand were drifting towards my real hand |
| | S8. It felt as if I had no longer a right hand, as if my right hand had disappeared |
| **Agency** | S9. The robotic hand moved just like I wanted it to, as if it was obeying my will |
| | S10. I felt as if I was controlling the movements of the robotic hand |
| | S11. I felt as if I was causing the movement I saw |
| | S12.Whenever I moved my fingers I expected the robotic finger to move in the same way |
| **Agency Control** | S13. I felt as if the robotic hand was controlling my will |
| | S14. I felt as if the robotic hand was controlling my movements |
| | S15. I could sense the movement from somewhere between my real hand and the robotic hand |
| | S16. It seemed as if the robotic hand had a will of its own |
| **IoM vividness** | S17. The perceived movement was clear as the natural movement of my fingers. |
| **IoM synchronism** | S18. The movement perceived with each vibration was synchronous with the one reproduced by the robotic hand (i.e. I perceived a flexion when the robotic fingers were flexing and vice versa) |
| **IoM velocity** | S19. The velocity of the perceived movement was similar to the one of the robotic fingers |
| **IoM range of motion** | S20. The perceived movement was large as the one reproduced by the robotic fingers |

*Table 1 - **The questionnaire**. The first 16 statements measure the experience of ownership and agency. The last 4 statements (S17-S20) were used only in experimental conditions involving vibrotactile stimulation to assess the illusion of movement (IoM).*

## 3.3 Data Analysis

Significance threshold was set to p-value lower than 0.05 for all tests and ANOVA. Where correction for multiple comparison was necessary, Bonferroni correction was applied. Effects size is reported as Cohen's d for t-test or Rank-Biserial Correlation (r) for Wilcoxon signed rank test and Mann-Whitney test.

Among all the data, only Ownership ratings from Exp B and PD from both experiments were normally distributed (Shapiro-Wilk test, p>0.05).

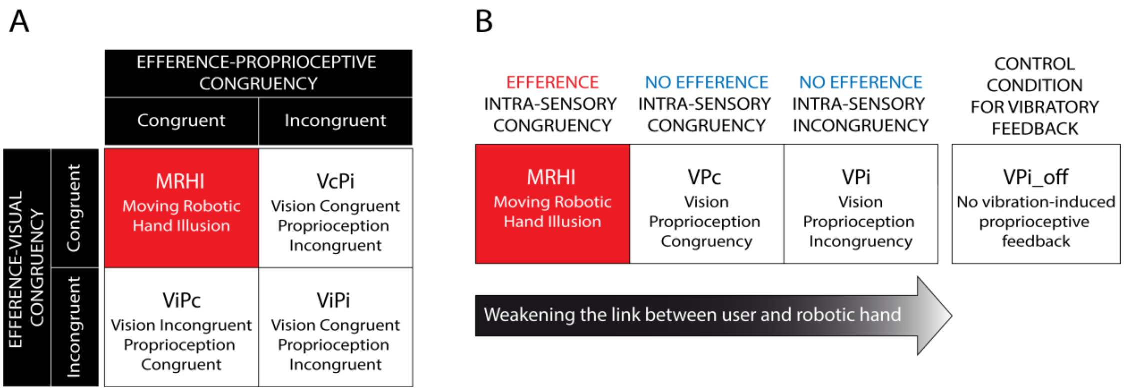


*Figure 6 - **Panel A**: 2x2 Experimental design for Experiment A. **Panel B**: experimental conditions of Experiment B. Common condition across the two experiments (MRHI) is highlighted in red.*

***Questionnaire Analysis***. Regarding Exp A, questionnaire ratings were processed using non-parametric two-way "Anova-like" test (Durbin test) with two factors (Figure 6A): the factor *efference-visual congruency* (two levels: congruent, incongruent) and the factor *efference-proprioceptive congruency* (two levels: congruent, incongruent). Wilcoxon signed rank was used for multiple comparison between experimental conditions (corrected for 2 comparisons).

Regarding Exp B, collected Ownership and Agency ratings (MRHI, Vision-Proprioception congruency, Vision-Proprioception incongruency and Vision-Proprioception incongruency_off conditions) (Figure 6B) were compared across conditions using a paired sample Student t-test and a Wilcoxon signed rank test, respectively (corrected for 6 comparisons).

Moreover, to verify the impact of the absence of motor command, Ownership and Agency indexes from different experiments were also compared through Mann-Whitney unpaired tests. In details, we compared:

i) the conditions from different experiments that presented all three streams of congruent information, i.e. the MRHI conditions;

ii) the conditions from different experiments that presented two streams of congruent information, i.e. Vision incongruent Proprioception congruent (Exp A) vs Vision-Proprioception congruency (Exp B) and Vision congruent Proprioception incongruent (Exp A) vs Vision-Proprioception congruency of (Exp B) (corrected for 2 comparison);

iii) the conditions from different experiments that did not present any couple of streams of congruent information, i.e. Vision incongruent Proprioception incongruent (Exp A) vs Vision-Proprioception incongruency (Exp B).

***Skin Conductance Analysis***. For Exp A, SC data were processed using non-parametric two-way "Anova-like" test (Durbin test) with two factors: the factor *efference-visual congruency* (two levels: congruent, incongruent) and the factor *efference-proprioceptive congruency* (two levels: congruent, incongruent). Wilcoxon signed rank was used for multiple comparison between experimental conditions (corrected for 2 comparisons).

For Exp B we employed a Wilcoxon signed rank test to compare SC data in MRHI, Vision-Proprioception congruency, Vision-Proprioception incongruency and Vision-Proprioception incongruency_off conditions (corrected for 6 comparisons).

***Proprioceptive Drift Analysis***. Data regarding PD were processed using a two-way repeated measure ANOVA with factors: *efference-visual congruency* (congruent, incongruent) and *efference-proprioceptive congruency* (congruent, incongruent) for Exp A, and using paired samples t-test comparisons for Exp B (corrected for 6 comparisons).

***Correlation Analysis***. Finally, for Exp A and B, correlation analyses (Pearson correlation coefficient) were performed between the Indexes of Ownership and Agency and the IoM



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assessment statements (Table 1) to evaluate the impact of the quality of the IoM on the induction of embodiment when the artificial proprioceptive feedback was involved.

## 3.4 Results

***Experiment A.*** A Durbin test run on Ownership index ratings showed a significant effect of *efference-visual congruency* (F(3)=4.031, p=0.011). No significant effect was found for *efference-proprioceptive congruency* (F(3)=0.005, p=0.999).

The post hoc analysis (Wilcoxon signed-rank test) of the Ownership Index revealed that the MRHI condition rating was significantly higher than the Vision incongruent Proprioception congruent rating (W=166.5, p=0.008, r=0.8), whereas ratings in Vision congruent Proprioception incongruent and Vision incongruent Proprioception incongruent were not significantly different (W=102, p=0.970) (Figure 7A, left).

A Durbin test run on Agency index ratings showed a significant main effect of *efference-visual congruency* (F(3)=17.974, p<0.001). No significant effect was found for *efference-proprioceptive congruency* (F(3)=0.020, p=0.996).

The post hoc analysis (Wilcoxon signed-rank test) of the Agency Index showed a significantly higher rating for MRHI condition compared to Vision incongruent Proprioception congruent (W=192.5, p=0.002, r=0.8). A significantly higher rating was found also for Vision congruent Proprioception incongruent compared to Vision incongruent Proprioception incongruent (W=172.0, p=0.004, r=0.8) (Figure 7A, right).

The correlation analysis between IoM assessment statements (collected only in Vision congruent Proprioception incongruent and Vision incongruent Proprioception incongruent conditions) and the related Ownership and Agency Indexes did not show any significant correlation (exact p-values are reported in Figure 8A).

A Durbin test run on SCR data showed a significant main effect of *efference-visual congruency* (F(3)=3.522, p=0.02). No significant effect was found for *efference-proprioceptive congruency* (F(3)=0.010, p=0.996). The post hoc analysis (Wilcoxon signed-rank test) of SC data did not reveal any significant comparison (MRHI vs Vision incongruent Proprioception congruent, W=148, p=0.114; Vision congruent Proprioception incongruent vs Vision incongruent Proprioception incongruent, W=118, p=0.648) (Figure 9, right). Finally, PD data analysis did not report any significant differences between the four conditions (Figure 9, left).

***Experiment B.*** Bonferroni-corrected paired sample t-test comparisons between Ownership ratings collected during Exp B revealed significantly higher ratings in MRHI condition compared to Vision-Proprioception incongruency (t(19)=3.208, p=0.027, d=0.7) and Vision-Proprioception incongruency_off (t(19)=3.8, p=0.006, d=0.9), while no significant difference was found with respect to Vision-Proprioception congruency (t(19)=0.720, p=0.999) (Figure 7). Additionally, participants gave significant higher ratings in Vision-Proprioception congruency condition with respect to Vision-Proprioception incongruency (t(19)=4.766, p<0.001, d=1.1) and Vision-Proprioception incongruency_off (t(19)=5.502, p<0.001, d=1.2). Finally Vision-Proprioception incongruency condition yielded ratings not significantly different from Vision-Proprioception incongruency_off (t(19)=1.633, p=0.714) (Figure 7B, left).

Concerning Agency ratings, Wilcoxon signed rank test revealed significantly higher ratings in MRHI condition compared to all other conditions (all W=210, p<0.001, r=1). No significant difference was found for Vision-Proprioception congruency condition ratings compared to Vision-Proprioception incongruency (W=128, p=0.402) and Vision-Proprioception incongruency_off (W=113, p=0.999). Finally, Vision-Proprioception incongruency condition yielded ratings not significantly different from Vision-Proprioception incongruency_off (W=56, p=0.726) (Figure 7B, right).

Correlational analysis revealed a significant positive correlation between IoM Synchronism and Ownership ratings (ρ=0.5; p<0.001) and a significant negative correlation between IoM Vividness and Agency ratings (ρ=-0.272; p=0.015). All other correlations were not significant (exact p-values are reported in Figure 8B).

PD and SCR data did not report any significant differences between conditions.

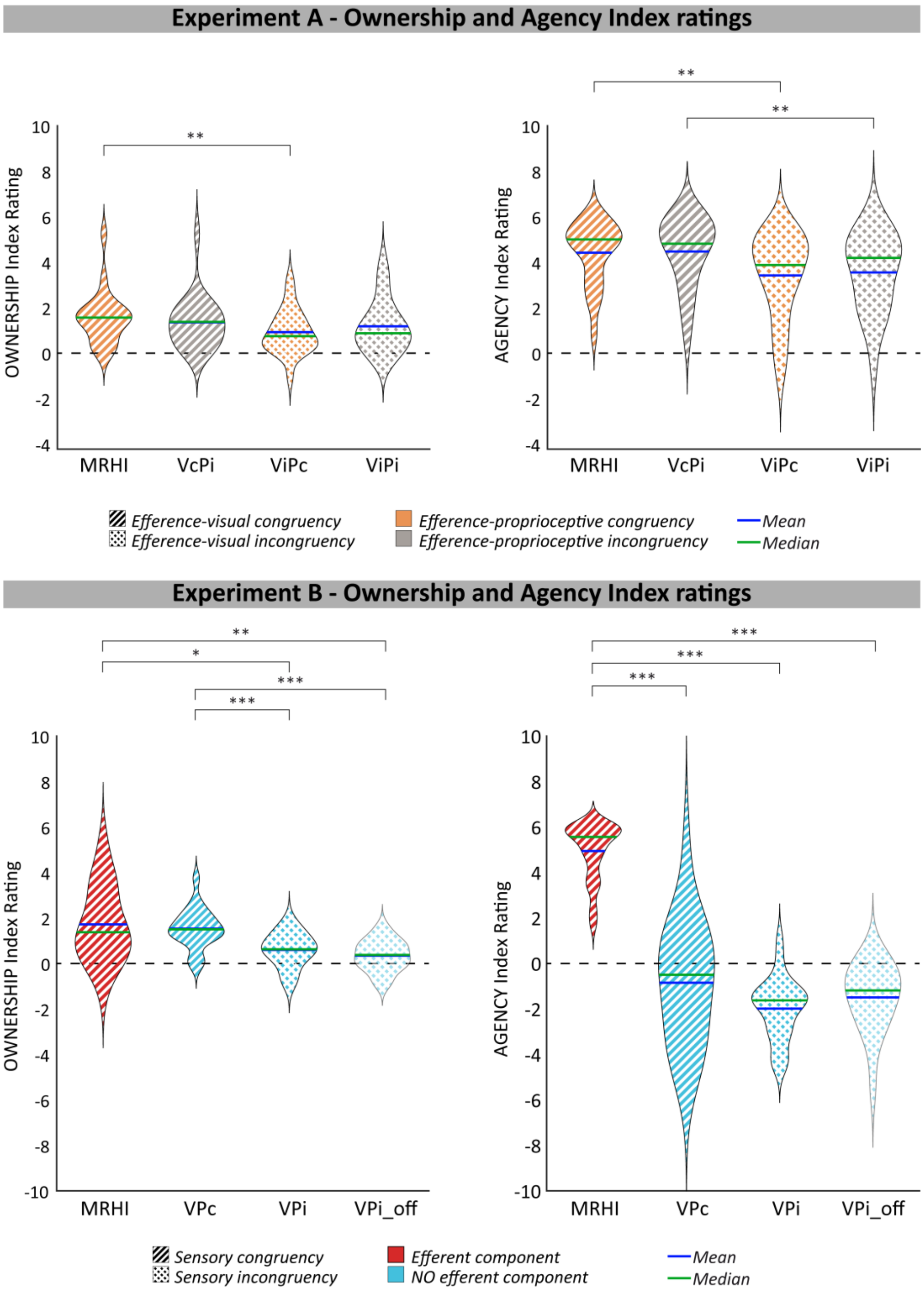


*Figure 7 – Violin plots showing Ownership Index (left) and Agency Index (right), for Experiment A (top) and Experiment B (bottom). **Experimental conditions for Exp A**: Moving Robotic Hand Illusion (MRHI), Vision congruent and Proprioception incongruent (VcPi), Vision incongruent and Proprioception congruent (ViPc) and Vision incongruent and Proprioception incongruent (ViPi). **Experimental conditions for Exp B**: Moving Robotic Hand Illusion (MRHI), Vision-Proprioception congruency (VPc), Vision-Proprioception incongruency (VPi) and Vision-Proprioception incongruency_off (VPi_off).*

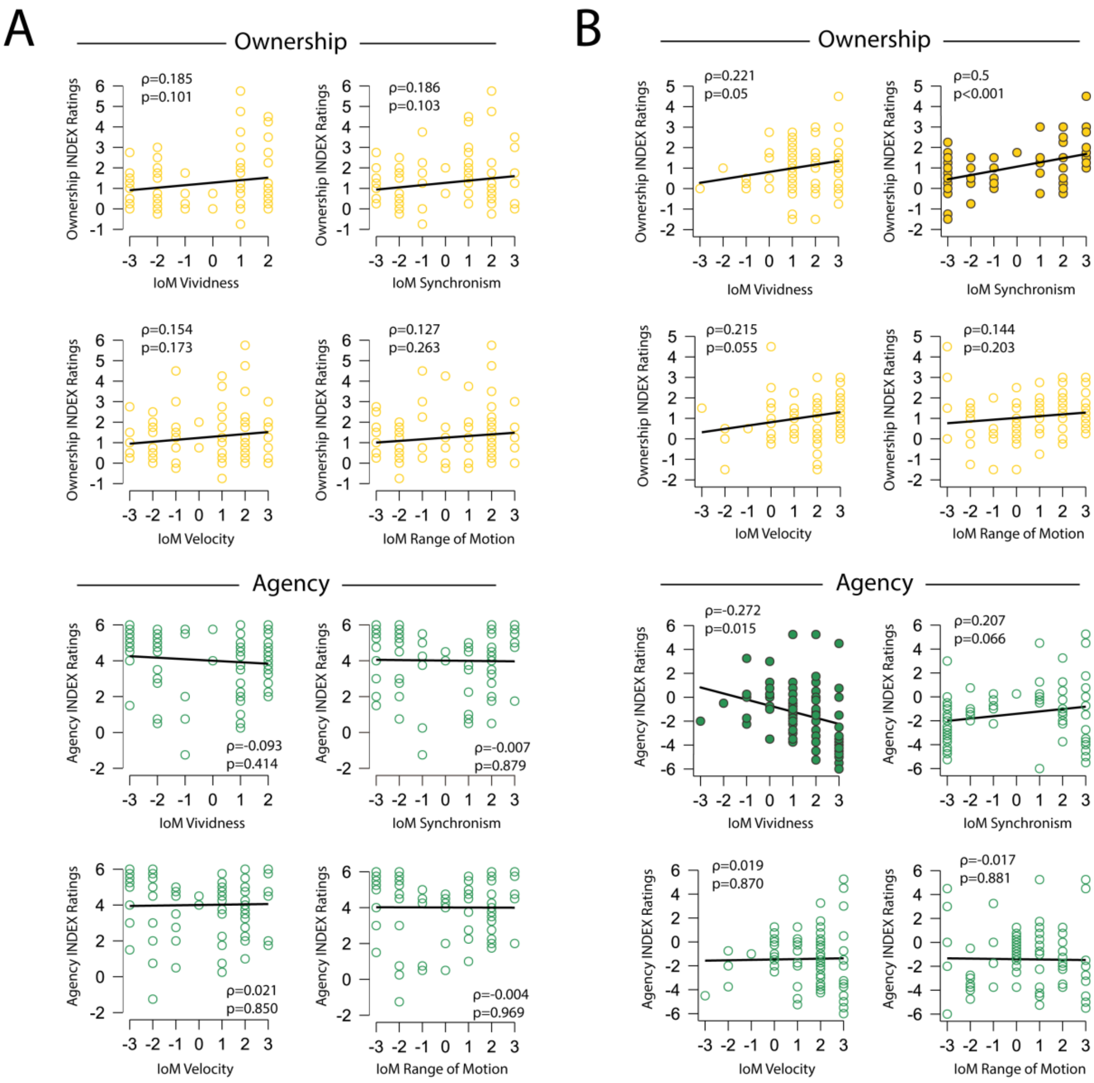


*Figure 8 - **Correlations** (Pearson's coefficient) between IoM assessment statements and Agency (green) or Ownership (yellow) Indexes ratings in Exp A (panel A) and Exp B (panel B). Plots with filled dots show significant correlations, while empty dots show non-significant ones.*

