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par

Atena FADAEIJOUYBARI

Acceptée sur proposition du jury

Prof. A. Ijspeert, président du jury
Prof. O. Blanke, Prof. H. Bleuler, directeurs de thèse
Prof. E. Burdet, rapporteur
Prof. Y. Kim, rapporteuse
Prof. S. Lacour, rapporteuse

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Atena F.

Abstract

Recent research has highlighted the crucial role of the processing of somatosensory signals involving the torso for global aspects of Bodily Self Consciousness (BSC), i.e., the experience of the conscious "I" as embodied and localized within bodily space. Compared to advances in hand or finger-based haptic interfaces, current haptic technology for the torso is relatively underdeveloped as its operations are limited to stationary conditions and laboratory environments. My thesis aims to design, implement and validate novel torso-worn tactile displays to investigate BSC in healthy individuals with specific emphasis on robot-induced presence hallucination (PH, illusory experience of feeling someone behind) and tactile gait agency.

First, I examined if torso-worn haptic interfaces can be used to induce specific alterations of BSC (passivity, self-touch, and PH) in healthy individuals by adapting a robotic system and paradigm previously established by our lab (Blanke et al. 2014) to the torso-worn haptic interface. In a feasibility study in healthy individuals, a torso-worn vibrotactile display (Study1) successfully induced the illusory sensations of being touched (passivity experience). Next, I developed CognoVest, a portable, torso-worn force interface that I designed to provide human-like poking stimuli on the user's back. Study 2 confirms the induction of illusory self-touch and passivity experiences by CognoVest and the induction of PH of mild to moderate intensity in healthy individuals. In Study 3, I extended the use of torso-worn haptic interfaces to the research on conscious action monitoring and investigated the sense of agency (SoA; a core aspect of BSC) for the entire body. To this aim, I developed the FeetBack system that examines the sensorimotor perception of tactile action consequences during locomotion, as previously tested by our lab for auditory and visual action consequences. Study 3 extends prior findings on the auditory or visual gait agency to the sense of touch and shows that delayed remapped tactile feedback systematically modulates SoA for walking. Finally, I examined and compared tactile spatial discrimination on the human back (Study 4) for force and vibrotactile stimulation, using interfaces realized in Study 2 and 3, thus providing a first direct (within-participant) evaluation of such interfaces.

At the intersection of haptics and behavioral neuroscience, my thesis makes contributions by taking the first steps towards the design, and validation of torso-worn haptic interfaces as well as their applications in stationary/mobile sensorimotor experimentation settings. My findings for tactile perception on the back suggest that designers can use force stimulators to design the torso-worn tactile interface to provide more ecological touch feedback with a (almost) similar level of tactile spatial discrimination accuracy as observed in widespread vibrotactile interfaces. I applied this approach to the design of the CognoVest that induced systematic change in self-other distinctions. Results with CognoVest might have important implications for developing wearable therapeutic devices to down-regulate specific psychotic symptoms in patients with PH experiences. Moreover, I showed that healthy walkers had strong SoA for remapped tactile feedback, suggesting that the FeetBack system could potentially be used to enhance gait awareness in patients with gait deficits.

Keywords

Bodily self-consciousness, torso-worn haptic interface, force vest, vibrotactile vest, tactile action consequence, presence hallucination, wearable haptics, sense of agency, bodily illusions, tactile spatial discrimination, self-consciousness.

Résumé

Des recherches récentes ont mis en évidence le rôle crucial du traitement des signaux somatosensoriels impliquant le torse pour les aspects globaux de la Bodily Self Consciousness (BSC), c'est-à-dire l'expérience du «je» conscient incarné et localisé dans l'espace corporel. Par rapport aux progrès des interfaces haptiques à la main ou au doigt, la technologie haptique actuelle pour le torse est relativement sous-développée car ses opérations sont limitées aux conditions stationnaires et aux environnements de laboratoire. Ma thèse vise à concevoir, mettre en œuvre et valider de nouvelles interfaces tactiles portés sur le torse pour étudier le BSC chez des individus en bonne santé avec un accent spécifique sur l'hallucination de présence induite par un robot (PH; « hallucination de présence », expérience illusoire de sentir quelqu'un derrière) et la surveillance tactile de la démarche consciente.

Tout d'abord, j'ai examiné si les interfaces haptiques portées sur le torse pouvaient être utilisées pour induire des altérations spécifiques de la conscience de son propre corps (BSC) en étudiant les sensations de passivité de contact tactile et d'halluciations de présence (PH) chez des individus en bonne santé en adaptant un système robotique et un paradigme préalablement établi par notre laboratoire (Blanke et al.2014) à l'interface portée sur le torse. Dans une étude de faisabilité chez des individus en bonne santé, un affichage vibrotactile porté sur le torse (étude 1) a induit avec succès les sensations illusoires d'être touché (expérience de passivité). Ensuite, j'ai développé CognoVest, une interface haptique portable, portée sur le torse, que j'ai conçue pour fournir des stimuli tactiles de type humain sur le dos du porteur. Les résultats de cette étude 2 confirment l'induction d'expériences illusoires de contact personnel et de passivité par CognoVest et l'induction de PH d'intensité légère à modérée chez les individus en bonne santé. Dans l'étude 3, j'ai étendu l'utilisation de ces interfaces haptiques portées sur le torse à la recherche sur les mécanismes sensori-moteurs pour l'ensemble du corps, un aspect fondamental de la conscience de son propre corps (BSC). Cette recherche offre des perspectives pour de nouveaux dispositifs de neuro-réadaptation. Dans ce but, j'ai développé le système FeetBack qui étudie une perception sensori-motrice renforcée lors de la locomotion, comme précédemment testé par notre laboratoire dans le cas de rétroactions auditives et visuelles. Cette étude 3 étend les résultats antérieurs de rétroactions de la marche purement auditives ou visuelles au sens tactile et montrent que cette rétroaction haptique module la conscience motrice de la marche de manière prévisible. Enfin, dans l'étude 4, j'ai examiné et comparé la localisation des points tactiles (PL) et la discrimination de direction (DD) sur le torse humain (dos) en utilisant les interfaces réalisées dans les études 2 et 3, fournissant ainsi une première évaluation directe (intra-participant) de ces interfaces.

À l'intersection de l'haptique et des neurosciences comportementales, ma thèse a apporté des contributions en faisant les premiers pas vers la conception et la validation d'interfaces haptiques portées sur le torse ainsi que de leurs applications dans des contextes d'expérimentation sensorimotrice stationnaire/mobile. Mes résultats pour la perception tactile sur le dos suggèrent que les concepteurs peuvent utiliser des stimulateurs de pression pour concevoir l'interface tactile portée sur le torse afin de fournir un retour tactile plus écologique avec un niveau (presque) similaire de précision de discrimination spatiale tactile comme observé dans les interfaces vibrotactiles répandues. J'ai appliqué cette approche à la conception du CognoVest qui a induit un changement systématique dans les distinctions entre soi et autrui. Cette découverte avec CognoVest pourrait avoir des implications importantes pour le développement de dispositifs thérapeutiques pour réguler à la baisse les symptômes psychotiques spécifiques chez les patients ayant des expériences de PH. De plus, j'ai montré que les marcheurs en bonne santé avaient une forte conscience motrice avec une retroaction tac-tile, ce qui suggère que le système FeetBack pourrait potentiellement être utilisé pour améliorer la conscience de la marche chez les patients présentant des déficits de marche, et ainsi contribuer à corriger de tels problèmes.

Mots-clés

Conscience de soi corporelle, interface haptique portée sur le torse, gilet de force, gilet vibrotactile, conséquence de l'action tactile, hallucination de présence, haptique portable, sens de l'action, illusions corporelles, discrimination spatiale tactile, conscience de soi.

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Chapter 1 Introduction

"Touch comes before sight, before speech. It is the first language and the last, and it always tells the truth."

Margaret Atwood

1.1 Motivation and overview

We live in this world as human beings, and we can distinguish ourselves from other beings. How is this possible? Is it simply because our physical body is separated from other living creatures? Cognitive neuroscientists have investigated the experience of the self and found that self-consciousness is the result of the multisensory mechanisms of the brain, rather than the body's purely physical composition (Blanke 2012; Blanke et al. 2015). Indeed, our brain integrates different bodily information (e.g., visual, touch, auditory, proprioception) to build a functional representation of the body. This phenomenon is known as bodily self-consciousness (BSC) and depends on integrating the constant flow of multisensory bodily signals (see Figure 1:1). Recently there has been growing interest in the empirical investigation of BSC (Botvinick and Cohen 1998; Ehrsson et al. 2005; Lenggenhager et al. 2007; Ionta et al. 2011; Blanke 2012; Blanke et al. 2014). In these studies, participants were exposed to conflicting multisensory bodily signals about the location, appearance, and synchrony of one's own body signals. This allowed researchers to study three important aspects of BSC: self-location, self-identification, first-person perspective, in order to investigate their multisensory origins and functional and neural mechanisms they may share. In addition, in ambiguous multisensory situations, participants are prone to report significant alteration of their bodily experience, known as illusory own body perception, that is of relevance for the clinical population (e.g., neurological and psychiatric patients (Llorca et al. 2016)) or even healthy individuals in specific circumstances (Botvinick and Cohen 1998; Lenggenhager et al. 2007; Blanke et al. 2014).

Researchers in cognitive neuroscience have recently highlighted the crucial role of processing somatosensory signals from the torso for global aspects of BSC, such as self-identification and self-location (Blanke 2012; Park and Blanke 2019). This theory was inspired by conceptual work in philosophy of mind (Metzinger 2004; Blanke and Metzinger 2009) and clinical studies (neurological patients with BSC disorders (Blanke et al. 2008)) and has recently been confirmed by experimental studies in healthy individuals (Ehrsson 2007; Lenggenhager et al. 2007; Blanke and Metzinger 2009; Blanke et al. 2014). Such paradigms involve applying repetitive tactile stimuli onto the back or chest, either combined with visual/vestibular stimulations or as a consequence of participants' actions (find more details in 1.2.1). In earlier studies, passive tactile stimulations were provided manually by experimenters (Ehrsson 2007; Lenggenhager et al. 2007). However, the manual procedure is not standardized and does not guarantee sufficient precision in time-delay and repeatability of tactile stimuli due to natural variability in human actions. Recently, technological advances in robotic have allowed researchers to registers active touch stimuli on the human torso in a multisensory conflict set, using leader-follower automated systems (Hara et al. 2011; Ionta et al. 2011; Blanke et al. 2014; Bernasconi et al. 2020) (in the present thesis we call them Front-Back robot; see Figure 1:2 and Figure 1:3). Despite these recent achievements, haptic technology is relatively underdeveloped, compared to the advances in auditory (e.g., sound specialization, 3D audio, etc.) and visual techniques (such as VR/AR technology, stereoscope view, etc.). For instance, while employing the leader-follower robot to provide tactile cues is limited to stationary conditions and laboratory environments, the emerging visual and auditory technologies allow researchers to handle varied multisensory incongruencies via small-scale and portable setups (Menzer et al. 2010; Knierim et al. 2020). Notably, the technological gap is even more severe for rendering tactile stimuli on the human torso. As an almost immovable part of the human body, the torso is less sensitive to tactile stimulations (Myles and Binseel 2007); however, it provides a large area to receive tactile cues. Moreover, due to significant morphological changes in the torso areas, the tactile interface design for the torso is complex and highly individual-dependent (Lindeman et al. 2006). Recent studies have addressed these issues using tactile torso textiles (e.g., braces, vests, etc.) that provide haptic sensation on the human torso (see Figure 1:7). These studies have demonstrated the promising potential of torso-worn haptic interfaces in various applications ranging from navigation (Ertan et al. 1998; Rupert 2000; Paun 2018; Viola et al. 2018), immersion in VR (Nescio 1991; Lemmens et al. 2009; Arafsha et al. 2015; Lentini et al. 2016) to sensory-substitution (Ertan et al. 1998; Johnson and Higgins 2006; Wacker et al. 2016; Buimer et al. 2018). Hence, in this thesis, I took the first step towards developing and using torso-worn tactile interfaces to investigate self-other distinction, Sense of Agency (SoA; for a detailed description, see 1.2.4), and tactile perception on the torso.