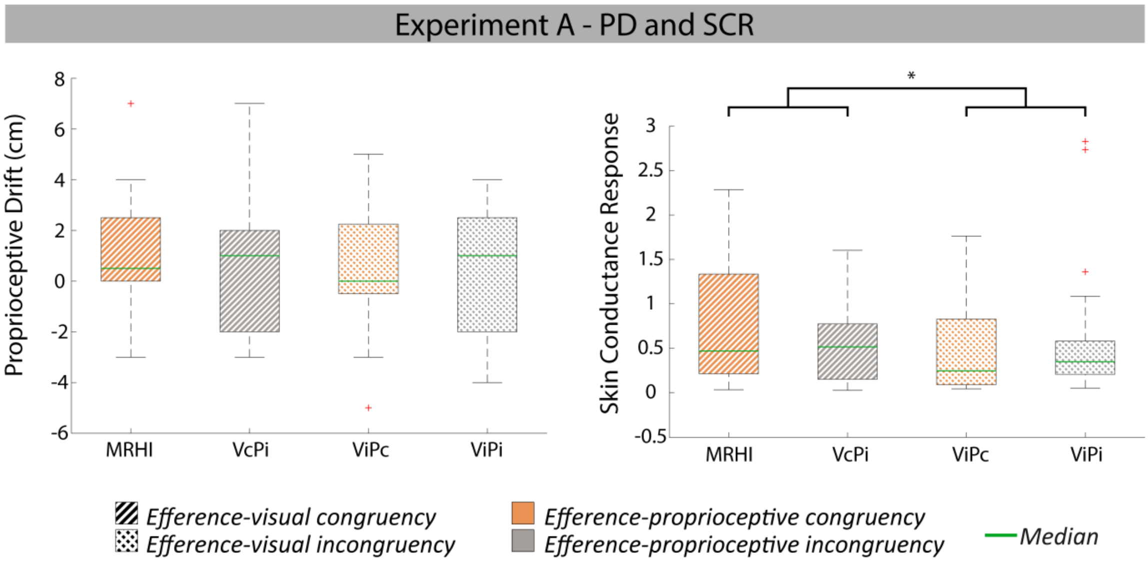


*Figure 9 - Box plots showing Proprioceptive Drift (left) and Skin Conductance Response (right), for Experiment A. Data from Experiment B are not shown as none of it yielded significant results.* ***Experimental conditions****: Moving Robotic Hand Illusion (MRHI), Vision congruent and Proprioception incongruent (VcPi), Vision incongruent and Proprioception congruent (ViPc) and Vision incongruent and Proprioception incongruent (ViPi).*

***Comparisons across experiments*****.** Mann-Whitney test revealed that Ownership Index ($W=197$, $p=0.946$) and Agency Index ($W=145$, $p=0.121$) ratings for MRHI condition were not significantly different across experiments.

Mann-Whitney test did not show any significant difference in ownership ratings for Vision incongruent Proprioception incongruent (Exp A) condition compared to Vision-Proprioception incongruency (ExpB) ($W=254$, $p=0.147$), whereas significantly higher agency ratings were found for Vision incongruent Proprioception incongruent (ExpA) condition compared to Vision-Proprioception incongruency (ExpB) ($W=398$, $p<0.001$, $r=0.9$).

Finally, Mann-Whitney test did not show any significant difference in ownership ratings for Vision incongruent Proprioception congruent (ExpA) compared to Vision-Proprioception congruency (ExpB) ($W=170$, $p=0.076$) nor for Vision congruent Proprioception incongruent (ExpA) compared to Vision-Proprioception congruency (ExpB) ($W=254$, $p=0.846$). Conversely, agency ratings in Vision incongruent Proprioception congruent (ExpA) ($W=356$, $r=0.8$) and Vision congruent Proprioception incongruent (ExpA) ($W=381$, $r=0.9$) were significantly higher compared to Vision-Proprioception congruency (ExpB) (all $p<0.001$). p-values were adjusted using Bonferroni correction (2 comparison) (Figure 10).

| | Three congruent streams | | Two congruent streams | | No congruent streams | |
|---|---|---|---|---|---|---|
| | Exp A | Exp B | Exp A | Exp B | Exp A | Exp B |
| **OWNERSHIP** | MRHI vs MRHI | | VcPi vs VPc | | ViPi vs VPi | |
| | | | ViPc vs VPc | | | |
| **AGENCY** | MRHI vs MRHI | | VcPi vs VPc | | ViPi vs VPi | |
| | | | ViPc vs VPc | | | |

*Figure 10 – **Comparisons across experiments**. Conditions from EXP A are compared against conditions from EXP B. Considered experimental conditions could present congruency among all available sources of information (MRHI), they could convey visuo-motor, proprioceptive-motor or visuo-proprioceptive congruent information (VcPi, ViPc, VPc respectively) or convey completely incongruent information (ViPi, VPi). The passage from EXP A (blue) to EXP B (orange) implied the loss of efferent component. Squares with red borders show significantly different comparisons.*

## 3.5 Discussions

In the embodiment of an artificial hand, the relative weights of i) the congruency between different streams of proprioceptive and visual sensory feedback, and ii) the congruency between them and motor commands, have been investigated employing a modified version of the Moving Hand Illusion. The aim of the study was to disentangle how vision, proprioception and motor command contribute to build the body schema of the hand performing a complex motor task. This has been done by combining the manipulation of the visual feedback, commonly exploited in the Rubber Hand Illusion, with a further modulation of the proprioceptive feedback, achieved through the Tendon Vibration Illusion (TVI). The experimental protocol led participants through a three-step loss of congruency between the streams of information involved in the sensorimotor loop, and despite not modelling the size of each step, this procedure allowed us to test the effect of the lost congruency on embodiment. In this novel systematic study, embodiment has been evaluated by assessing the specific impact on ownership and agency.

Congruency between sensory feedbacks (afferences) and the motor command (efference) has been investigated in the first experiment (Experiment A). In line with the presence of a significant main effect of the visuo-motor congruency, participants perceived a higher level of ownership over the robotic hand when the visual feedback was congruent with the sent motor command. Conversely, the absence of a main effect of proprioceptive-motor congruency seems to suggest that, when the motor command is present, the role of proprioception in modulating the feeling of ownership is not relevant.

Similarly to what happens with ownership, discrepancy between the executed and the observed movement led to a lower feeling of agency. Significant main effect of visuo-motor congruency and absence of a main effect of the proprioceptive-motor congruency depict a situation where visual feedback seems to drive *agency,* while proprioception has a negligible effect. The prevalence of visuomotor on proprioceptive-motor congruency, further confirmed by SC data, can be due to a higher impact of vision, which is known to override conflicting proprioception, i.e. visual capture (Pavani, Spence, and Driver 2000), or to a low efficacy of the technique adopted to alter proprioception.

During a movement, even though self-produced activations of the muscle receptors could interact with vibration, TVI has been reported to generate summative clear sensations, rather than just disturbing the natural proprioception (Cordo et al. 1995). Moreover, we limited the impact of inter-subject variability in perceived vividness intensity, velocity and range of motion (Naito et al. 1999; Bisio et al. 2019; Sittig, van der Gon, and Gielen 1985; Tidoni et al. 2014) by employing a within subject experimental design and by testing only optimal responders to the illusion (participants with pre-test clear and stable IoM).

A further explanation for the prevalence of visuomotor congruency can be found by looking at our experiment in a multisensory integration Bayesian framework (M.O. Ernst and Banks 2002; Fetsch, Deangelis, and Angelaki 2013; Knill and Pouget 2004; Van Atteveldt et al. 2014). A pre-determined weight is assigned to each sensory modality according to how relevant and trusted it is in relation to the task (Beers, Sittig, and Gon 1999). When the sensory information is felt, following a Kalman filter approach (Denève, Duhamel, and Pouget 2007), the weight is corrected depending on how much its signal is noisy. While we are familiar with altered visual stream, let's think for instance about looking at something in the mirror or in the dark, experiencing artificially altered proprioception is not common as well. We can hypothesize that, compared to vision, which seems to be computed in a more cognitively flexible manner (Pylyshyn 1999), proprioception is computed and exploited at lower and more rigid level, because this sense is more stuck to the body. Altered proprioception could have had a noisier signal, leading participants' brain to consider it not reliable. A further possible cause of reduced reliability of proprioception might be due to the movement of the hand, which through several mechanisms such as spinal gating (Press, Kok, and Yon 2020; Seki and Fetz 2012) may have attenuated the sensory signal. In parallel or alternatively with an enhanced weight of vision, a reduced weight of proprioception during Bayesian multisensory integration could justify the presented results.

Once assessed that inter-sensory congruency seems not to be crucial in the presence of the motor command, we addressed the question of what happens to embodiment if the participant's motor command is removed.

Indeed, in its absence the sole presence of visual and proprioceptive information sources could have determined a rebalance of the weight of the factors contributing to build the hand representation. To verify this hypothesis, in Experiment B, we manipulated the congruency between visual and proprioceptive feedback while participants laid their hand still, watched the robotic hand movements and received its corresponding proprioceptive feedback conveyed through TVI. Although participants did not do any actual movement (apart in the MRHI condition) we decided to measure not only the ownership but also the agency, for two main reasons: i) to effectively compare the same outcomes of the two experiments and ii) to replicate similar previous study (Kalckert and Ehrsson 2012) in which the agency was evaluated in active as well as in passive movements.

As long as participants received congruent sensory feedbacks, *ownership* did not decrease significantly, regardless if the movement of the observed robotic hand was self-generated (MRHI condition) or controlled by the computer (Vision-Proprioception congruency condition). Spatiotemporal congruency between senses completely makes up for the lack of the motor component, so that ownership index significantly and positively correlated with the rating that participants gave to the perceived IoM Synchronism. In general, synchronism is foundational for brain plasticity, e.g. spike-timing-dependent or Hebbian plasticity (Song, Miller, and Abbott 2000), and in particular, spatiotemporal congruency plays a key role in multisensory integration (Meredith and Stein 1986) and body schema formation, e.g. the Rubber Hand Illusion paradigm (Mioli et al. 2018; D'Alonzo and Cipriani 2012; Bassolino et al. 2018).

Differently to what happens with ownership, results showed a drop of *agency* ratings due to the absence of participants' motor commands, so that the only condition when participants actively controlled the robotic hand (MHRI) was significantly different to all others. In line with existing literature, those results suggest that the sense of agency can be perceived only when an active movement is present (Kalckert and Ehrsson 2012), and candidate the motor efference as agency prerequisite.

Unexpectedly, we did not find any significant change of the perceived position of the real hand. Proprioceptive drift was previously demonstrated in the Moving Hand Illusion (Shibuya, Unenaka, and Ohki 2018; Kalckert and Ehrsson 2012; Romano et al. 2015; Sato et al. 2018). However, the robotic hand employed in our experiments did not wear any aesthetic glove and we assessed the drift at the end of each session when participants already stopped moving their own hand. It may be possible that the absence of drift measured when the efferent component ceased to be could have been due to a weak visual embodiment of the robotic hand.

The comprehensive overview of both experiments suggests that ownership and agency may be independently processed by the human brain and the presence or absence of the efferent component can modulate the salience of visual/proprioceptive integration.

To confirm and highlight these results, we performed a comparison between conditions from the two experiments having the same number of congruent streams of information. The two experiments can be compared because no significant difference was found between ownership and agency indexes of their common condition (MRHI). Agency showed a major drop in Experiment B: ratings were always significantly lower than Experiment A. Conversely, two congruent streams of information, regardless of how the pair is made up, are enough to let ownership survive the removal of motor command (Vision-Proprioception congruency ownership rating is not significantly lower than both Vision congruent Proprioception incongruent and Vision incongruent Proprioception congruent conditions).



Mttia Pinardi

## 3.6 Conclusion

Every day, while we interact with the environment, different sensory modalities provide complementary and overlapping information, which our brain integrates to produce the most likely estimation of what is happening, and of the current status of the body. Day after day, the multisensory nature of perception carves our body representation through a lifetime of experience (Blanke 2012; Tsakiris 2017).

Embodiment is a multifaced concept that requires complex estimations and deals with a settled knowledge. Agency can be perceived only when efferent component is present, while ownership can arise also in its absence, but a single source of information experienced in a limited span of time is not enough; either visuo-motor congruency or inter-sensory congruency are needed.

Interestingly, our results suggest a further speculation. It is known that our brain uses a copy of the motor command, known as efference copy, to predict the sensory consequence of the action we are going to execute (D. Wolpert, Ghahramani, and Jordan 1995; Shadmehr and Krakauer 2008). We strongly suggest that the second source of information needed to "double check" if a limb, or of a robotic hand, is part of our body can be gathered either from senses or from the prediction generated from the efference copy, which is treated as an additional sensory modality also in the construction of embodiment.

# Chapter 4

# Internal Models for Motor Control and Sensorimotor Loop

## 4.1 Introduction

The role of afferent and efferent information in influencing the body schema and thus the embodiment of a robotic hand, has been discussed so far. In paragraph 2.3.2 it was mentioned how the body schema is intimately linked to motor control and to the theory of Internal Models. Given how strictly motor control, internal models and sensorimotor loop are related, and their importance in determining embodiment, it is now useful to delve into the role of the body schema in this scenario. Internal models are hypothetical flowcharts that our brain uses to plan motor commands, to predict the sensory consequences of movements and to adjust and fine-tune commands in order to interact efficiently with the environment, accounting for any possible perturbation (D. Wolpert, Ghahramani, and Jordan 1995). There are mainly two different types of internal model: *Inverse model* and *Direct model* (also known as forward model) (D. M. Wolpert, Ghahramani, and Flanagan 2001)(Figure 11). Both models rely on the body schema for their correct functioning.

The *Inverse model* is responsible for planning motor commands required to reach a certain body state, e.g. desired position, taking into account the system that will need to process the motor command, i.e. our body. Hence, information represented in the body schema, like the size of limbs, joint angles and the current position of effectors are fundamental for a correct planning of movement kinematics. As an example, our sensorimotor system will implement a feedforward control policy to predict and plan the required arm kinematics for a ballistic movement, e.g. a ball throw, and to do this it shall take into account the length of each arm segment, their position in space before initiating the movement and so on.