In **Study**[1] **1** and **2** of my thesis, I focused on a specific psychosis symptom, named Presence Hallucination (PH; detailed information in 1.2.3). Presence Hallucination (PH) is a strange sensation, during which one feels that there is someone nearby when in reality there is no one present (James 1985). This subjective experience has been reported by individuals suffering from neurological (e.g., Parkinson's Disease) or psychiatric (e.g., schizophrenia) illnesses as well as healthy individuals in extreme conditions, like high mountain climbing, extreme divers, or elderly individuals suffering from bereavement (Brugger et al. 1999; Geiger 2009). Our group recently revealed its underlying brain mechanism and network and linked them to deficits in BSC (Blanke et al. 2014). They induced PH and related own-body illusions artificially in the laboratory, in a non-invasive fashion, by providing contradictory somatosensory-motor signals between users' hands and torso (back; see Figure 1:2). Considering the technology-dependent nature of PH research, so far, our group has developed and employed two stationary robotic systems aiming to experimentally induce PH, including "standing" (Blanke et al. 2014) and "supine" robots (see Figure 1:3; MRI-compatible robot particularly for neuroimaging study (Hara et al. 2014)). These robotic systems are capable of providing somatosensory-motor conflicts between participants' hands and back. However, currently no wearable and portable PH system exists. The importance of a wearable system is that it provides the possibility of studying PH in more ecological settings (daily living and real-life conditions outside the laboratory in the clinics). This is crucial in clinical populations where the PH is reported to occur at a particular time and in

[1] Each study presented in an individual chapter.

specific environments (Williams et al. 2008; Fénelon et al. 2011) as well as for the testing of PH in healthy subjects far from the research laboratory (i.e. hiking, extreme mountaineering).

In **Study 1**, I took an initial step towards developing a semi-wearable vibrotactile PH system by integrating a torso-worn vibrotactile interface and a one-handed haptic interface. In a feasibility study, I replicated the standard PH effects to show the possibility of this novel PH induction system and find essential criteria for the future design. Furthermore, to determine the human's back vibrotactile perception and its correlation with induction of PH-related phenomenon with the proposed setup, I added a vibrotactile localization task to the original study. My results showed that with our semi-wearable, vibrotactile setup, I could induce the illusory sensations in healthy participants of being touched by somebody else (i.e. passivity experience); however, our experimental setup failed to induce the illusory experience of touching one's own back (i.e. self-touch) and, importantly, of the PH. Participants' post-experiment debriefings revealed that the simple vibration sensation was not an appropriate replacement for the natural human poking stimuli. My main practical conclusion was that the ideal torso-worn tactile interface for PH studies should provide localized, equally perceived tactile stimuli while guaranteeing correct fit, firm support, and free-breathing.

While vibrotactile displays have commonly been used in many recent wearable haptic interfaces (Wall et al. 2001; Lindeman and Yanagida 2003; Johnson and Higgins 2006; Lieberman and Breazeal 2007; Wacker et al. 2016; Buimer et al. 2018; Paun 2018; Barone et al. 2019; Richardson et al. 2019), limited research has been published on the use of force displays to provide collision-type touch stimuli (a more common haptic experience in daily life) on the users' skin (Lopes et al. 2015; Delazio et al. 2018; Garcia-Valle et al. 2018). This might be because compared to vibrotactile devices, force feedback interfaces demand higher considerations in the interface design and handling procedure, as they are often heavier, and their perceptions depend upon the actual physical contact with the skin. In **Study 2**, I addressed this issue by placing light force actuators in custom 3D printed boxes that can be mechanically adjusted at different distances with respect to the skin. I further characterized "human finger poking" and showed that embedded force actuators could provide comparable feedback. I fixed these actuator boxes to a Y-harness brace and named the whole system CognoVest. I conducted a behavioral study with CognoVest that investigated illusory induction of PH and related passivity symptoms (i.e., where ones' actions are perceived as not self-generated and caused by an external entity). My data confirmed the induction of illusory self-touch and passivity experiences by CognoVest, as well as the induction of PH of mild to moderate intensity in healthy individuals. I argue that the system and obtained results are of interest for the future development of wearable therapeutic devices to down-regulate or control PH-related symptoms in psychosis patients.

In **Study 3**, I extended the application of torso-worn haptic interfaces to a mobile sensorimotor manipulation setting and conducted research into the sense of agency (SoA; an important aspect of BSC (Jeannerod 2003; Jeannerod and Pacherie 2004); see 1.2.4) for full-body movement and neurorehabilitation devices. While the integration of the audio-visual feedback into the sensorimotor control has been widely investigated for both body parts, or full-body movements, to the best of our knowledge, there is no individual study investigating the effect of tactile action consequence on the SoA and the accompanying motor adaptation. The lack of studies investigating the consequences of tactile feedback could be due to the fact that the spatiotemporal manipulation of the actual sense of touch is not technically possible. In **Study 3**, I addressed this issue by employing a tactile remapping technique that reproduces the real touch action consequence, in our case, the foot rolling sensations, onto the skin of the users' torso. To this aim, I developed the FeetBack system that investigates the sensorimotor perception of tactile action consequences during locomotion as previously tested by our lab for auditory (Menzer et al. 2010) and visual (Kannape and Blanke 2013) action consequences (for more details, see 1.2.4). FeetBack is a novel portable torso-worn vibrotactile display integrated with an automatized wearable gait measurement system and provides step-related remapped feedback in the form of vibrotactile apparent movement (VAM) on the users' back during free walking. My data were in line with prior findings on the auditory (Menzer et al. 2010) or visual gait agency (Kannape et al. 2014) that delayed feedback changes SoA for walking in a systematic manner even when presented in the form of remapped tactile feedback. I also observed a general impact of tactile remapped feedback on the participants' stride time deviation; nevertheless, this was not specific to the delay or systematic as in prior studies. These are promising results with respect to developing devices for gait and gait awareness that are of relevance for clinical populations suffering from gait abnormalities.