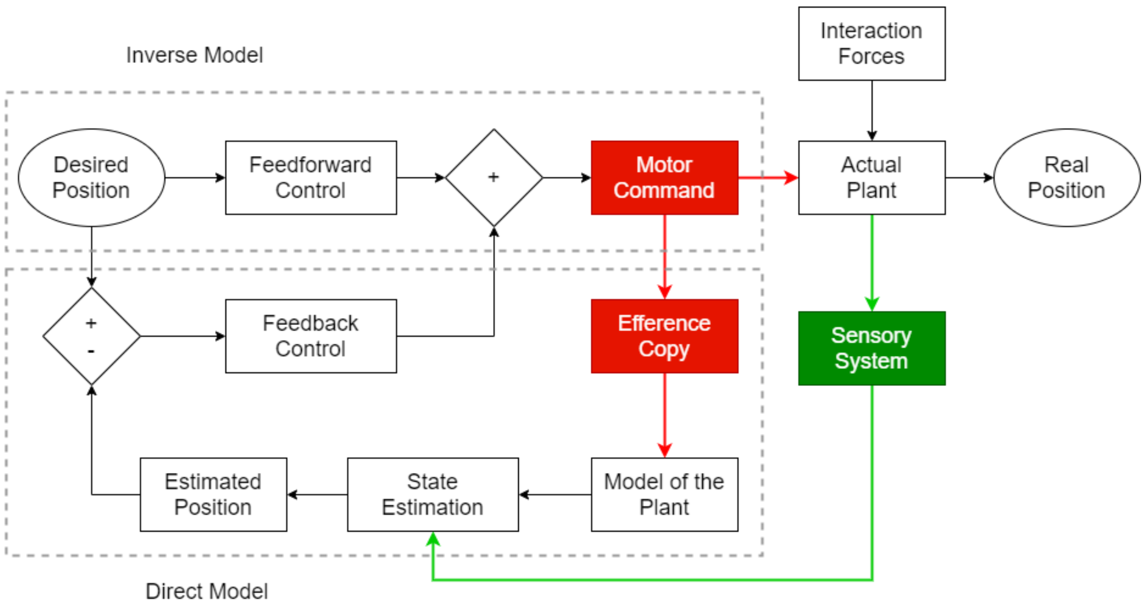


*Figure 11 – **Representation of Inverse and Direct models**. Red elements refer to the motor (efferent) component, while green elements refer to the sensory (afferent) component. Elements included in the dotted lines are the main components of Inverse and Direct models, as specified in figure.*

The *Direct model* can roughly be seen as the opposite of the Inverse model. In this case, the starting point is the motor command, or to be more precise the efference copy. The efference copy is a carbon copy of the motor command which is not used to produce a real movement, but it is used instead as the source of information to predict the sensory consequences of our movement (Shadmehr and Krakauer 2008). To predict the sensory consequences of a movement implies generating a prediction about the new body schema as well. In Figure 11, the predicted body schema can be identified with the State Estimation block. This version of the body schema shall be integrated with the actual body schema as testified by the sensory system. This process will allow to estimate the position and configuration of our body, which will be compared against the desired position and, if any conflict or mismatch arises, the feedback control policy will adjust the motor command to reduce the difference between actual and desired position as much as possible (de Vignemont 2010).

The role of efference copy as an additional sensory afference used to doublecheck if a body part belongs to us, as highlighted in chapter 3, can be easily framed in the Internal Models theory as discussed above, and fits well with the role played by the body schema. Before delving into the concept of human augmentation and the insertion of supernumerary robotic limb in the somatosensory loop, it is important to carefully consider the possible double role of sensory afference. Indeed, just like the efferent component, whose primary role is to promote body movement, can be used also to provide sensory information, it is possible that the afferent component, which carries sensory feedbacks, contributes to alter motor command in a specific and task-related way. To test this hypothesis, an experiment on motor control during object lifting was run.

Motor control is often studied by considering at least two different level of information processing. On a higher, more cognitive level, the creation of a motor command to interact with an object in the environment, for example lifting a weight, is first influenced by the feedback that we receive from the object itself before any interaction (e.g. visual feedback of size, shape, material etc.). Successively, an efferent signal is planned accordingly, conveying information regarding the kinematic or dynamic approach required for an optimal interaction with the object. When finally grasping and lifting the weight, the sensory afference fed back to the control policy system, as shown in Figure 12, is compared with the expected sensory consequences of the executed action. If necessary, corrections of movement kinematics will be implemented to reduce the discrepancy between prediction and actual sensory feedback (Figure 12) (Shadmehr, Smith, and Krakauer 2010; Shadmehr and Krakauer 2008; D. Wolpert, Ghahramani, and Jordan 1995). A clearer role of the sensory afference carrying information regarding the arm kinematics can be better understood if we shift the focus on a lower, sensorimotor level of information processing. This kind of sensory feedback is mainly

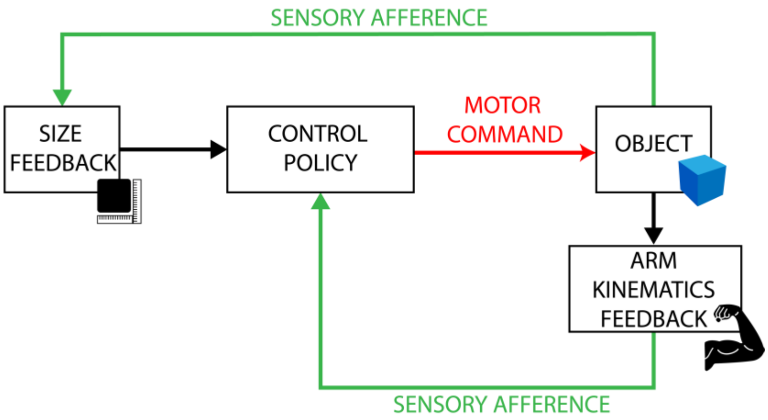


*Figure 12 - Theoretical model of high-level motor control during object lifting.*

composed of proprioceptive information. Proprioception is the ability to sense the position and forces of one's own body (Tuthill and Azim 2018), and one of the main sources of information regarding our movements in space and interaction with objects (U. Proske and Gandevia 2012). The multifaceted nature of proprioception is revealed by the variety of sensory receptors which convey proprioceptive feedback: muscle spindles, Golgi tendon organs and, to a certain extent, cutaneous mechanoreceptors as well. Muscle spindles are particularly interesting in relation to the topic discussed in the present paper. Located along other muscle fibers, thanks to its sensory fibers Ia an II, muscle spindle can communicate variations of muscle fibers length and the velocity of these variations. Muscle stretch, which is one of the components of proprioception, activates fibers Ia (Figure 13) (U. Proske and Gandevia 2012; Uwe Proske 2015). It is used both to modulate alpha motor neuron responsible of muscle activity and to send proprioceptive information to a higher-level processing for the motor control previously described. Motor control models discussed so far highlight the weight of proprioceptive information flowing from a low to a high-level processing in determining movement kinematics. Given this assumption, we investigate the possibility of inducing motor adjustment during object lifting by artificially manipulating the proprioceptive feedback conveyed through Ia sensory fibers.

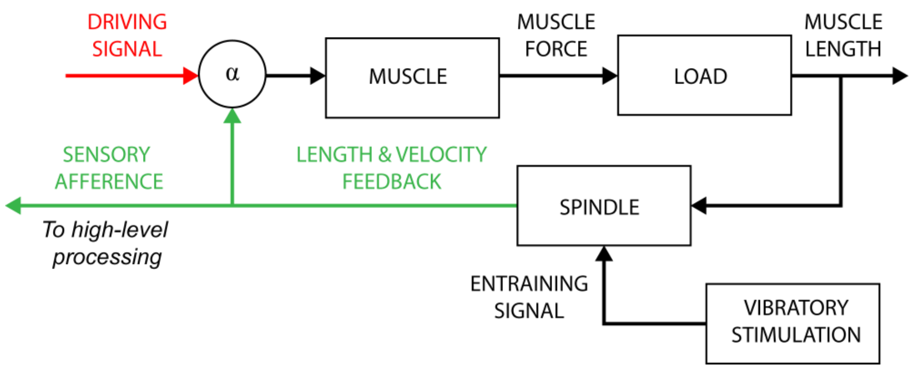


*Figure 13 - Theoretical model of low-level muscle control during object lifting.*

To this end, we employed the Tendon Vibration Illusion (TVI) (Goodwin, McCloskey, and Matthews 1972), introduced in Chapter 3.1. TVI, first described in 1972, is still one of the most powerful tools to manipulate proprioception. It consists in delivering a vibratory stimulation above a muscle tendon to evoke an illusion of movement (IoM). Indeed, Ia fibers have been shown to optimally respond to a certain range of vibration frequency, i.e. 60-80 Hz, above which their activity becomes a sub-harmonic of the vibratory stimulation frequency, decreasing the efficacy of the stimulation itself (Roll and Vedel 1982). Elicited discharge of spindle fibers generates an IoM of flexion if an extensor muscle is stimulated and vice versa (Figure 14). TVI can be used to provide the movement sensation for a completely relaxed limb (Roll and Vedel 1982; Ferrari, Clemente, and Cipriani 2019), to alter the perceived position of a limb during muscle contraction (Capaday and Cooke 1983) and to influence the perceived speed of a moving limb (Cordo et al. 1995).

Despite using the same technique exploited in the experiment discussed in Chapter 3, there is a noteworthy difference. While in the previous experiment we evoked a flexion IoM which was delayed with respect to the real flexion movement of the participants' fingers, i.e. an incongruent illusion, in the present study we evoked a flexion IoM of the forearm during the lifting of a weight, executed by flexing the forearm. We expected this IoM to interact with the natural sensation of a flexion created by the lifting movement (Cordo et al. 1995). Therefore, while receiving vibrotactile stimulation, participants should have perceived the lifting movement as faster than expected. The result of the proprioceptive illusion was still a discrepancy between the planned motor command and the sensory feedback related to it (i.e. faster than expected movement), but in this case it stemmed from an additive interaction between real movement sensation and proprioceptive feedback and not from a conflict between them, as it did in experiments from Chapter 3.

We hypothesized that, upon receiving a faster than expected movement feedback, a discrepancy between expected and perceived arm kinematics would emerge and the brain would adjust the lifting by slow down movement to minimize this error. Additionally, to further assess the validity of the hypothesis, we tested it during the interaction with two differently sized objects. Despite having same weight, similarly looking objects with different size are approached and lifted differently from a movement kinematics point of view, especially regarding grip and load force (Flanagan and Beltzner 2000; Buckingham, Michelakakis, and Cole 2016). This creates two different weight lifting scenarios in which movements, albeit being similar, differ in at least one parameter (force).

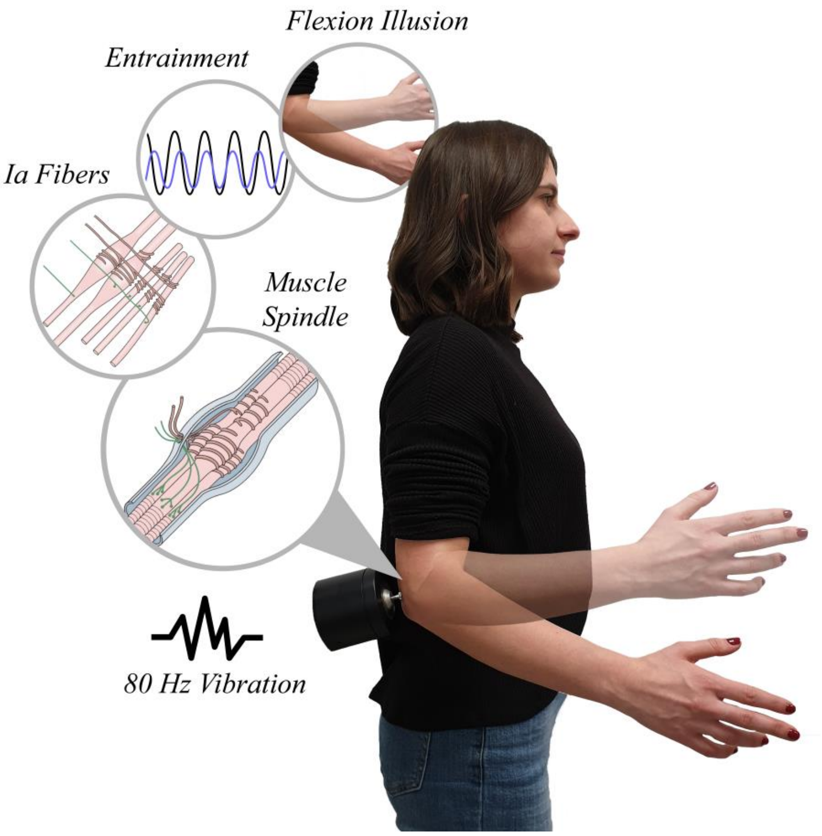


*Figure 14 – **Schematic representation of TVI mechanism**. 80 Hz vibration applied on the distal tendon of the triceps muscle stimulates the muscle spindle. Ia fibers' activity is modulated by the vibration through frequency entrainment. The sensory feedback sent back to the brain mimics the stretching of the extensor muscle, tricking the brain into thinking that the forearm is flexing (illusion of flexion).*

## 4.2 Methods

12 naive participants (7 men; right handed; age 21-25 years old) took part in the study. All participants were healthy and claimed to have normal vision and proprioceptive sensations. All participants provided written informed consent in accordance with the declaration of Helsinki and following amendments and with the Ethical Committee of the Campus Bio-Medico University.

### 4.2.1 Apparatus

Two objects with equal weight (200g) but different size (small: 9x9x3 cm; large: 9x9x9 cm) and similar texture appearance were employed. A plastic handle was attached to the superior face of each object so that participants could interact with them without inferring information about size through hand grasping configuration. A gyroscope and an accelerometer embedded into a magneto-inertial measurement unit (M-IMU, LSM9DS1, by STMicroelectronics Inc., gyroscope full scale: ±245 dps, accelerometer fullscale: ±2g) were positioned on the objects to measure angular velocity and acceleration during lifting and connected to a STM32F446 Nucleo Board (by STMicroelectronics Inc.) through $I^2C$. The reference frame of both the gyroscope and the accelerometer are reported in Figure 15C. Data from gyroscope and accelerometer were recorded through a custom developed software (sampling rate: 250 Hz) on a laptop, connected to the board via serial communication. In order to stimulate the muscle tendon with an 80Hz vibration and generate a flexion IoM, we employed a 24mm eccentric Vibrator Motor (13mm type by Precision Microdrive model No. 324-102), placed on the distal tendon of the dominant side triceps muscle (Figure 15A).

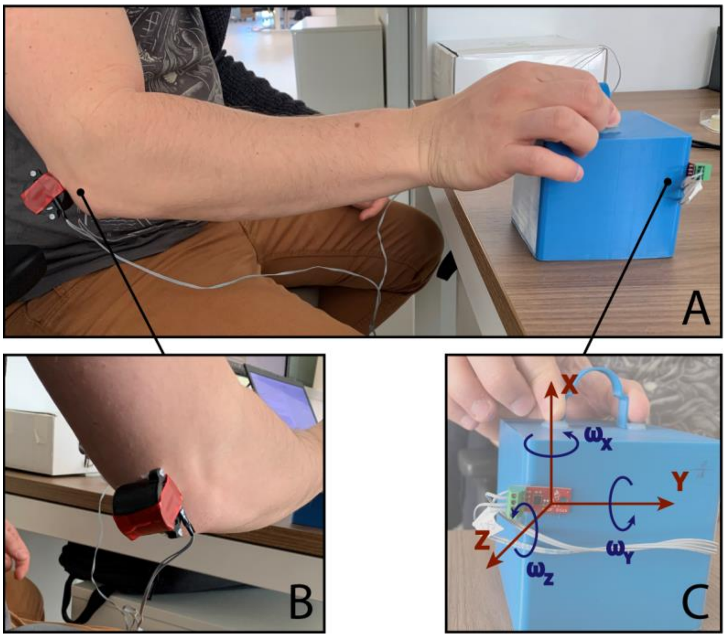


*Figure 15 - **Experimental setup**. **Panel A**: Participant's arm in resting position. Lifting movement begins when acoustic signal is played and continues for approximately 2 seconds. During lifting, participants were instructed to only move the forearm and keep the rest of the arm as still as possible; **Panel B**: the vibrator motor was placed on the distal tendon of the triceps muscle. The vibratory stimulation was delivered for 2 seconds, starting with acoustic signal, and for the entire duration of the lifting movement, in SA and LA conditions; **Panel C**: Reference frame for gyroscope and accelerometer.*

### 4.2.2 Pre-Test

Participants underwent a pre-test in which the experimenter placed the vibrator motor, adjusting its position to reach a stable and clearly perceived IoM of forearm flexion (Figure 15, Panel B) without inducing any involuntary movement. Once the vibrators position was set, consecutive short vibrotactile stimulations were delivered, to allow participants to familiarize with the IoM. Immediately after the stimulation, participants were asked to answer a questionnaire with the following purposes: i) check if the IoM was clear and consistent with the expected movement sensation (Q1: During the vibrotactile stimulation I perceived an extension movement, Q2: During the vibrotactile stimulation I perceived a flexion movement); ii) quantify the vividness of the IoM (Q3: The perceived movement is clear/vivid as the natural movement of my forearm); iii) assess the presence of any aftereffect (Q4: At the end of the vibration, I feel as if my forearm was moving in the opposite direction, coming back to the starting position).

Participants had to answer by using a 7-point Likert scale where -3 meant ‘‘strongly disagree’’, 0 meant ‘‘neither agree or disagree’’, and +3 meant ‘‘strongly agree’’. Three participants were excluded from the experiment because they provided a rating below -2 for the question Q3 or they reported a movement sensation inconsistent with the expected one. The number of participants that took part to the following phase was 9.