While most of the previous research on tactile perception have mainly focused on distal body parts such as fingers, hands, forearms (Cholewiak and Collins 2003; Oakley et al. 2005; Azadi and Jones 2013; Sofia and Jones 2013; Medina et al. 2018), tactile perception on the torso areas have been investigated to a surprisingly lesser extent. To broaden the current knowledge of tactile perception on the torso, in **Study 4**, I examined and compared tactile point localization (PL) and direction discrimination (DD) on the human torso (back) for force and vibrotactile stimulation using interfaces realized in Study 2 and 3. My data showed a strong positive correlation between performances with both stimulators; however, accuracies were slightly higher with vibrotactile (61-71%) than the force (55-68%) stimulations across tasks. Moreover, for the first time, I investigated the association between performances of two tasks using within participants' design and found that tactile performance extends across tasks (PL and DD) for force stimulations but not for vibrotactile ones. I also report directional anisotropy (direction dependencies) in both tasks and both types of stimulations, with participants making fewer localization errors in the horizontal than vertical axes.

In the following sections, I review some of the fundamental theories and works needed to understand the scientific background of the studies presented in chapters 2 to 5 (each chapter includes one study). First, I introduce BSC, as related to the current thesis, with a specific focus on the robot-induced presence hallucination and sense of agency. Then, I introduce relevant literature on tactile perception and spatial discrimination on the torso. Subsequently, I review the recent torso-worn haptic displays developed in the literature.

1.2 Bodily self-consciousness

Humans experience an "I," located in one's own body, and is experienced as the subject and agent of perception, action, and thought. This is an important aspect of self-consciousness, namely the feeling that conscious experiences are bound to the self and experience a unitary entity (the "I") (Gallagher 2000; Jeannerod 2003; Blanke and Metzinger 2009; Blanke et al. 2015). Research in clinical and basic human neuroscience has recently investigated bodily aspects of self-consciousness, based on the processing of sensorimotor and/or multisensory bodily signals (bodily self-consciousness: BSC) (Blanke et al. 2008; Blanke and Metzinger 2009; Blanke 2012). Indeed, the human brain integrates multiple sensory information (see Figure 1:1) that is received from inside and outside of the body to build the conscious experience of the self. The spatiotemporal integration of these signals is important for self representation and for its differentiation from other agents (Ehrsson et al. 2005; Blanke and Metzinger 2009; Tsakiris 2010; Aspell et al. 2011; Blanke 2012). Hence, disturbances in the multisensory mechanism of the brain can lead to temporal alternation, such as in experimentally induced bodily illusions (Botvinick and Cohen 1998; Ehrsson 2007; Lenggenhager et al. 2007; Aspell et al. 2011) or more stable alternation, as in pathologic conditions (Diederich et al. 2009; Nierula et al. 2017; Pozeg et al. 2017; Ronchi et al. 2018) of BSC. In both states, due to impaired BSC mechanisms, people may even experience illusory replication of their own body, i.e., perceiving a second own body or a second self (i.e., double) in the environment (Ronchi et al. 2018).

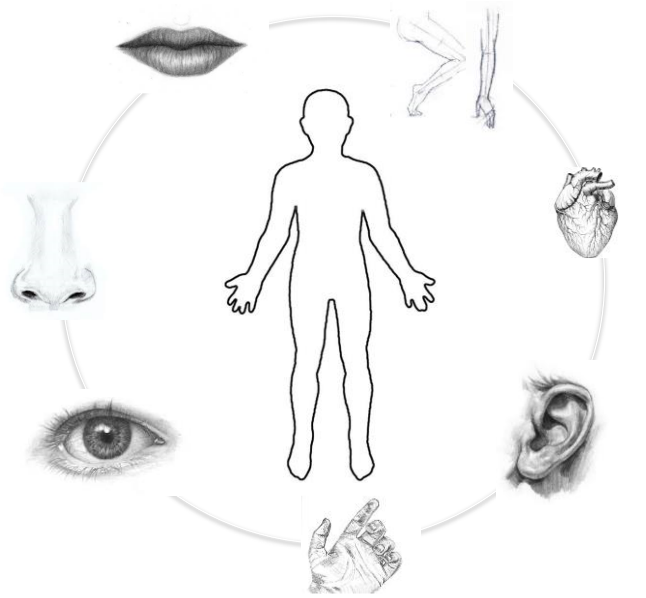

Figure 1:1 Bodily signals.

Humans receive a constant flow of sensory inputs ranging from visual, auditory, olfactory, and tactile information that not only inform them about the environment but, particularly in combination with vestibular and interoceptive feedback, are crucial to creating an integrated, unitary representation of our body. This representation, in turn, shapes how humans perceive and interact with the environment. In this view, the body representation in the brain is a complex crossroad where multisensory information is integrated to build the basis for bodily self-consciousness (BSC) (Blanke 2012).

1.2.1 Experimental manipulation of BSC

While investigating BSC disorders in clinical populations is important to understand the relationship between the representation of the body and the self, this technique may suffer from several limitations. For instance, such studies generally involve a limited number of patients (i.e., the small sample size of clinical studies) and, most likely, cannot explain normal bodily self-consciousness mechanism in healthy subjects due to the long-term pathological history of these patients. Recently, the experimental manipulation of bodily signals (that is, bodily self-consciousness) has been recognized as a powerful approach to investigate BSC and its underlying brain mechanism. In this approach, participants would be exposed to the conflicting (spatially or temporally) sensorimotor information of their own body, which leads to altered states of BSC, such as changes in self-identification, self-location, and first-person perspective. The Rubber Hand Illusion is the most popular experimental paradigm that induces illusory body-parts ownership of a fake hand via delivering conflicted visuotactile signals (Botvinick and Cohen 1998). Lenggenhager et al. (2007) extended this concept to the Full-Body-Illusion by providing tactile stimuli on the participant's torso. Out-of-Body-Experiences (OBE, a sensation of being outside one's own body) were investigated by Ehrsson (2012) by delivering incongruent visuotactile signals again to the participant's torso. Yet, experimentation of these paradigms is complicated as bodily signals are consistently present, updated, and transferred across various senses as well as via motor and visceral signals (Blanke 2012). To control precisely visual and tactile stimulations, recent studies have used video, virtual reality (VR) (Lenggenhager et al. 2007), and robotic technologies (Dummer et al. 2009; Hara et al. 2011; Blanke et al. 2014; Bernasconi et al. 2020). These ensure good repeatability, precise spatiotemporal control resolution, and dynamic manipulation of temporal synchrony. For instance, Ionta et al. (2011) deployed robotically-controlled multisensory conflicts that manipulate the synchrony between the stroking of the participant’s back and the back of a visually presented virtual human body to induce changes in self-location. More recently, the development of MRI-compatible robotic technology has allowed performing these paradigms in MRI environments (Ionta et al. 2011; Hara et al. 2014), thereby allowing the investigations of the neural mechanisms of these illusions with precision (Rognini and Blanke 2016).