### 4.2.3 Experimental Protocol

Participants sat comfortably on a chair in front of a table, and they were shown the two objects, in order to have full visual information regarding their size. The dominant elbow was bent at approximately 90 deg and the hand was positioned close to the object handle (resting position) (Figure 15A). After participants visually acknowledged the objects size, an acoustic signal triggered the beginning of the trial. Participants had to lift one of the two objects by grasping the handle with thumb and index finger of the dominant hand, trying to move only the forearm while keeping the rest of the arm as still as possible. The lifting movement lasted 2 seconds, after which a second acoustic signal marked the end of the trial and the experimenter removed the object from the participants' hand and placed it back on the table. After that, participants could return to the resting position. The experiment consisted of 4 conditions: Small Natural (SN), Large Natural (LN), Small Altered (SA) and Large Altered (LA). In SN and LN condition participants had to lift the small or the large object, respectively. Conversely, SA and LA condition mirrored the previous two conditions, with the addition of the vibrotactile stimulation administered through the vibrator motor for the entire duration of the lifting phase (2 seconds). Before running the experiment, participants performed a brief training in order to familiarize with the task, using an object that was not included in the experimental protocol.

## 4.3 Data Analysis

For each lifting phase, we considered the x axis of the accelerometer, because it was in the same direction of the lifting movement and therefore the most informative one. Moreover, we considered the norm of the angular velocity vector recorded at each sample. Additionally, we removed the first 100ms of recording for every trial in order to remove the offset. As an example, we report data of a representative subject in Figure 16. Acceleration and angular velocity values are shown over time during the whole duration of two lifting trials, one for each experimental condition. Furthermore, we summarized accelerometer and angular velocity by computing their *Root Mean Square* ($\omega_{RMS}$ and $a_{RMS}$ respectively). Acceleration data were not normally distributed (Shapiro-Wilk $p<0.05$), hence a Durbin test was used considering as factors the *Size* (small, large) and the *Proprioception* (natural, altered). Conversely, angular velocity data were normally distributed (Shapiro-Wilk $p>0{,}05$), hence two-way repeated measure ANOVA was run considering as factors the *Size* (small, large) and the *Proprioception* (natural, altered).

## 4.4 Results

***Acceleration***. Durbin test revealed a significant effect of both *Proprioception* ($F(3)=3.062$, $p=0.045$) and *Size* ($F(3)=5.123$, $p=0.006$) (Figure 17, Left).

***Angular Velocity***. Two-way rmANOVA revealed a significant effect for *Size* ($F(1,8)=19.586$, $p=0.002$), whereas not effect for *Proprioception* ($F(1,8)=0.938$, $p=0.360$) or for the interaction between the two factors ($F(1,8)=0.006$, $p=0.939$) (Figure 17, Right).

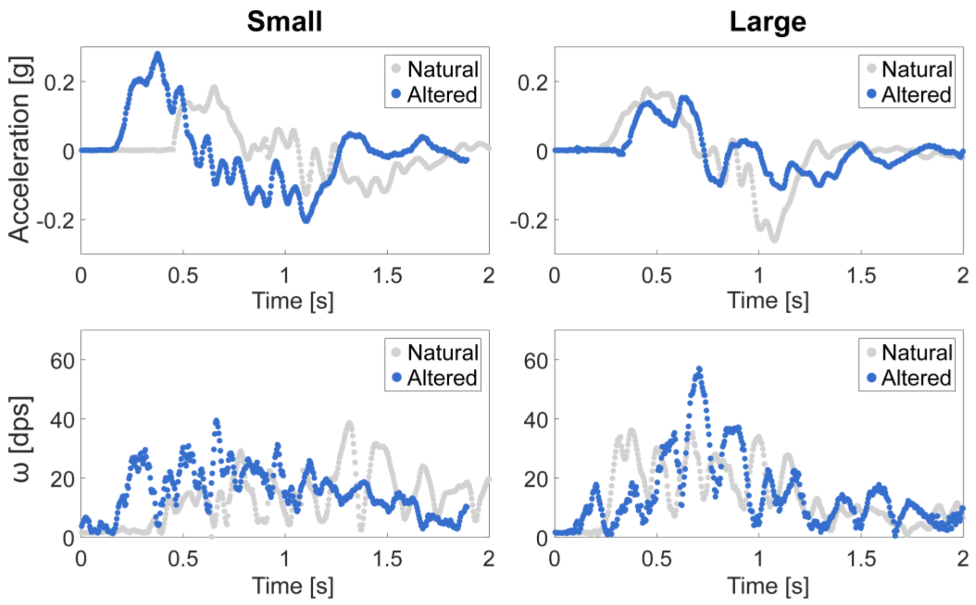


*Figure 16 - Values of Acceleration and Angular velocity over time while the subject was receiving the vibratory stimulation (blue dots) or during normal lifting condition (grey dots).*

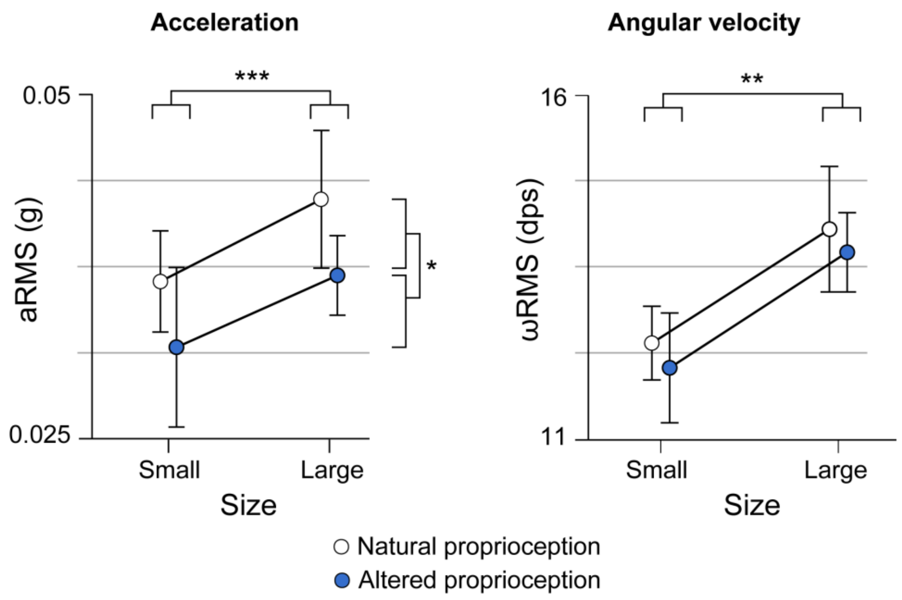


*Figure 17 - Average of Acceleration (Left) and Angular velocity (Right) for all participants across conditions. Significant effect of size is present in both dataset (**=p<0.01). Significant effect of proprioception is present in acceleration data (*=p<0.05). The large object was always lifted with higher acceleration and angular velocity, independently from modulation of proprioception. Additionally, both small and large object were lifted with lower acceleration when proprioceptive feedback was altered through TVI.*

## 4.5 Discussion and Conclusion

The goal of the present work was to investigate the possibility of inducing alterations in movement kinematics by artificially modulate proprioceptive feedback during lifting of weights. Data obtained show that participants lifted both small and large objects with a lower acceleration when proprioceptive feedback was altered through TVI compared to control condition (i.e. lifting without any vibratory stimulation). This result suggests a modulation of lifting kinematics, specifically acceleration, when the movement was perceived as faster than expected, thus confirming our starting hypothesis. Furthermore, the larger weight was always lifted with both higher acceleration and angular velocity compared to the smaller one. This additional results, in line with actual knowledge on kinematic approach to different sized objects (Grandy and Westwood 2006; Buckingham 2014), is interesting as it shows that TVI successfully modulated at least one kinematic parameter (acceleration) despite the differences in lifting movements, generated by different objects. The lack of a significant effect of proprioception in angular velocity data can be easily explained if considering that variables taken into account are the RMS values evaluated for the whole duration of the task. Indeed, since the subjects were instructed to execute the task between the two trigger sounds, it is reasonable that the overall lifting velocity did not change between different proprioceptive conditions. Conversely, since acceleration describes how the velocity changes over time, variations in instantaneous velocity should influence the value of the overall acceleration, as it does.

# Chapter 5

# Human Augmentation

## 5.1 Introduction

The research discussed so far paved the way for discussing human augmentation, and how it could greatly benefit from a closed sensorimotor loop, in which the user can seamlessly exchange information with the technology he is interacting with. The concept of human augmentation refers to the use of methodologies, tools and devices originally designed to compensate the loss of function, to improve the abilities of healthy individual beyond the limitations typical of the human being (Di Pino, Maravita, et al. 2014). This relatively new, fascinating concept has immediately captured the interest of the broad audience, as testified by how it permeates cinema, sci-fi literature and gaming industry. Augmented human with bionic arms, artificial eyes for enhanced vision and cybernetic brain implants for superior intellect are the leitmotiv of modern science fiction. A whole literary genre, born in the early eighties, and named "Cyberpunk" revolves around the idea of human augmentation. In the same years, this concept was also explored by the artist Stelarc, which controlled an additional body-worn robotic hand in his work "Third Hand". The attention this topic received from a broader audience resonated within the scientific community, and in recent years it captured the attention of researchers as well. Indeed, the potential of human augmentation is huge and the advantage it could give to users, or augmented humans, is now more concrete than ever. Robotic devices have recently been used not only for replacing lost limbs or overcoming disabilities, but also for enhancing physical performances (Leigh, Agrawal, and Maes 2018; Di Pino, Maravita, et al. 2014). Despite how sci-fi it might sound, the combined effort of the scientific community to reach a proper human augmentation should not be surprising. Indeed, the strive for improvement is typical of the human being. Since the discovery of fire, human being have always searched for a way to improve their interaction with the world, their proficiency in everyday task and, ultimately, their chance of survival (Ambrose 2001). The biggest differences with today's improvement, i.e. human augmentation, lies in the goal: once it was mere survival, while now it is to go beyond the limits imposed by nature. However, it can be considered natural for the goal to evolve along with the means to reach it.

## 5.2 Embodiment of Supernumerary Robotic Limbs

An important role in human augmentation is played by Supernumerary Robotic Limbs (SRLs), to the point of becoming a new research area in the field of human robotics. SRLs are additional robotic limbs, ideally wearable, which are employed by the user, together with his or her natural limb, to reach a higher level of performance. Augmentation through SRLs is considered appealing for a wide range of applications, e.g. from handling hazardous materials to health care applications or even to improve multitasking capabilities. For this reasons, several SRL prototypes exist nowadays, and they are mainly designed to help users in manual works, supporting the human body and minimizing the human load (Veronneau et al. 2019; Parietti, Chan, and Asada 2014), thus allowing to perform tasks safely and stably while the robotic system sustains the user's body by leaning against walls and surrounding structures (Parietti and Asada 2016). These wearable systems are ultimately employed as extremely advanced task-oriented tools, and just like it happened with tools, a debated aspect of SRLs systems is their integration into the body schema. Indeed, in the latest years a new scientific question arose: can an artificial limb be considered as something more than a mere tool? Can it become, somehow, part of our body? The reason behind this intriguing question is the demonstration that integrating non-corporeal objects into the existing body schema increases the intuitiveness in their control (Manoharan and Park 2019). Some researcher went even further, discussing the possibility that the proficiency in the use of a tool, or maybe even an SRL, may emerge from the integration of that specific tool into the body schema (Arbib et al. 2009; Farnè, Serino, and Làdavas 2007; Cardinali et al. 2012). Being the SRL a sophisticated tool, it is interesting to understand how a tool becomes embodied, i.e. integrated into the body schema.

At first there was a wide, initial agreement on the fact that active tool-use was necessary for its integration into the body schema. The integration in the body representation was testified by several results. For example, the Peripersonal Space (PPS) was proven to be extended after repeated tool use (Farnè, Serino, and Làdavas 2007; Neppi-Mòdona et al. 2007). PPS is the space immediately surrounding our body and is considered an important region of multisensory integration (somatosensory, visual and auditory information) where the majority of meaningful interactions with the environment happens (Rizzolatti et al. 1997; Martel et al. 2016). Actively using a tool to explore the far space made that space become near, by extending the PPS to incorporate the tool, as tested through cross-modal extinction, for example (Farnè, Iriki, and Làdavas 2005). It seemed, at first, that a tool had to a give a functional advantage to the body part interacting with it to be integrated into the body schema. Additionally, active tool used provoked a skin conductance response when a needle touched the tool, similarly to what happened if the needle approached the subject's real hand (Rossetti et al. 2015). This effect, coherently with the same effect on the Rubber Hand Illusion paradigm, can be considered a proof of tool embodiment. Finally, extended tool use (i.e. a mechanical grabber used to interact with distant objects) promoted a modification of free-hand movement kinematics as if the subject's arm was longer. Indeed, participants took longer to reach velocity and deceleration peaks, during free-hand reaching movement after tool use, and the amplitude of both peaks was smaller as well (Cardinali et al. 2009). However, a fascinating twist happened when researchers discovered that some of these effects were present even with a passive functional experience with the tool, and managed to modify PPS by using a computational model able to recreate the conditions of tool-use PPS remapping by employing a multisensory integration training (Serino et al. 2015).

Far from being completely solved, this question suggests that the tool use itself is not directly responsible for plastic modifications of the body schema. On the other hand, the optimal integration of multisensory inputs coming from the interaction with the tool, be it passive or active, seem a much more plausible cause for body schema modifications, i.e. embodiment. In the framework of SRL embodiment, this observation underlines the important of considering the SRL when studying the sensorimotor loop. Indeed, the integration of SRL into the body schema might benefit greatly from its insertion in the closed loop, creating a new human-machine hybrid where both actors (human and robot) are able to exchange afferent and efferent information seamlessly. However, despite this interesting food for thought, little effort has been put into research and implementation of a closed loop for the SRL, and research has mainly focused on other factors favouring SRL embodiment, such as emulating human's arm shape and dynamics (Llorens-Bonilla, Parietti, and Asada 2012).

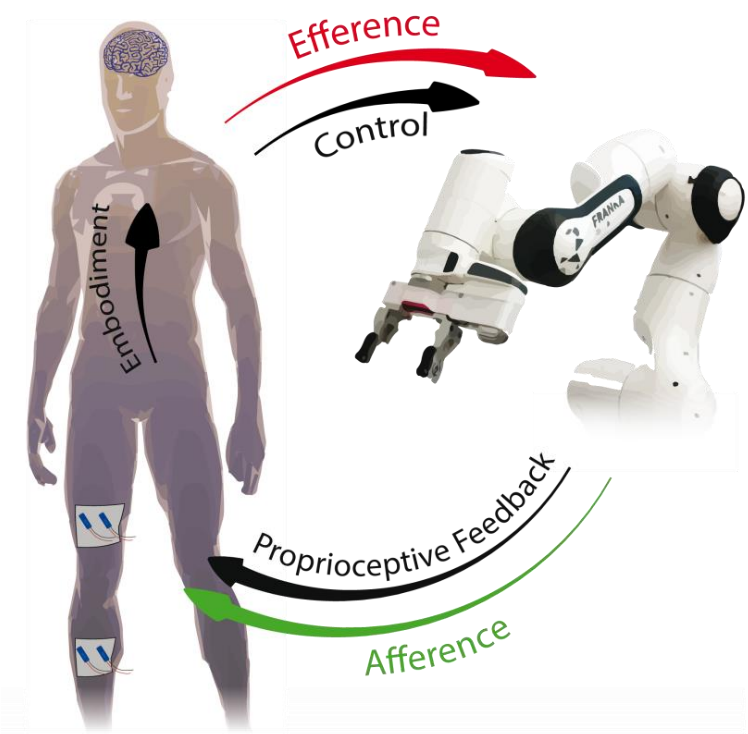


*Figure 18 - **SRL loop scheme**: the robot control represents the efferent component (red); the proprioceptive feedback represents the afferent component (green) required to close the loop. Vibrotactile stimulation can be used to provide sensory feedback through vibrators placed on the human skin. The sensory feedback also improves the SRL integration into the body schema (i.e. embodiment).*

Establishing a bi-directional communication through the addition of a sensory feedback could allow to close the loop and achieve a better human-robot interaction (see Figure 18). Some studies investigated the role of the sensory feedback in improving the control of external tools, demonstrating an increase in accuracy during reaching and stabilization task. Moreover, sensory feedback, in particular supplementary vibrotactile stimulation, has been studied as an alternative to visual feedback. Indeed, our body's movements do not need to be constantly monitored through visual attention, and we obtain the necessary information from proprioception (U. Proske and Gandevia 2012). Visual control might be necessary for extremely precise and dexterous movement, but generally speaking, proprioception alone is enough to inform us about the configuration and movement of our own body. As an additional benefit, the contribution of proprioception eases the cognitive burden that a constant visual monitoring would imply. Additionally, vibrotactile stimulation represents a non-invasive, low cost and easily implemented solution (Dennerlein, Millman, and Howe 1997). Hence, scientific literature about sensory feedback has demonstrate that, in the absence of visual feedback, supplemental vibrotactile stimulation induced improvement of motor learning compared to normal proprioception (Risi et al. 2019; Krueger et al. 2017; Cuppone et al. 2016).