1.2.2 Torso-centered BSC

Research on cognitive neuroscience (experimental or neuroimaging) has exclusively concentrated on the investigation of either exteroceptive signals (sensory signals originating from the space outside the body such as tactile, visual, auditory; e-BSC) or interoceptive signals (sensory signals received from the visceral organs such as cardiac, respiratory, etc.; i-BSC) to explain the underlying mechanism in experimentally and neurologically altered states of BSC (Park and Blanke 2019). However, it has been shown that separating the contribution of these two signals is not possible as we experience a single coherent self rather than separate exteroceptive and interoceptive selves (Jeannerod 2003; Blanke 2012). Only recently, Park and Blanke (2019) proposed an x-BSC system with no interoceptive or exteroceptive preference and is based on torso-centered signals. According to their proposal, multisensory stimulation involving torso regions leads to alterations of global aspects of BSC, such as self-identification and self-location. They explained this hypothesis using the spatial law of multisensory integration that states inputs from different modalities can be integrated more efficiently when they occur closer in space (Blanke et al. 2015). Since visceral organs are located on the torso, interoceptive cues (e.g., heartbeat, respiration) are spatially collocated with bodily signals from the torso (visual, vestibular, somatosensory), which may benefit multisensory perception of torso-centered exteroceptive signals with interoceptive signals. In this process, somatosensory signals play a unique role because they can happen in the form of both exteroceptive and interoceptive input. For instance, inspiratory– expiratory respiration cycle and cardiac contractions both lead to mechanical stimulation of the chest (at the pleura or skin chest, and the internal wall of the chest, respectively), which eventually activate the somatosensory system (Park and Blanke 2019).

While the concept of torso-centered global BSC was first inspired by conceptual work in philosophy of mind (Metzinger 2004; Blanke and Metzinger 2009) and clinical data in neurological patients (with BSC disorders) (Ehrsson 2007; Blanke et al. 2008), it was tested and confirmed recently in experimental works with healthy individuals. Such studies investigated visuotactile and visuo-vestibular stimulations at the torso for the induction of more global changes in BSC, such as “full-body,” “out-of-body,” or “body-swap” illusions (Ehrsson 2007; Lenggenhager et al. 2007; Aspell et al. 2011; Petkova et al. 2011). To do so, they used paradigms that involve the repetitive tactile stimulation on the back or chest of a participant who can view the stroking of a human body (via real-time video) or virtual reality animation (via a head-mounted display), in front of her/him, at a farther location. For instance, in the full-body illusion, participants self-identify with the seen virtual body (change in self-identification) and show a forward drift in self-location (the experience of where ‘‘I’’ am in space) toward the position of the virtual body. Recently Blanke et al. (2014) used torso-related sensorimotor paradigm (instead of multisensory) to investigate the presence of hallucination and relevant illusory own-body perceptions experimentally in normal participants. The following section is dedicated to the concept of PH and the recent achievements on robot-induced PH in healthy individuals.

1.2.3 Presence hallucination

PH is a strange sensation, during which one feels that there is someone nearby when in reality there is no one present. William James, a psychologist, described PH firstly in 1902: *"It often happens that a hallucination is imperfectly developed: the person affected will feel a 'presence' in the room, definitely localized, (…) and yet neither seen, heard, touched, nor cognized in any of the usual 'sensible' ways."* (James 1985). The same phenomenon was described by Jaspers (Jaspers 1990) in 1913 with the title of leibhaftige Bewusstheit: *"There are patients who have a certain feeling (in the mental sense) or awareness that someone is close by, behind them or above them, someone that they can in no way perceive with the external senses, yet whose actual/concrete presence is directly/clearly experienced"* (translation by Koehler and Sauer (Koehler and Sauer 1984)).

The PH has been reported in several pathological conditions, consisting of schizophrenia and "schizotypal personality disorder" (Spitzer and Williams 1980; Koehler and Sauer 1984), Parkinson's disease (PD) (Williams et al. 2008; Fénelon et al. 2011), and dementia with Lewy bodies (Chan and Rossor 2002; Nagahama et al. 2009). PH may also occur as an epileptic aura (Biraben et al. 2001; Landtblom 2006; Picard 2010) or following brain damage (Persinger 1994; Brugger et al. 1996). Concerning the frequency of PH, the result of an online study in Parkinson's disease (PD) patients has shown that 35 individuals reported the PH (of an undefined person) out of 216 PD patients (Diederich et al. 2009), and it is known as early PD psychosis symptoms (Creese et al. 2017). PD patients described this vivid sensation as a "perception." For instance, one patient said "I turned back, but nobody is there," a third said: "I take a look; I do not see anything, but it is engraved in my mind" (Diederich et al. 2009). PH was reported even in healthy individuals. For instance, there are anecdotal reports of PH occurring in extreme circumstances, like during shipwrecks or high-altitude mountain climbing (Podoll and Robinson 2001).