However, to favor the adaptation of the body schema, embodiment and consequently the robot control, it might be relevant to convey to the user also the position of the robot in the space. The human brain estimates the position of the body through both visual and proprioceptive information. The latter becomes especially important in the forward/backward direction where the estimate relies more on proprioception than on vision (Beers, Wolpert, and Haggard 2002). As anticipated before, rich proprioceptive feedback may also relieve the user from focusing his gaze continuously on the robot. To investigate how sensory feedback, relying proprioceptive information through sensory substitution, can help closing the loop between human and robot, the proposed system was developed and validated, with the aim of informing the user about the posture of a supernumerary robotic arm. Proprioceptive feedback was provided through a custom vibrotactile stimulation device, hereafter called ViPro.

## 5.3 Methods

### 5.3.1 System Design

To control up to eight pairs of eccentric motors (Model: 307-103 by Precision Microdrives Inc.), a Printed Circuit Board was designed. The board drived the stimulation on the basis of the sensory data read in real time by the robot. In the present work, only two pairs of vibrators were used. Each couple of vibrators referred to a single dof and, within the couple, one vibrator was used to represent positive encoded values and the other one to convey negative values. The logical schematic of the ViPro board is presented in Figure 19. The frequency and the vibration intensity of the stimulators were coupled, and they were controlled by the embedded micrcontroller (STM32F446 by STMicroelectronics Inc.), which generated a Pulse Width Modulation (PWM) signal in order to define the supply voltage of the vibrators according to the following relationship:

$$V_i(t) = \frac{\delta_i(t)}{T} V_A \qquad 1$$

Denoting $T$ as the period of the PWM signal and equal to 1 ms, while $V_A$ as the maximal supply voltage of the vibrators and equal to 3.6 V; the parameter $\delta_i(t)$ as the duty cycle of the vibrators control signal (computed for each $i$ dof considered), proportional to the specific information provided to the user; the $\delta$ range of variation depended on the type of feedback implemented. Thus, to summarize, the amplitude of the stimulator was proportional to the robot state information to be provided. Since the robot represented an additional arm to be used in three-handed manipulation tasks (Abdi et al. 2016), the feedback device was placed on the subject's leg which was not involved in the task, in order not to contaminate the natural proprioceptive feedback coming from the arms. A planar task involving two degrees of freedom (and consequently two joints of the robot) was designed to reduce the complexity of the problem in a preliminary study.

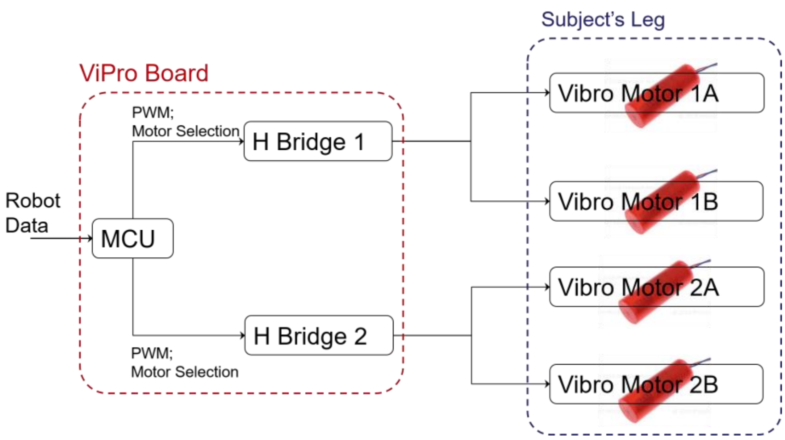

*Figure 19 – **Logical Schematic** of the ViPro system for two couples of motors. The instantaneous supply voltage of the vibrators, thus their vibration, is controlled by the MCU through two independent motor drivers (L293DD by STMicroelectronics Inc.). Each motor driver refers to a dof and controls a couple of vibrators. Then, according to the sign of the information to be provided, the MCU selects which one of the two vibrators has to be turned on (A for positive values and B for negative ones).*

Vibrators were placed distant enough from the bones and from each other so that the user could easily identify which motors were vibrating and clearly perceive the vibration amplitude. This resulted in placing one couple of motors on the vastus lateralis (1A) and the biceps femoris (1B), and the other one on the gastrocnemius lateralis (2A) and medialis (2B) (see Figure 20). In both cases, motors labeled with A referred to positive values of the feedback, while the ones labeled with B referred to negative values.

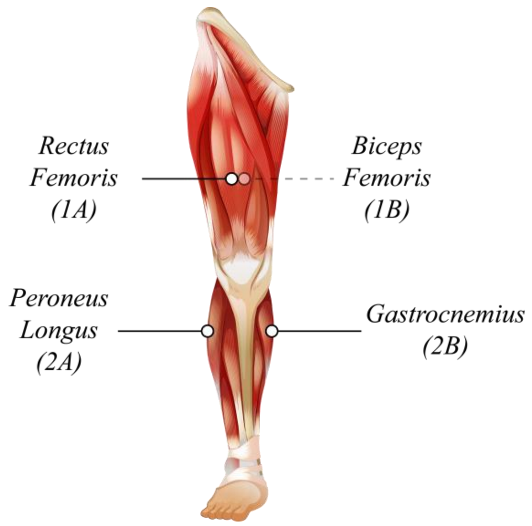


*Figure 20 - **Eccentric motor placement** on the subject's leg: 1A) Vastus lateralis;1B) Biceps Femoris; 2A) Gastrocnemius lateralis; 2B) Gastrocnemiusmedialis*

## 5.3.2 Feedback Approaches

The sensory feedback has been investigated in many studies, encoding different information, such as the device end-point position, the joint velocity, the interaction force, the error meant as the distance from the target position, just to name a few. However, none of these studies involved SRL (Krueger et al. 2017; Earley et al. 2017; Sengül et al. 2013). To perform a preliminary validation of the system, two different approaches have been selected to represent the robot state: a kinematic approach and a dynamic one. The first method represented the state of the robot as the position of the robot end-effector in the workspace, expressed in the cartesian space (*i.e.* $X_{EE}$, $Y_{EE}$ in Figure 21); whereas the latter conveyed the torques which are applied to the active joints of the robot (*i.e.* $J_2$ and $J_4$ in Figure 21).

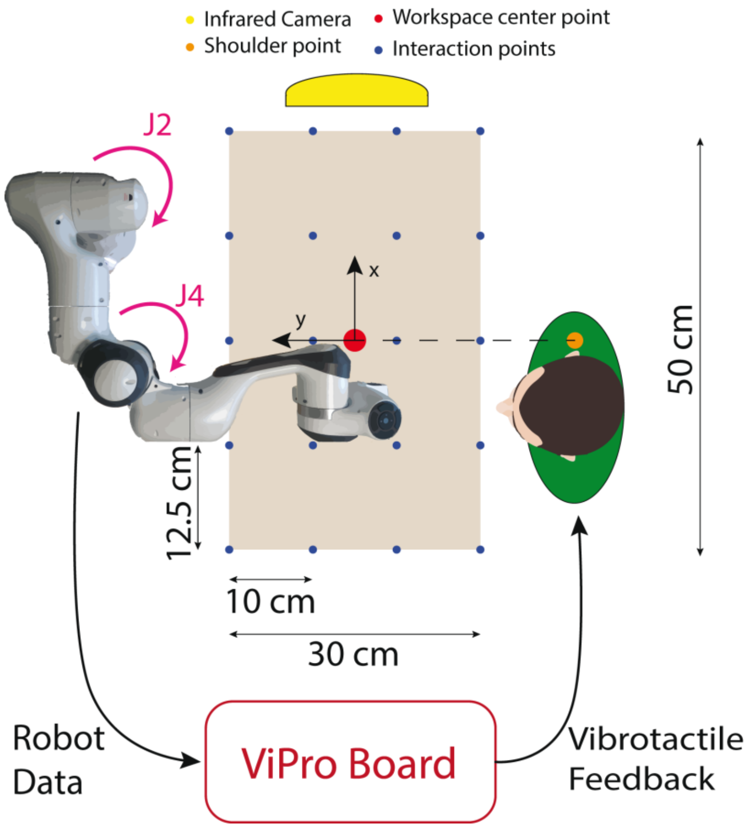


*Figure 21 - **Experimental setup scheme**: a 7 dof anthropomorphic manipulator was employed as SRL; the subject was seated in front of the robot, with the right shoulder (orange dot) aligned with the center of the workspace (red dot); the workspace was a 30x50 cm rectangle subdivided into 20 equally spaced target points (blue dots). Robot state data were sent through serial communication to the ViPro board, that converted them into vibration controlling four eccentric motors placed on the user's leg skin. Robot state is represented using the end-effector position in the cartesian space ($\boldsymbol{X_{EE}}$, $\boldsymbol{Y_{EE}}$) or the torques applied to the two active joints J2 and J4.*

The kinematic approach was expected to be the easiest to understand, since it was a linear mapping; conversely, the dynamic one requirered the learning of a non-linear mapping to understand the feedforward model of the robotic arm, but it may perform better in case of external disturbs such as obstacles or force fields.

Referring to the motor placement (Figure 20), motors 1A-1B drove the $X_{EE}$ value and motors 2A-2B drove the $Y_{EE}$ information, in case the kinematic approach was used; otherwise, if the dynamic method was employed, $J_2$ value was driven by the motors couple 1A-1B and $J_4$ by the couple 2A-2B.

### 5.3.3 Experimental Setup

A 7 dof robotic manipulator, the Panda robot by Franka Emika GmbH, has been used as SRL. Only two robot dof (second and fourth joint) have been enabled. The robot was controlled through an interface developed in c++ language, using the Qt libraries, running on a computer with Ubuntu 16.04 O.S. The control application generated a random sequence of points in the workspace that the robot must reach, then it acquired the robot state and sent the information (position or torque values) to the ViPro board. The robot moved the end-effector on a plane, 30 cm above a table. Robot motions were planned to be human-like, *i.e.* implementing minimum jerk trajectories. In particular, each movement from the center point to the target one had a linear path and the same duration, *i.e.* four seconds. The workspace consisted of a 30 cm x 50 cm rectangle upon a table, clearly highlighted with adhesive tape. As shown in Figure 21 and Figure 22, the subject was seated on a chair in front of the robot, close enough to the table to comfortably reach with the hand every point of the workspace.

Subject's right shoulder was aligned with the center of the workspace. The dimensions took into account both the robot workspace and the average range of motion of the human arm. Twenty equally-spaced points within the workspace represented the target positions (blue dots in Figure 21). Subjects and robot moved on two parallel planes so that they did not collide. The subject moved his arm onto the table's plane, holding a plastic handle with spherical wheels, whereas the robot moved onto an upper plane (Figure 22). To ensure planar movements, the subject is asked to keep his back close to the chair and the handle touching the table during the whole experiment. Each movement, both for the robot and the hand, started from the center of the workspace. A Polaris Vicra Camera (by Northern Digital Incorporated) was used to detect the position of the end-effector and the subject's hand, using passive reflective markers attached to the robot and the plastic handle. The robot end-effector was provided with an additional handle to simplify the placement of the motion tracking markers.

The infrared camera was placed sideways so that it had both markers within its field of view. The vibrators have been manually placed on the subject's right leg, as show in Figure 20, adjusting their position so that the subject could clearly perceive the full frequency range of the stimulation and easily discriminate which vibrator is delivering the stimulation (Wentink et al. 2011).

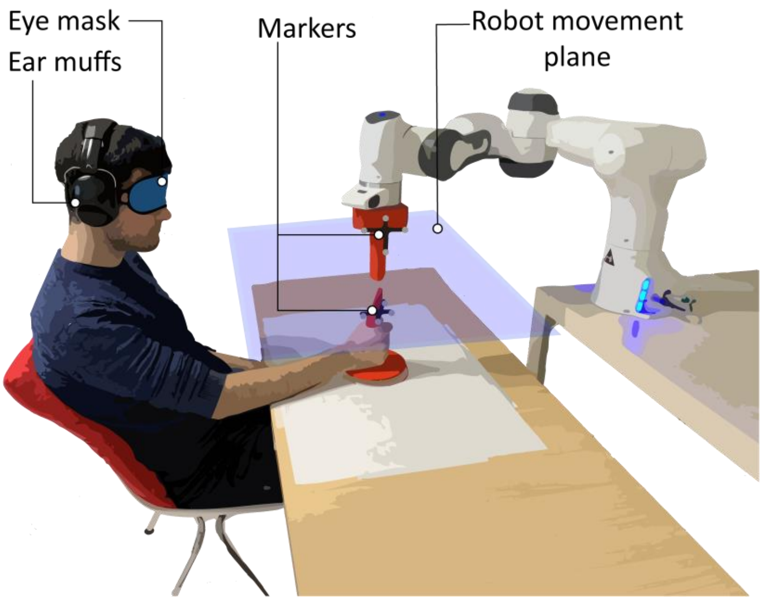


*Figure 22 - **Experimental setup** with a subject seated in front of the robot. The subject held with his right hand a plastic handle. Another plastic tool was attached to the robot end-effector. Passive markers were attached on both handles to track them using an infrared camera. The subject moved the handle on the table; the robot tool moved on a parallel plane. The subject wore earmuffs and eye mask to suppress auditory and visual feedback.*

### 5.3.4 Experimental Protocol

Three subjects (two right-handed, one male, aged from 23 to 25 years old) naive to the aim of the study, were recruited to run a pilot experiment to validate the system. Subjects signed a written informed consent and experimental procedures were approved by the Ethics Committee of the Università Campus Bio-Medico di Roma (EMBODY protocol) and carried out according to the Declaration of Helsinki. The robot performs planar movements starting from the center of the workspace (highlighted with the red dot in Figure 21). While the robot is moving the subject receives the vibrotactile stimulation and, after the robot movement, subject is asked to move the handle on the table, reaching the same in-plane position of the robot end-effector. No cue on the feedback encoding or how it was mapped on the motors was given to the subject. To be able to assess even subtle advantages given by the proprioceptive feedback, subjects executed the task blindfolded. Earmuffs and eye mask were used to suppress auditory and visual feedback. Each subject performed the two conditions (type of feedback), in a randomized order in two different days. The experimental protocol was composed of three phases (see Figure 23): i) Familiarization; ii) Learning; iii) Test. The protocol steps are described as follows:

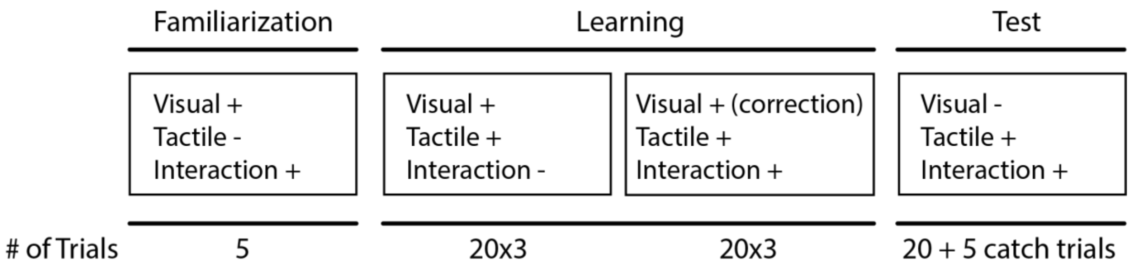


*Figure 23 - **Experimental Protocol phases**: 1) Familiarization: the subject familiarized with the experimental setup by performing the task while receiving no vibrotactile feedback; 2a) Learning: the subject could see the robot motion and perceive the vibration but he/she did not perform the task; 2b) Learning: the subject received the feedback and he/she executed the task blindfolded, looking at the actual robot position only at the end of the trial to estimate the error magnitude; 3) Test: the subject performed the task blindfolded, receiving the vibrotactile feedback with informative content 20 times and without it 5 times (catch trials).*

***Familiarization***. The familiarization phase allowed the subject to understand the task. During this phase the subject had a visual feedback (not wearing eye mask), but no vibrotactile feedback was given. The robot reached five random points in the workspace. At the end of each robot movement, the subject was asked to move the handle on the table, reach the in-plane position of the end-effector and then return to the starting position.

***Learning***. The learning phase is subdivided into two steps: i) the subject had only to observe and associate the vibrotactile stimulus on the leg with the spatial motion of the robot without performing any movement. Auditory feedback was suppressed by earmuffs, as in all the other phases. The robot performed three series of 20 movements, randomly selected among the points highlighted on the workspace (see Figure 21). The aim of this phase was to allow the subject to correlate the vibrotactile feedback to the position reached by the robot end-effector; ii) the robot performed again three series of 20 random movements. The subject perceived the proprioceptive feedback but was blindfolded. At the end of each robot movement (when the motors stopped vibrating) the subject had to reach the point of the workspace corresponding to the position of the robot. Once the subject completed the reaching movement, the subject was allowed to see robot to understand if he/she reached the right position. In case of error, the subject corrected the position and performed the interaction. At the end of the movement, both robot and subject returned to the starting position.

***Test***. In the test phase the robot executed a series of 25 random movements. Twenty of them were associated with an informative vibrotactile feedback, whereas five movements were "catch trials" (or "control points") and provided a non-informative feedback with a sinusoidal vibration pattern (with random phase shift), in order to confirm that an eventual improvement in the performance was due to the information provided through the motors and not to the vibration itself. Subjects were blindfolded for the whole phase and they were asked to reach the correct position, depending on the received feedback.

## 5.4 Data Analysis

The robot end-effector and the handle position were tracked using the infrared camera and processed in Matlab 2017. Since the handles could also rotate during the task, two constant homogeneous transformation matrices were taken into account in the data analysis to compute the actual position of the handle centers, since the tracked markers were placed on their side, according to the equation:

$$T_h^b = T_m^b \cdot T_h^m \qquad 2$$

denoting $T_h^b$ as the 4x4 homogeneous transformation matrix that represents the handle pose $h$ in the base reference frame $b$; $T_m^b$ as the tracked marker pose and $T_h^m$ as the constant transformation between the handle center and the attached marker. Equation 2 was applied to both the hand and robot handles, using the corresponding constant matrix $T_h^m$. Performances were evaluated measuring two indexes: i) *position error*, normalized with respect to the distance between the starting and target points; ii) *time* needed to execute the task.

The position error was computed as the cartesian norm between the handle and end-effector position on the plane, at the end of the task. The error was then normalized, dividing it by the distance between the starting and target points. This was a measure of the difficulty of the task, considering that far target required higher duration to be reached, and/or higher velocity which results in less accuracy. We did not consider the accuracy to be strictly related to the proprioception, which is known not to be homogeneous in space (the accuracy in locating the hand is higher if the hand is closer to the body), because the task did not rely on proprioception only, even though the subject was blind-folded. Indeed, active movements and somatosensory information derived from the interaction between hand, handle and table were always present. The task started when the robot and the vibrotactile feedback stopped and it ended when the subject reached the target. Finally, the time measure was then divided by the distance between the starting and target points, used as index of the trial difficulty. Considering the low size of the population enrolled, in order to check whether there was a within subject difference between the two feedbacks provided, we evaluated the effect size by computing the Cohen's d (Sawilowsky 2009; Fritz, Morris, and Richler 2012).

## 5.5 Results

The average errors among the three subjects, during the test trials, are respectively (89.5 $\pm$37.2) mm using the position feedback and (194.8 $\pm$ 88.5) mm employing the torque feedback. These are absolute values, not normalized, and are spatially distributed as depicted in Figure 24. Taking into account the trial difficulty (represented by the distance between the starting and target points), the average error value became 48% $\pm$12% in the kinematic approach and 118% $\pm$72 % in the dynamic one. Especially in the latter method, the targets which caused the higher errors are the ones close to the center, i.e. the easiest ones (as visible in Figure 25); whereas the error values employing the position feedback are approximately equally distributed in the workspace.

Figure 26 shows the median of the percentage error value and the trial duration for the two feedback types (computed among the 20 test trials) and for the control trials for the three subjects. The normalized position errors, using the cartesian position feedback, are smaller than the ones recorded providing the joint torque encoding, with a huge difference between the two (d=4.278) (Sawilowsky 2009).

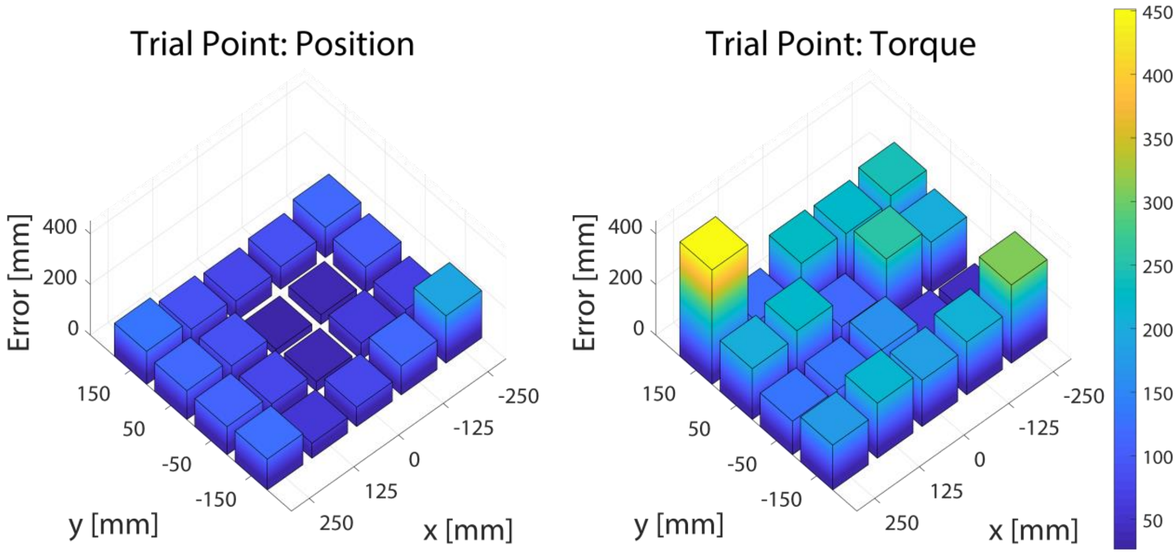


*Figure 24 - Spatial distribution of the average error over the workspace using the position and torque feedback encoding. Each bar represents a target point. Bar height is the average error value for all the subjects corresponding to that point.*

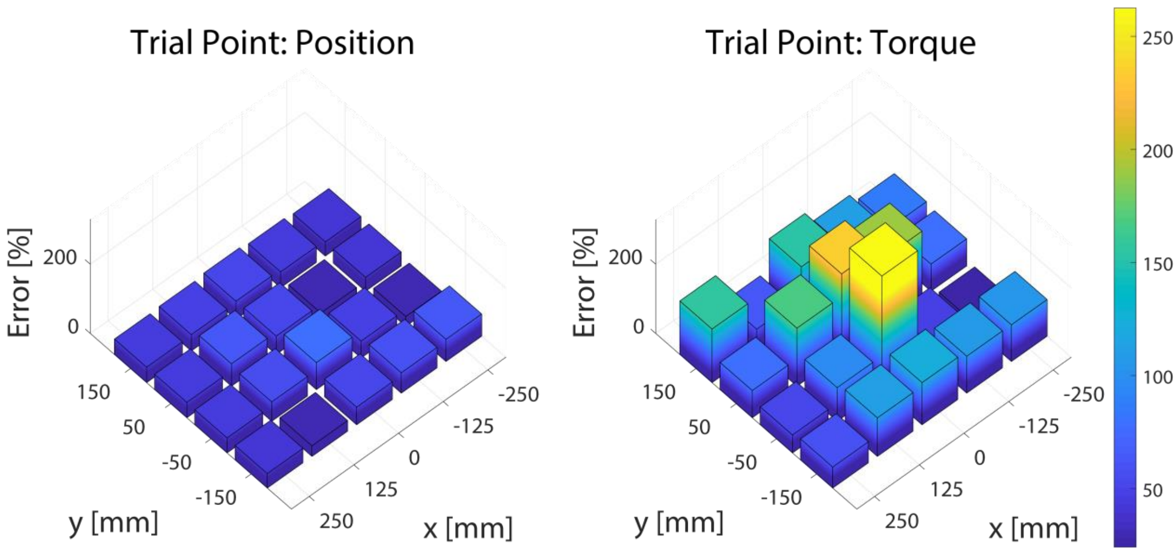


*Figure 25 - Spatial distribution of the average normalized error over the workspace using the position and torque feedback encoding. Each bar represents a target point. The bar height is the average error value (divided by the starting-target points distance) for all the subjects corresponding to that point.*

On the other hand, if we look at the control points, there is a small difference between the errors obtained with the non-informative feedback and the ones achieved with the dynamic feedback approach (d=0.313). On the contrary, the kinematic encoding approach allows to achieve performance hugely better (d=2.826) than the control trials, in term of errors. Very large differences have been found among the two feedback approaches in term of task duration (d=1.682); the mean duration of each trial (corresponding to one target point) is (9.10 s ±1.68) s and (7.26 s ±1.46) s for the torque and position feedback respectively. The same trend is found also taking into account the trial difficulty, *i.e.* diving the value by the distance to be traveled (d=2.239).

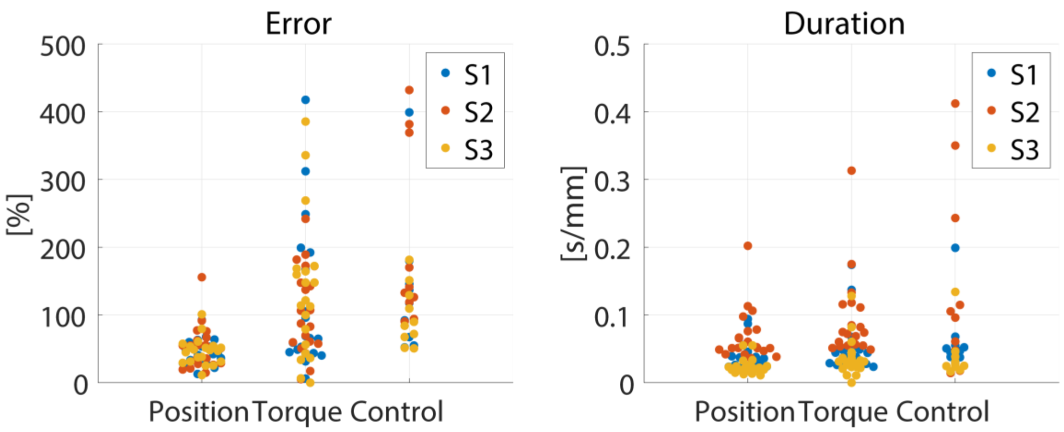


*Figure 26 - Left: Normalized position error during the test phase (twenty trials per subject) for subjects S1, S2 and S3, using the Position and Torque feedback or in the Control trials. Right: Trial duration during the test phase (twenty trials per subject), for subjects S1, S2 and S3, using the Position and Torque feedback or during the Catch trials, all divided by the distance from the target.*

## 5.6 Discussion

The results of the comparison with the catch trials suggests that the position encoding is an effective feedback to let the user understand the position of the supernumerary limb, even without visual feedback. Conversely, providing the torque feedback leads to the same outcomes of a non-informative vibrotactile stimulation. Moreover, this approach achieved the worst performance in the closest, and thus easiest, targets. However, these results could have been affected by the trajectory implemented to control the robot. Indeed, the robot movement duration was always the same, i.e. four seconds, even for small distances. Such slow movements are not well represented by joint torques, especially because of the robot configuration that has been adapted to the planar task. The torques required to slowly move the two active joints, especially because of the robot configuration that has been adapted to the planar task, probably present no perceivable differences among the selected workspace, even though the δ variability range (Eq. 1) was in each case adjusted according to the minimum and maximum values achievable with the employed feedback. To better understand the effectiveness of torque feedback, an additional, more complex, task should be tested. The results prove the validity of the proposed system which seems effective in converting the state of a supernumerary robotic arm, coded using position feedback, into vibrotactile stimulation easily understandable by subjects. The significant difference between the performance achieved employing the position feedback and the ones obtained in the catch trials is a concrete evidence of that validation. Moreover, the learning time is not a negligible aspect. The choice of sixty trials for the two learning phases allowed to complete the whole experiment in a short span, *i.e.* less than one hour and half. Such short time could have been enough to learn how to benefit from the simpler feedback (cartesian position), but too short for the more complex dynamic feedback (torque). It is worth noting also that the error magnitude is partially due to the inaccuracies of human beings in identifying the position of their own arm when blindfolded. A weakness of this protocol could have been the use of the right arm and right leg instead of the dominant ones for each subject. Nevertheless, since each subject was tested with the same hand (and leg) on both the conditions, this choice may have affected the error magnitude, but not the overall comparison results.

## 5.7 Conclusion

The presented work tests the possibility of providing proprioceptive feedback for a supernumerary robotic arm, using a vibrotactile stimulation. The discussed platform overcomes the lack of a proprioceptive feedback, meant as the state of the entire device, in the use of SRL by employing a sensory substitution paradigm. Indeed, the proprioceptive feedback has been conveyed through a vibrotactile stimulation on the subjects' leg skin, using four eccentric motors. The system has been validated on three subjects using two different feedback encoding strategies: a kinematic approach, conveying the end-effector cartesian position and a dynamic method, using the torques recorded on the active joints. The results proved the effectiveness of the proprioceptive feedback system for a SRL using the position approach, showing better performance (d=2.826) compared to catch trials (providing non-informative feedback). On the other hand, the torques approach outcomes seem significantly worse. Nevertheless, those results could be affected by the choice of a planar task and the trajectory planning implemented for the robot motions. Besides possible limitations of the protocol employed (i.e. the lack of dynamic interactions with the environment, the use of right limbs instead of dominant ones), the proposed system showed to be a valid test-bed to implement future more complex and refined tasks to investigate the encoding of supernumerary limbs proprioceptive feedback.

While the platform tested proved to be quite successful in conveying proprioceptive information on the position of an SRL, the entire task was designed to be completed offline by the subjects. However, during everyday life we integrate sensory information, e.g. proprioceptive cues, within our sensorimotor loop in real time, and we are able to control and correct our movement with an extremely short time delay. The divergence between real life motor control and the experimental paradigm discussed above, i.e. real time versus offline information processing, led to a sub-optimal scenario in which the afferent component was not evaluated as seamlessly as it happens with proprioceptive information coming from our own body. Additionally, an offline task requires to keep in mind the information vital for the correct task completion. This means that subjects had to make an additional cognitive effort to store this information in the working memory, or even brief term memory, something that is not necessary during normal, real time, sensorimotor activity. For these reasons a further study was conducted to improve the afferent component in the sensorimotor loop involving human and SRL.

# Chapter 6

# Improvement of the Afferent component in the Sensorimotor Loop

## 6.1 Introduction

To really benefit from an SRL, the user needs to be able to send command and receive feedbacks from the SRL seamlessly, as it happens with his own body. Concerning the afferent component, when trying to close the sensorimotor loop between human and robot, research has often focused on one of the main sources of information regarding body posture and configuration: *proprioception* (U. Proske and Gandevia 2012; Pinardi et al. 2020). Indeed, several types of proprioceptive feedback have been delivered through vibrotactile stimulation, such as device end-point position, the joint velocity, the interaction force and the error, meant as the distance from the target position, just to name a few (Krueger et al. 2017; Earley et al. 2017; Sengül et al. 2013; Noccaro et al. 2020).

Nevertheless, as emerged also from the last experiment examined, a pivotal aspect of this process has been overlooked so far: during our daily routine, we can constantly integrate proprioceptive information to obtain an optimal motor control of our body (Körding and Wolpert 2006) without waiting for a specific movement to end, i.e. *in real time*. However, despite being studied in relation to prosthesis control or in a virtual environment, real-time delivery and decoding of proprioceptive feedback has never been tested for a proper SRL. However, real time sensory information processing poses some additional challenges. First of all, while the cognitive burden represented by mnemonic processes required by an offline task is removed, it is in fact substituted with another cognitive burden: the additional processing of supplementary (i.e. not originally present) sensory information. Moreover, in the present work a sensory substitution paradigm is employed (Kristjánsson et al. 2016), meaning that information regarding one sensory domain, i.e. proprioception, are conveyed using a different sensory modality, i.e. touch. Hence subjects will need to translate, in real time, a certain pattern of vibrotactile stimulation into proprioceptive information (i.e. robot position in space). Obviously, being sensory substitution a conversion from one sensory "language" to another, subject will also need to learn the correspondence between the two "languages", or sensory modalities. This means that a training will be mandatory, as it happened with the previous experiment, but the question, which constitutes the last challenge for this experiment, is: how long is going to take for the subject not only to learn a sensorimotor task, but to master it to the point of being able to complete it in real time? We might speculate that, given enough time, the human brain can learn anything, but in this case, time is of essence, not only for the feasibility of the study, but also to make the integration of SRL into the body schema more viable.