It has been suggested that PH is a disorder of body representation in general and sensorimotor integration in particular (Brugger et al. 1996; Arzy et al. 2006; Blanke et al. 2008). This phenomenon has been tested recently by using robotic devices that are able to provide specific sensorimotor conflict between hands and back. As a first experimental study, Blanke et al. (2014) developed a front-back robot that registers poking-like sensations on the participants' back as a consequence of hand movements. Participants manipulated the front haptic interface using their right index finger (via 3D printed finger support) to control the position of the back robot, which in turn provides touch-cues to the participant's back. Blanke et al. (2014) found that participants felt an illusory experience of touching their own back (Self-touch) in the synchronous condition. A further experimental condition, in which participants received a delayed touch on the back, showed that participants felt the illusory sensation of being touched by somebody else (passivity experience) and of feeling someone behind them (PH). Moreover, during post-condition debriefing, five (out of 17) subjects reported having experienced a PH. In the consequent study, the authors developed an fMRI-compatible version of their setup, allowing inducing the PH in the scanner. The results obtained from healthy subjects demonstrated the underlying brain regions, involved in PH (PH network), which also correspond to what has been seen in neurological patients, suggesting that the robotically-induced PH has similar brain mechanisms like the PH evidenced in patients (Bernasconi et al. 2020).

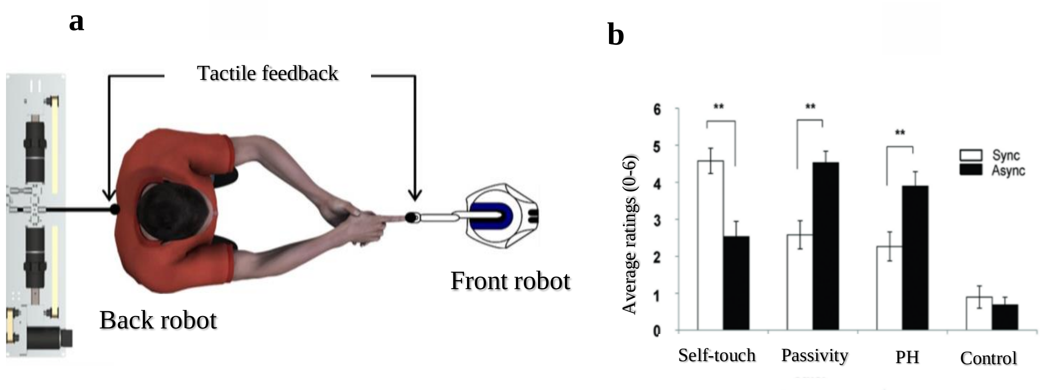

Figure 1:2 Robot-induced bodily illusions.

(a) Experimental setup employed in (Blanke et al. 2014): participants produce forward-backward poking movement with the front robot, and consequently, they received tapping-like tactile stimuli, produced by the back robot, on their back with and without temporal delay (delayed by 500 ms). (b) Results of the behavioral study with the robotic system. Assessing subjective experience following two minutes of robotic sensorimotor stimulation. In the synchronous condition, participants perceived only spatial sensorimotor mismatches between the pokes and the corresponding touches. A temporal mismatch was added in the asynchronous, and participants reported stronger self-touch, passivity, and presence hallucination sensations. (adapted from (Blanke et al. 2014))

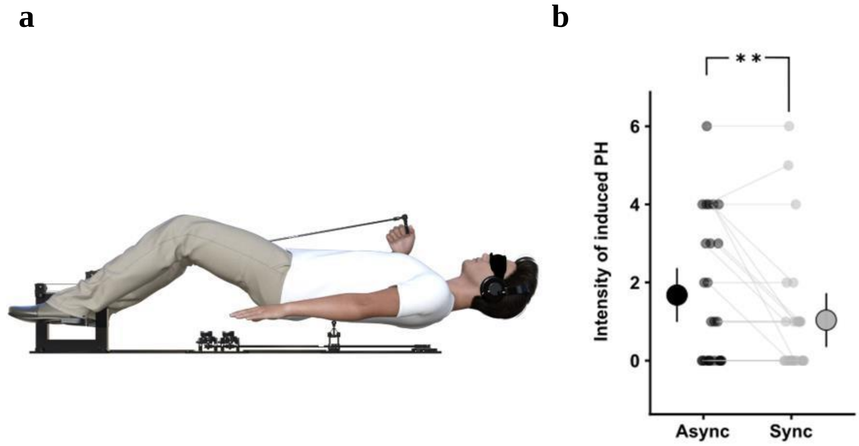

Figure 1:3 Robotically-induced presence hallucination in the MRI environment.

(a) MRI-compatible robotic system used in (Bernasconi et al. 2020). Participants were instructed to move the front robot with their right hand, and the back robot delivered the touch to the participant's back either synchronously or asynchronous (500ms delay between their movement and the sensory feedback received on the back). (b) Result of behavioral study (Bernasconi et al. 2020): subjective responses from Linkert-scale questionnaire. The presence of hallucination was reported stronger (*, $p<0.05$), in the asynchronous (Async), compared to the synchronous (sync) experimental condition.

1.2.4 Sense of agency

Human actions are one of the important ways to interact with the external world (Jeannerod and Pacherie 2004). When we move or observe someone else moving, we can automatically attribute those actions to its corresponding agent; in other words, we differentiate ourselves from the environment and even from other agents (Daprati et al. 1997; Jeannerod 2003; Jeannerod and Pacherie 2004). This automatic recognition of the author of action is known as the sense of agency (SoA). SoA describes the feeling of being in control and of being the author of one's actions (Gallagher 2000). It has been proposed that the SoA relies on a mechanism named the internal forward framework. Figure 1:4, which is capable of discriminating self-produced from externally generated actions or other relevant sensory signals. According to the internal forward model, for any motor command sent to muscles, a copy is sent to the sensory areas (efference copy) to predict the sensory feedback. If the actual sensory feedback matches the predicted one, the sensory feedback is attenuated, and we attribute this action to ourselves (Frith et al. 2000). Sensory attenuation happens automatically by the brain for the self-generated feedback, which results in them being less strongly perceived, e.g., we cannot tickle ourselves (Blakemore et al. 2000). However, any mismatch between the predicted and desired state leads to judging self-generated actions as externally generated. In general, the internal forward model is accepted for sensorimotor control, motor estimation, prediction, and motor learning (Wolpert et al. 1995). It may also explain the passivity experiences reported in schizophrenic patients, where a patient feels that his own actions are being created, not by himself, but by some outside force (Schneider 1957; Frith et al. 2000; Schneider 2007). Passivity experiences range from delusions of control, though insertion to auditory-verbal hallucinations, and these all reflect abnormalities in SoA (Schneider 1957; Frith and Done 1989; Fourneret and Jeannerod 1998; Schneider 2007).