To face those challenges and shed light on the feasibility of a real time approach to the processing of sensory feedback coming from an SRL, ad additional study was run. The vibrotactile stimulation device employed in the previous experiment has been adapted to test the feasibility of a vibrotactile stimulation device for conveying and testing proprioceptive information of the robot posture and movement trajectory in real time, conveyed through an easily understandable kinematic feedback (Noccaro et al. 2020). We employed vibrotactile stimulation to convey proprioceptive feedback, since it is non-invasive, highly informative and easy to implement in a variety of experimental setups (Dennerlein, Millman, and Howe 1997).

## 6.2 Methods

### 6.2.1 System Design

We designed a custom Printed Circuit Board to control four eccentric vibrator motors (Model: 307-103 by Precision Microdrives Inc.), driving the stimulation on the basis of the robot kinematic data, read in real time. We tested the system on a 2 dof task. Vibrators were divided in two couple: each couple referred to a single dof and, within the couple, one vibrator (A) was used to represent positive encoded values and the other one (B) to convey negative values. The logical schematic of the board, called ViPro, is presented in **Errore. L'origine riferimento non è stata trovata.**.

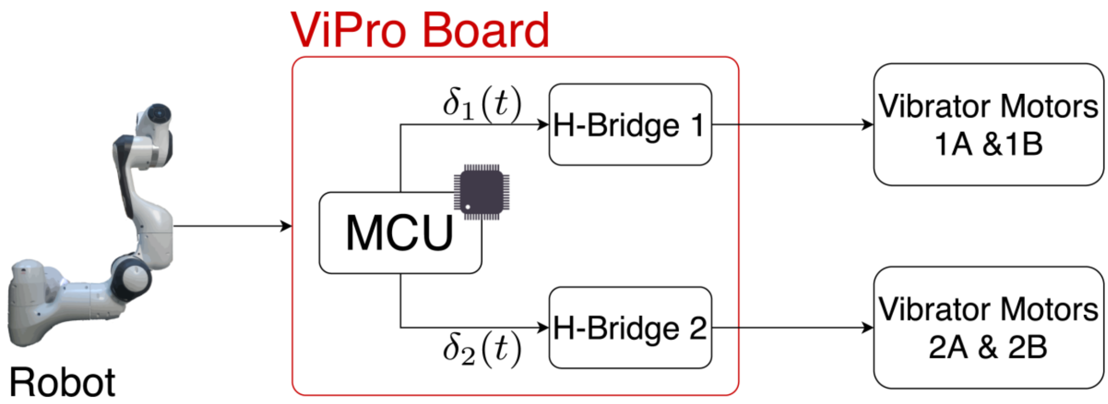


*Figure 27 - **Logical Schematic** of the ViPro system for two couples of motors. The instantaneous supply voltage of the vibrators, thus their vibration, was controlled by the MCU through two independent motor drivers (L293DD by STMicroelectronics Inc.). Each motor driver referred to a dof and controlled a couple of vibrators. Then, according to the sign of the information to be provided, i.e. the distance of the robot end-effector from the center of the workspace, the MCU selected which vibrator had to be turned on (A for positive values and B for negative ones).*

The frequency and the vibration intensity were coupled according to the product datasheet, and modulated by the embedded microcontroller (STM32F446 by STMicroelectronics Inc.), which generated a Pulse Width Modulation (PWM) signal to define the following supply voltage of the vibrators:

$$V_i(t) = \frac{\delta_i(t)}{T} V_A \qquad (3)$$

denoting $V_A$ the maximal supply voltage of the vibrators (equal to 3.6 V) and $\delta_i(t)$ the duty cycle of the vibrators control signal (computed for both dofs considered), which was proportional to the 2D end-effector position of the robot during the movement, with respect to the center of the workspace. The robot is thought as an additional arm to be used eventually in three-handed tasks (Abdi et al. 2016). Thus, we opted to place the four vibrators on the subject's leg, which was not involved in the task, in order not to interfere with the natural proprioceptive feedback coming from the arms. One couple of motors was placed on the skin upon the gracilis (2A) and vastus lateralis (2B), and the other one upon the tibialis anterior (1A) and gastrocnemius (1B) (see Figure 29, left). The distance between the vibrators allowed subjects to understand both the amplitude and the source of the vibration (Wentink et al. 2011).

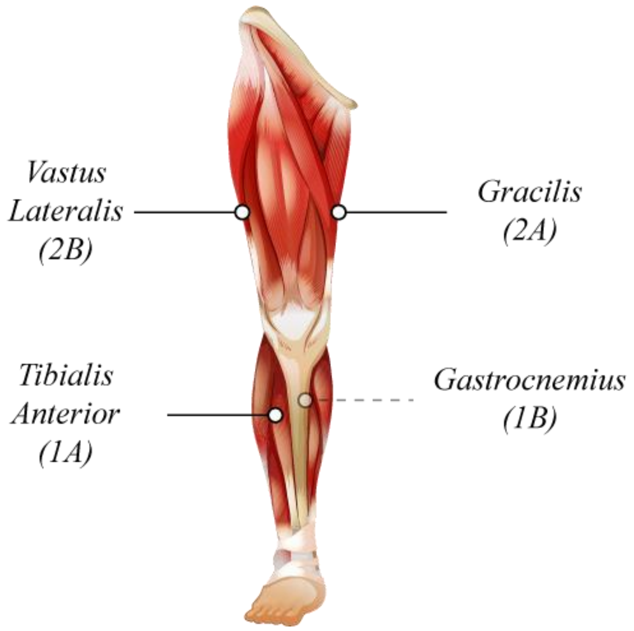


*Figure 28 - Eccentric motor placement on the subject's leg: 2A) Gracilis; 2B) Vastus lateralis; 1A) Tibialis anterior; 1B) Gastrocnemius.*

We delivered the state of the robot as the end-effector position, expressed in the cartesian space, with respect to the workspace center. Referring to the motor placement (Figure 28, left), motors 1A-1B drove the $X_{EE}$ value, while 2A-2B drove the $Y_{EE}$ value, with $X_{EE} = Y_{EE} = 0$ with the end-effector in the workspace center (see Figure 29). It is important to note that the sensory feedback subjects were receiving, despite being the result of a sensory substitution, was designed to behave similarly to a proper proprioceptive signal: subjects received a continuous vibratory stimulation for as long as the robot end effector was not in the workspace center, and the vibration was modulated on the basis of the distance between end-effector and center. Vibration ceased only between one trial and another, to avoid sensory adaptation.

### 6.2.2 Experimental Setup

The setup used shared some similarities with the study previously described (Noccaro et al. 2020). As shown in Figure 29, subjects were seated in front of a transparent table with their right shoulder aligned with the second joint pivot of the robot. The robot was displaced in order to move on a lower plane (2 cm below the table) compared to subjects, so that they could see the robotic arm moving below the transparent table. A number of points equal to the total number of trials (248 points) were randomly generated within the workspace and they represented target positions the robot had to reach. Subjects moved their arm onto the table's plane, holding a plastic handle which could slide on the table with minimal friction. A seven dof robotic manipulator, the Panda robot by Franka Emika GmbH, has been used as SRL. Only two robot dof (second and fourth joint) have been enabled. The robot is controlled through an interface developed in C++ language, using the Qt libraries, running on a computer with Ubuntu 16.04 O.S. Robot motions were planned to be human-like, i.e. implementing minimum jerk trajectories. Each movement had a duration ranging from 1.5 to 3.5 seconds. Movements were organized in groups of four trajectories, going from the center of the workspace to three consecutive points, and then going back to the center once again, as shown in Figure 30. This was intended to diminish the error propagation when subjects replicated the movement of the robot relying only on proprioceptive feedback. The workspace consisted of a 45 cm x 50 cm rectangle upon the transparent table.

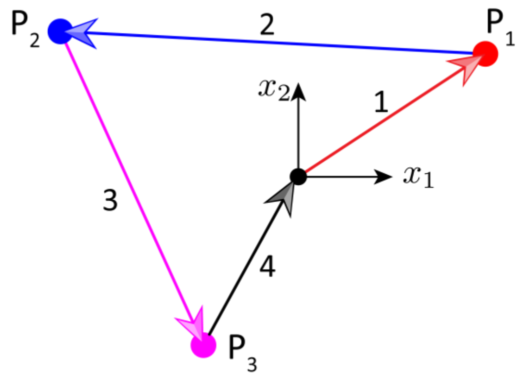


*Figure 30 – **Representation of a group of four trajectories**. The center point is represented by the black dot. P1, P2 and P3 are the successive, randomly-generated points in space that the robot had to reach. After the robot reached the last point (P3), it returned to the home position, i.e. center point..*

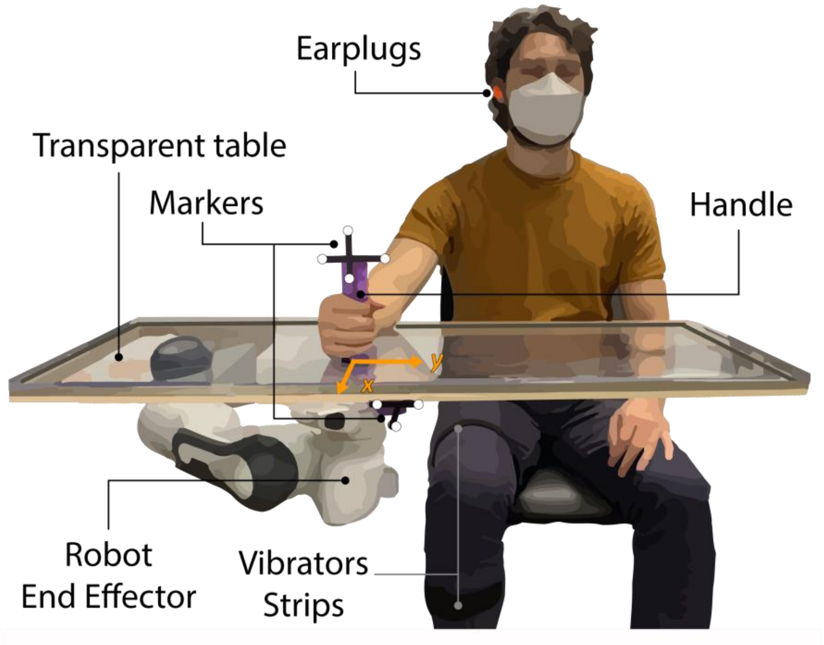


*Figure 29 - Experimental setup with a subject seated laterally to the robot. The subject held with his right hand a custom plastic handle. Another custom plastic support was attached to the robot end-effector. Passive markers were attached to both handle and support to track them using infrared cameras. The subject moved the handle on the transparent table while the robot end-effector moved below the table. The subject wore disposable earplugs and kept his eyes closed to suppress auditory and visual feedback.*

To ensure planar movements, subjects were asked to keep his back close to the chair and the handle touching the table during the whole experiment. Two infrared cameras (Prime x22 by Optitrack) were used to track the position of the end-effector and the subject's handle, using passive reflective markers. The vibrators have been manually placed on the subject's right leg, as show in Figure 28, with the use of adjustable cloth strips which allowed to fine-tune the vibrators position.

### 6.2.3 Experimental Protocol

Four subjects (all right-handed, two female, aged 27$\pm$ 3) naive to the aim of the study, were recruited to run a pilot experiment. Participants were enrolled after having signed a written informed consent and experimental procedures were approved by the Ethics Committee of the Università Campus Bio-Medico di Roma (EMBODY protocol) and carried out according to the Declaration of Helsinki. While the robot was moving, subjects received the vibrotactile stimulation and were asked to follow the robot as closely as possible, by moving the handle on the table, for the whole duration of the robot motions. The trial started when the robot started moving and ended when the subjects stopped their motion. After subjects ended their movement, the robot started moving again and the next trial begun. The experimental protocol was composed of three phases: i) Familiarization; ii) Learning; iii) Test. The protocol steps are described as follows:

***Familiarization.*** The familiarization phase allowed subjects to experience the task first-hand, while receiving both visual and vibrotactile feedback. The robot reached eight different random points in the workspace. Subjects were asked to follow the robot end-effector by moving the handle on the table. Auditory feedback was suppressed by wearing earplugs, as in all the other successive phases.

***Learning.*** The learning phase was subdivided into three steps: i) during learning phase A, subjects had to observe the robot moving and pay attention to the vibratory feedback, and they were instructed to associate the vibrotactile stimulus on the leg with the spatial motion of the robot without performing any movement. The robot performed 10 series of 4 movements each (from center to point P1, P2, P3 and back to center), with each point randomly generated within the workspace. The aim of this phase was to allow the subject to understand the meaning of the vibratory pattern he/she received, by correlating the vibrotactile feedback to the position reached by the robot end-effector; ii) learning phase B, repeated the same scenario of learning

A (10 series of 4 movements each, with new randomly generated points within the workspace), but this time subjects were instructed to follow the robot by moving the handle on the table. This phase had the goal to reinforce the association between vibrotactile feedback and robot movement, obtained during Learning A, as it was demonstrated that active movements facilitate associative learning (Trewartha and Flanagan 2017); iii) learning C was similar to learning B but subjects were instructed to keep their eyes closed during the robot following (no visual feedback) and to open them only when they were satisfied with the reached position, at the end of the robot movement (when the vibratory feedback ceased). The robot performed 25 series of 4 movement each. By doing this, subjects were able to understand if they successfully reached the end-effector position, thus receiving a direct visual confirmation regarding their performance in the task and completing the learning process.

***Test.*** Subjects executed the test without visual feedback (eyes closed) and were asked to follow the robot end-effector with the handle by relying exclusively on the vibratory feedback. The robot executed 15 series of 4 movements each, with each point randomly generated within the workspace. To avoid error's drift, when the robot came back to the center, the experimenter re-aligned the subject's handle to the center.

## 6.3 Data Analysis

The robot end-effector and the handle position were tracked using the infrared cameras and processed using Matlab 2017. Since the handles could also rotate during the task and the tracked markers were placed on their side, two constant homogeneous transformation matrices were taken into account in the data analysis to compute the actual position of the handle centers, according to the equation:

$$T_h^b = T_m^b \cdot T_h^m \qquad 4$$

denoting $T_h^b$ the 4x4 homogeneous transformation matrix that represents the handle pose $h$ in the base reference frame $b$; $T_m^b$ the tracked marker pose and $T_h^m$ the constant transformation between the handle center and the attached marker. Equation 4 was applied to both the hand and robot handles, using the corresponding constant matrix $T_h^m$.

Performance were evaluated only during the *test* session, measuring two indexes: i) *position error*, computed as the Euclidean distance from the handle and the robot end-effector on the plane, for every time sample during each movement; ii) *delay* between the onset of the robot's and subject's movements.

## 6.4 Results

We computed the *Position Error* in two cases: i) in real time, i.e. considering the position error without any further processing, and ii) by applying a time shift to the recorded handle position equal to the subject's delay within the specific trial. Specifically, we considered the latter case in order to control for the effect of physiological reaction time. Subjects obtained an average *Position Error* equal to (0.084 $\pm$ 0.010) m and an average *Shifted Position Error* equal to (0.084 $\pm$ 0.003) m (see Fig. 4). Concerning the computed *Delays* (see Figure 31), subjects started moving, on average, (1.169 $\pm$ 0.408) s after the robot movement onset.

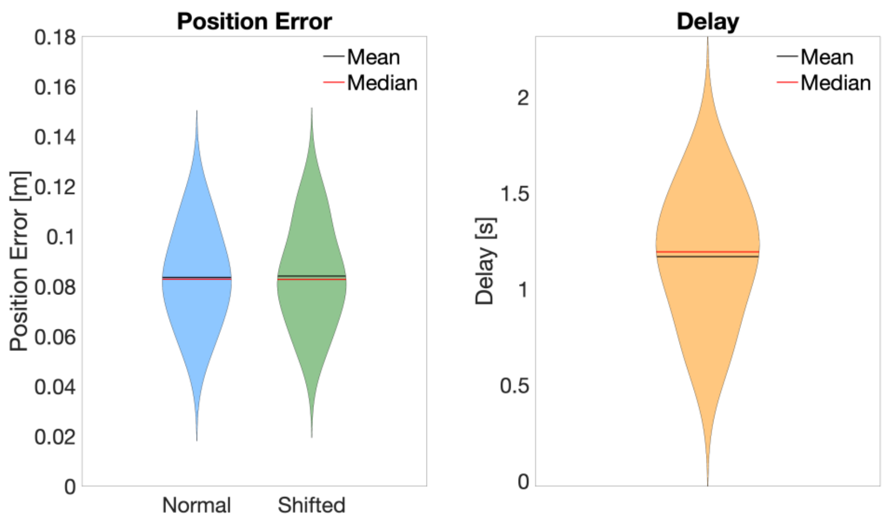


*Figure 31 - Average Position Error (normal and shifted) and average Delay computed along all test trials.*

## 6.5 Discussion and Conclusions

In the presented work a system which employs vibrotactile stimulation to provide in real time the proprioceptive feedback of a supernumerary robotic limb was tested, in order to verify the feasibility of the real time processing of sensory feedback regarding the position in space of an SRL. The system has been validated on four subjects using a kinematic approach, conveying the end-effector cartesian position with respect to the center of the workspace, through four eccentric-motor vibrators positioned on the subjects' leg. Results showed that subjects obtained, on average, a *Position Error* of approximately 8 cm. This might seem a non-trivial error, but it is worth noting that the performance of subjects was analyzed during the *test* phase, when they were relying only on vibration-coded proprioceptive information for judging the robot position. This, in addition to the relatively brief learning phase subjects underwent, and a probable parallax error related to the subjects' point of view, can easily justify a *Position Error* of such magnitude. Another interesting aspect which advocates for the reliability of the presented setup is the relatively low SD of the *Position Error* (≤ 1 cm). Finally, the subjects' *Delay*, around 1 s, can account not only for the physiological reaction-time but also for the additional cognitive process required to translate the vibration pattern into information related to the trajectory on the plane. Implementing longer training sessions could improve subjects' accuracy by reducing *Position Error* even further and decrease the cognitive load by making the task more intuitive, which translates into smaller *Delays*. To be more specific, implement a longer learning session in which visual feedback is gradually removed, could facilitate the passage from full visual feedback to exclusive proprioceptive reliance. Finally, analyzing subjects' performance during learning phase should provide a clear view of how the shift from vision to proprioception impacts the decoding of real time SRL kinematics feedback. Once these preliminary results are confirmed, the present setup can be easily exploited to test the efficacy of more complex feedbacks, such as joint angles or dynamic feedbacks, for real time tracking of SRL, in order to close the sensorimotor loop between human and robot and integrate the SRL into the human body schema.

## Chapter 7

# Conclusion and Outlook

During our everyday life, afferent and efferent information flows continuously between our brain and our body. This seamless exchange of inputs and outputs is often named sensorimotor loop. Multisensory information inside the loop is not just exchanged, though, it is integrated following specific patterns and computational principles (Blanke 2012). Research nowadays agrees that the approach our brain adopts for computing multisensory integration follows the rules of Bayesian statistics: multisensory inputs are assigned a specific weight based on their reliance, and, according to this weight, they are combined with the knowledge coming from our past experience, to guide our posterior judgement (Körding and Wolpert 2006; Chandrasekaran 2017). This perceptual judgment can take many forms: from locating a stimulus in the environment to deciding if a body parts belongs to us. Hence Bayesian computational approach can lead us to feel embodiment and, according to the theory of Internal Models, can even improve the motor control (D. Wolpert, Ghahramani, and Jordan 1995).

An extremely fascinating aspect of the sensorimotor loop and its mechanisms is that they can be applied to object not natively belonging to our body, leading, for example, to a feeling of ownership or agency over an artificial hand (Botvinick and Cohen 1998), or to the improved control of a robotic limb (Manoharan and Park 2019). These objects are ultimately tools, designed to help the human being reach better performances or compensate the loss of function. The possibility to embody powerful but foreign tools, by including them into our body schema, led to the stunning concept of human augmentation as a mean to go beyond the natural limitations imposed to the human being (Di Pino, Maravita, et al. 2014). Human augmentation, which permeates not only science, but literature and arts as well, could have several possible applicative scenarios, e.g. from handling hazardous materials to health care applications or even to improve multitasking capabilities, and it could be argued to be the next step in the millennial human strive to improve our interaction with the environment.

However, despite the broad interest generated by human augmentation and its potential, some important aspects of the topic have not been investigated yet. Hence, the present work aimed at shedding light on the specific roles of the main actors involved in the sensorimotor loop and how this loop can be "closed" around the human user and the supernumerary robotic limb, to boost its embodiment and control.

## 7.1 Major Contributions and Novel Findings

***Specific contributions of afferent and efferent components in the sensorimotor loop***. A proficient interaction with the environment requires a continuous and harmonic flow of afferent and efferent information. This sensorimotor loop is constitutive for movement planning and motor control (Kawato 1999; Shadmehr and Krakauer 2008), and for inducing embodiment. Indeed, whenever an action is performed, a certain level of spatial and temporal congruency links the planned motor command and its effect, thus the integrated multisensory feedbacks well match the anticipated sensory consequence of the movement. Over a lifetime, this congruent multisensory integration leads to what we call embodiment (Medina, Khurana, and Coslett 2015; Tsakiris 2017). Multisensory information and motor planning are both part of the sensorimotor loop, and together contribute to build the representation of the body, but their specific role is yet to be clarified. Hence, in this novel systematic study, the relative contribution of afferent and efferent components in determining embodiment for a robotic hand, was investigated for the first time. By manipulating visual feedback, proprioceptive feedback, and participants' active movements, it was found that ownership and agency may be independently processed by the human brain and thus the presence or absence of the efferent component can modulate the salience of visual/proprioceptive integration differently for ownership or agency.

To be more specific, in the presence of motor command, inter-sensory congruency seems not to be crucial, so that congruency between at least one sensory feedback and motor command is enough to raise ownership and agency. Conversely, in the absence of motor command, agency cannot be felt, while spatiotemporal congruency between vision and proprioception is enough to feel ownership, as it completely makes up for the lack of the efferent component. Our results suggest a further novel speculation: in accordance with the theory of internal models, the prediction about the sensory consequences of our actions, generated from the efference copy, could be employed as an additional sensory modality for determining embodiment.

***Kinematic adjustments resulting from altered sensory feedback.*** Motor control models discussed in Chapter 4.1 highlight the weight of proprioceptive information flowing from a low to a high-level processing in determining movement kinematics (Körding and Wolpert 2004). Starting from this assumption, we investigated the possibility of inducing motor adjustment during object lifting by artificially manipulating the proprioceptive feedback. Exploiting the Tendon Vibration Illusion in an innovative way (i.e. during object lifting) we successfully modulated at least one kinematic parameter (acceleration) despite the differences in lifting movements, generated by different objects. This adjustment was most probably caused by the error reduction policy employed by the sensorimotor system.

***Position encoding as an efficient feedback to close the loop.*** Establishing a bi-directional communication between human and robot through the addition of a sensory feedback could allow to close the control loop and achieve a better human-robot interaction. In particular, to favour the adaptation of the body schema, embodiment and consequently the robot control, it might be relevant to convey to the user the position of the robot in the space, before its potential interaction force. The present work suggests that position encoding is a simple feedback to let the user understand the position of the supernumerary limb, even without visual feedback. Additionally, the proposed system seems effective in converting the state of a supernumerary robotic arm, coded using position feedback, into a vibrotactile stimulation easily understandable by participants.

***Feasibility of a real-time processing of an SRL sensory feedback.*** To really benefit from an SRL, the user needs to be able to send command and receive feedbacks from the SRL seamlessly, as it happens with his or her own body. Nevertheless, as emerged also from the last experiment examined, a pivotal aspect of this process has been overlooked so far: during our daily routine, we can constantly integrate proprioceptive information to obtain an optimal motor control of our body without waiting for a specific movement to end, i.e. *in real time*. The proposed system, which relies on patterns of vibrotactile stimulation to deliver proprioceptive information concerning the robot position, showed, for the first time, that participants were able to understand the cartesian space position of the SRL in real time, with a relatively small delay and position error.

## 7.2 Future Works and Open Questions

Future works will focus on the study of alternative sensory feedbacks that could be highly informative during a meaningful human-robot interaction, as well as the control of the SRL exerted directly by the subject. Additionally, new experimental paradigms to study SRL embodiment will be developed and careful attention shall be paid to ethical and practical issues emerging from the topic of human augmentation.

### 7.2.1 Human-Robot Interaction

As stated in Subchapter 6.2.1, the experimental setup described in Chapter 6 was designed considering the implementation of a three-handed task (Abdi et al. 2016). Indeed, the true nature of human augmentation consists in the possibility of reaching unprecedented levels of performance, which could be obtained by exploiting an additional arm to complete a complex and demanding task that would otherwise require the aid of another agent (e.g. a co-worker). As discussed in Chapters 5 and 6, this has already been attempted (Parietti and Asada 2016; Parietti, Chan, and Asada 2014), but so far authors focused solely on the implementation of a wearable SRL, without paying attention to the inclusion of the SRL itself in the sensorimotor loop. By the designing a three-handed task complex enough to exploit the potential of human augmentation, and at the same time implementing a rich feedback system, it should be possible to enhance the human-robot interaction and boost the embodiment of the SRL. In order to do so, there are some key aspects worth discussing. First of all, to create a rich feedback it is necessary to select feedback types that would be more useful in that specific situation or task: the position feedback tested in Chapter 6 was appropriate for the feasibility test carried out in that specific experimental setup, but it might not be an optimal choice during a physical interaction between human and robot. Indeed, a feedback concerning the forces exchanged between two actors (i.e. participant and SRL) during the interaction could be more informative (Sengül et al. 2013). Hence, future works will implement and study new types of feedback that would be valuable during a human-SRL interaction like force feedbacks or joint angles.

Moreover, as discussed previously in Chapter 2.4, to study how to close a sensorimotor loop, it is necessary to consider both efferent and afferent components. In the present work, as a first step toward human augmentation, only the afferent component has been studied. This was done to simplify the experimental setup and avoid inserting another variable that could have acted as a disturbing factor when trying to understand how to best manage the sensory information to be fed back to the user. Nevertheless, once the study on sensory feedback will be complete, and the best sensory feedback type and stimulation modality will be chosen, the next mandatory step shall be to implement the efferent component as well: the user will need to move his own arms during the interaction and to command the SRL as well, relying not only on vision, but on a supplementary sensory feedback to guide the SRL for completing the task. Of course, this raises more challenges: it will be important to consider the cognitive burden the user will have to face. The human brain is likely not used to control more than four limbs and managing an interaction with an additional limb might be challenging for an untrained participant. Additionally, as discussed in Chapter 6.1, the participants brain will also need to compute a conversion of the feedback information from one sensory modality to another, because of the sensory substitution technique adopted (Nanay 2017). To summarize, future works will need to design an experimental setup based on a three-handed task, involving both user and SRL, where a highly informative yet easily understandable sensory feedback is sent back to the user, who will need to intuitively control the SRL during the interaction.

### 7.2.2 Assessment of SRL Embodiment

The present work focused on creating the necessary conditions to boost embodiment and control of a supernumerary robotic limb, i.e. closing the sensorimotor loop involving user and SRL. In other words, finding a way to close the loop is a prerequisite for SRL embodiment. Once the loop will be closed by efficiently combining afferent and efferent information into a seamless multisensory flow, it will be time to assess the embodiment of SRL, and this poses a non-trivial challenge. Some of the most common methods and techniques usually employed to test ownership and agency are discussed briefly in Subchapters 2.1.1 and 2.1.2. However, assessing the embodiment of SRL requires careful consideration: some of the methods previously discussed may not be usable, and some of the logics underlying the assessment of embodiment in other contexts may not apply. For example, some authors (Nabeshima, Kuniyoshi, and Lungarella 2007) proposed a classification of tools based on how easily they can be assimilated into our body schema (i.e. embodied). According to the authors, tools can be classified as primary (easily internalized) and secondary (hard to internalize). To incorporate the tools into the body schema, one needs not only to interact with the tool, but to know and understand its "behaviour" from a dynamical point of view, meaning that the user needs to become familiar with parameters typical of that tool such as inertia parameters, shape etc. etc. This process is relatively easy with a stick (primary tool), and definitely harder with an SRL (secondary tool) because of the intrinsic complexity of the robot itself, considering for example its degrees of freedom, irregular shape and dynamic and kinematic behaviour. The situation is made even more difficult because humans can become familiar with a tool thanks to a process known as "dynamic touch": the ability to understand features such as the length of an object by estimating inertia parameters though the kinesthetic response of the object in our hands (Turvey 1996; Miller et al. 2018). Intuitively, this relies heavily on physical continuity between hand/arm and the object, which is not necessarily present when dealing with SRL, at least in the first steps of the research progress, and even if it is, it might be more difficult to deduce inertia parameters because of the body contact surface (i.e. shoulder or back).

Moreover, one of the most powerful technique to assess embodiment of external objects is the procedure of the Rubber Hand Illusion, already described in Subchapter 2.1.1. However, as flexible as it may be, the RHI protocol might not be suitable for the SRL scenario. Indeed, an approach based on an explicit assessment of embodiment may lead to disappointing results. A more subtle approach, based on an implicit assessment might be more successful: analysing the kinematics of the participants after they interacted for some time with the SRL might reveal an altered motor behaviour coherent with the integration of the SRL into the body schema (Cardinali et al. 2009). Thus, future works will focus on designing new methods and techniques for successfully assess embodiment of SRL.

### 7.2.3 Long Term Impact of Human Augmentation

In the present work, human augmentation was considered not only as a simple human-tool interaction, but as a scenario in which a new man-machine hybrid is born, relying on the integration of the SRL into the body schema. This consideration carries a weight, from a clinical point of view, that is worth discussing, especially because of the consequences it might have on the user. Indeed, one of the greatest features of the human brain is its ability to adapt and change in response to external stimuli, i.e. brain plasticity: brain structure and connectivity are shaped by our interaction with the world, be it a positive one, which promotes a new function (e.g. learning) or a negative one, that suppress a sensorimotor function (e.g. injury or lesion) (Pascual-Leone et al. 2005; Chen, Cohen, and Hallett 2002; Hensch 2005). The brain plasticity processes related to human augmentation has already been discussed in detail by other authors (Di Pino, Maravita, et al. 2014), but in the present work I would like to consider a parallelism between the SRL-based augmentation discussed so far and the phenomenon called phantom limb pain. Phantom limb pain (Ramachandran, Rogers-Ramachandran, and Cobb 1995) has been described as the result of an aberrant brain plasticity in amputee resulting in the sharp feeling of still possessing the missing limb, together with distressing sensations like a strong itch or even a crippling pain that can take years to heal. Ultimately, this condition arises because something was taken from the body, leaving it fragmented. The man-machine hybrid mentioned previously, resulting from a successful human augmentation, is though as a temporary scenario: the user should be able to employ the SRL dexterously, perceiving it as a limb of his/her own, but only for the duration of a specific task. It is important to consider what would happen when the SRL is removed after repeated session of human-robot interaction or extensive training, leaving the user without something, i.e. the SRL, that was previously embodied. Fortunately, the scenario of a phantom robotic limb pain is an unlikely one. The Rubber Hand Illusion, and its motor counterpart, the Moving Hand Illusion do not have any type of long- or short-term consequences on subjects, even though the aim is quite different, because the RHI paradigm has the objective of boosting the embodiment of an artificial hand, while human augmentation, as discussed before, aims at something more: a human-machine dyad. For this reason, while the chance of inducing any kind of distress by embodying the SRL is extremely low, it is still a matter worth of attention when studying human augmentation.

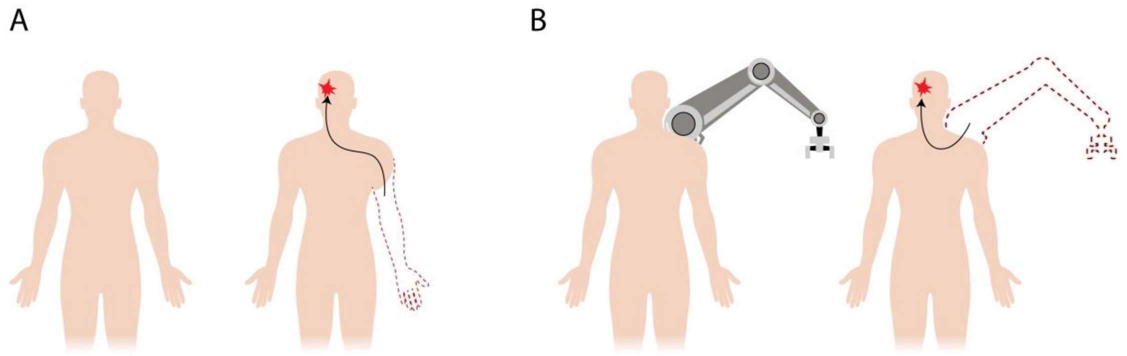


*Figure 32 – Parallelism between Phantom Limb Pain (A) and hypothetical Phantom Robotic Limb Pain (B). The missing afference from the amputated limb causes an aberrant brain plasticity which generates distressing sensations. The SRL, if removed after being integrated into the body schema, might cause a similar scenario.*

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