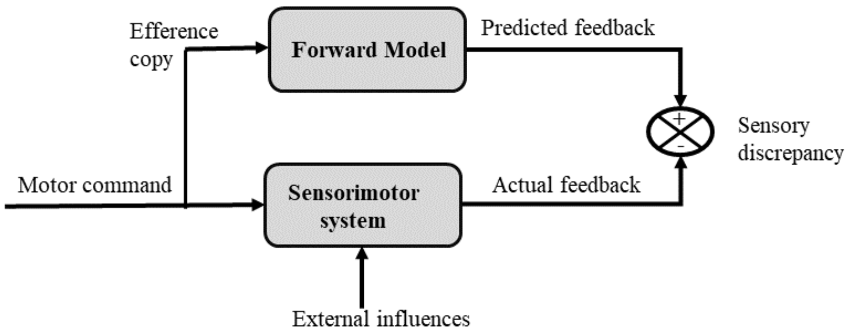

Figure 1:4 Intental forward model scheme adopted from (Blakemore et al. 2000).

Forward models (upper branch) and sensorimotor processing (lower branch) efficiently predict future states of the system and actual sensory feedback, respectively. These predictions are compared to make humans aware of abnormal behavior. If there is a mismatch between the predicted and actual sensory feedback, that action is misattributed.

Following the early work by Nielsen (1963), there has been intensive research on the sense of agency where the participants' conscious action monitoring or motor awareness (MA) was investigated by introducing the spatiotemporal mismatches between their self-generated actions and the feedback (visual or auditory) they received (Fourneret and Jeannerod 1998; Franck et al. 2001; Knoblich and Kircher 2004; Knoblich and Repp 2009). Some of these studies used intentional binding paradigms (Suzuki et al. 2019), such as bottom pressing, which evaluates compression of the time interval between an intentional action (e.g., a button press) and its outcome (e.g., a brief auditory tone) (Sato and Yasuda 2005; Repp and Knoblich 2007; Sato 2008; Knoblich and Repp 2009). However, these studies only referred to a specific aspect of the agency, which depends on the immediate action-outcome rather than the actual sensorimotor component and movement. On the other hand, other agency studies investigated how and to what extent participants can consciously access their motor performance by using paradigms that include goal-oriented but continuous limb movements, e.g., hand drawing, opening and closing hand (Fourneret and Jeannerod 1998; Slachevsky et al. 2001; Knoblich and Kircher 2004; Salomon et al. 2011). For instance, hand drawing studies (Nielsen 1963; Fourneret and Jeannerod 1998; Slachevsky et al. 2001) have revealed that participants automatically aligned their hand trajectories with a visual target on the computer screen while compensating for a displayed spatial deviation. They were often unaware of their online corrections and judged many of these actions as non-deviated. Yet, there is still a large bias in goal-directed movements because of reaching that goal. The main distinction between SoA and movement details comes with locomotion research. Locomotion is cyclic, more rarely immediately goal-directed, and generally considered a highly automatic and unconscious action (Grillner and Wallen 1985; Armstrong 1988). Gait agency research not only can investigate the SoA as in previous paradigms but also motor adaptation that is distinct from SoA and independent of reaching a target or achieving a goal/immediate action outcome. Additionally, such research would allow us to investigate full-body SoA as participants move their entire bodies during locomotion. As a pioneer work, Menzer et al. (2010) investigated auditory SoA during free walking using a paradigm in which participants judged their SoA for temporally delayed sounds of their footfalls during free walking (see Figure 1:5). Kannape and Blanke (2013) also measured SoA during gait movements using visuomotor conflicts. Both walking SoA studies found a systematic and predictable relationship between SoA judgments and the extent of the temporal delay (Kannape and Blanke 2013). They also demonstrated periodic adjustments in participants walking speed.

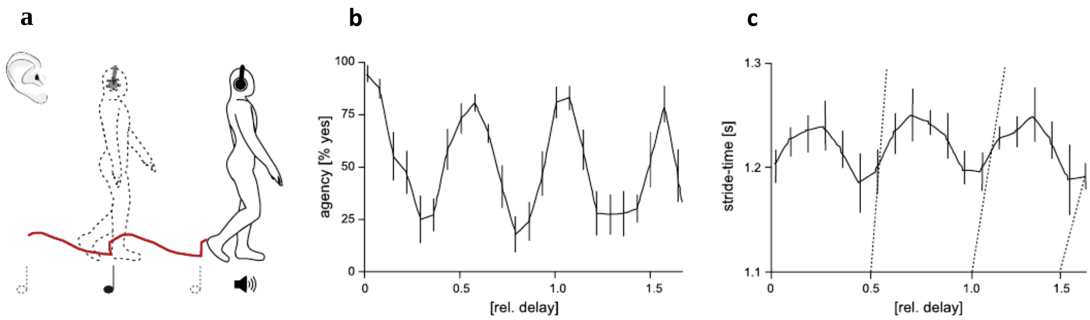

Figure 1:5 Auditory-motor conflict during free walking.

(a) Participants wore specially adapted shoes which were equipped with open microphones. Participants received auditory feedback of their footsteps with a specific range of delays (19 random delays of up to 1800 ms) while walking continuously in a 20 m by 4 m hallway. (b) Corrected-agency judgment across normalized delay conditions. Agency judgment changes as a function of delay with a sinusoidal pattern. The maximum agency was observed for trials with half-cycle and full-cycle delay, while the minimum was observed for out-of-phase trials. (c) Gait period as a function of the normalized delay. The average gait period demonstrates small but systematic variation with the delay period in a sinusoidal pattern. Based on (Menzer et al. 2010) and (Kannape and Blanke 2012).

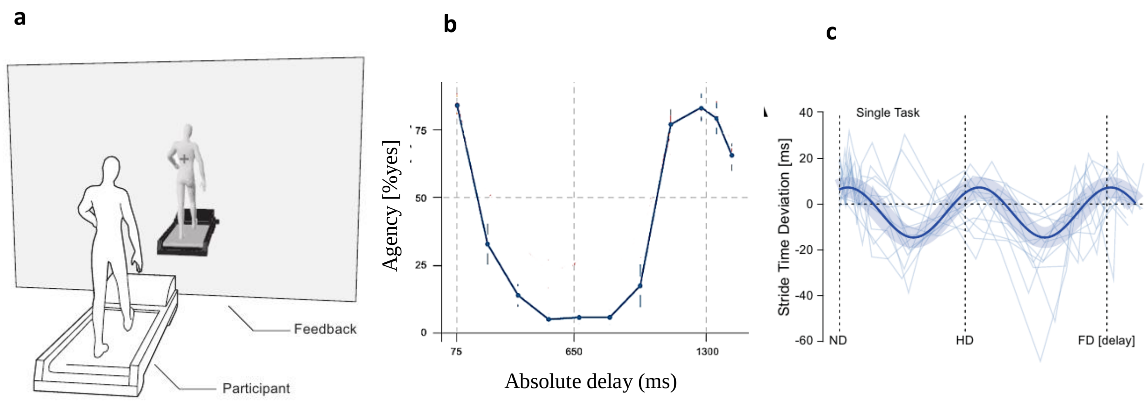

Figure 1:6 Visual-motor conflict during treadmill walking based on (Kannape and Blanke 2013).

(a) Experimental setup. Participants were asked to walk on a treadmill continuously, and an optical motion capture system was used to detect their movements. These movements were mapped onto an individually adapted life-size avatar and projected on a screen placed 2 m in front of the participants. Visual feedback was provided with different delays (0 to 1500 ms with an intrinsic delay of 75 ms). (b) Agency changes as a function of delay with a u-shaped pattern. The highest agency can be seen for no-delay and full-delay conditions, while the agency is lowest for trials with half-cycle delays. (c) stride time deviation changes systematically as a function of delay with the sinusoidal pattern.

1.3 Touch perception on the torso

Human beings perceive tactile sensations (e.g., vibration, static pressure, dynamic pressure, etc.) via particular sensory end organs, known as mechanoreceptors in the skin. Physiologists have revealed that the sensitivity of mechanoreceptors rely on their receptive field size (large receptor have poorer spatial resolution), density (many receptors in a given area resulting in high spatial acuity), frequency range (receptors do not perceive signals outside their range), and the type of stimulation (skin motion or continued pressure) (Verrillo 1966; Johansson and Vallbo 1983; Vallbo et al. 1984; Bolanowski et al. 1994; Vallbo et al. 1995; Johnson and Yoshioka 2002). More importantly, different body parts may contain various combinations of specific receptors, leading to differing perceptual capabilities in different body regions. Since there is no particular study investigating the mechanoreceptors' innervation in the torso area, researchers often benefit from the results of research on the human forearm to explain the underlying receptor fields in the torso area. Vallbo et al. (1995) identified five types of mechanoreceptor units, including two types of slow-adapting units and three types of fast-adapting units. Merkel disks and Rufini endings, as slow-adapting receptive fields, respond when the nerve is continually compressed (i.e., by sustained skin displacement); hence, they are sensitive to static or low-frequency (0.4-10 Hz) skin deformation.

On the other hand, fast-adapting units, including hair follicles, field units, and Pacinian corpuscles, produce a transient response to the onset and offset of stimulation, resulting in the perception of dynamic skin stimulations. While field units innervate skin between hairs, with large receptive fields, hair follicles are located at the base of follicles governing the perception of touch and low-frequency vibration (10-100 Hz) by deflection of hairs. However, perception of high-frequency skin deformation (i.e., at least 100 Hz) can reflect responses of Pacinian corpuscles, which are typically located in deeper tissues and have a very large receptive field (~1mm). Pacinian corpuscles exhibit a U-shaped function at high frequencies (100 to 1000 Hz), where maximum sensitivity occurred at 220 Hz. They also exhibit both spatial and temporal summation: reduced thresholds with an increased area of excitation and increased duration of vibration. While studying the anatomical structures underlying the skin can provide fundamental insights about the functionality of each distinct mechanoreceptor, in reality, the tactile perception results from integrated inputs of receptors in a given skin area. Therefore, the best practice technique to evaluate the multi-receptor perception and global tactile perceptual limitations is conducting psychophysical experiments. Considering applications of torso-worn tactile displays that provide spatially-encoded tactile information, two general aspects of the tactile spatial resolution are often required: How well can a user distinguish tactile cues applied to neighboring locations on the torso? And how well a user can spatially localize contacts on the torso? The former is referred to as tactile spatial acuity, and the latter is tactile spatial localization. Since the mid-19th century, a considerable number of studies have employed various psychophysical measures, via manual stimulation or wearable systems, to evaluate tactile spatial acuity and localization on the surface of the human body, particularly the human torso. In the following, we review some of these studies.

1.3.1 Tactile spatial acuity

Two classical techniques to measure the spatial acuity of the human skin are “two-point discrimination” and “point-localization” (Weber 1834). The two-point discrimination test assesses the ability to discriminate two nearby, distinct points of stimuli from one. Although in the related literature, the two-point discrimination was predominantly employed to evaluate the spatial acuity of the skin, recent studies have questioned the validity of this measure as it is vulnerable to several possible confounds. For instance, discrimination of one from two-point stimuli can happen simply based on intensity cues rather than spatial cues (Johnson and Phillips 1981; Johnson 1994; Stevens and Patterson 1995; Craig and Johnson 2000; Tong et al. 2013). Alternatively, point-localization can be determined by applying two successive stimuli at nearby loci and asking the user to judge whether points stimuli were at the same location or not. Hence, it does not seem to show the limitations of classical two-point discrimination (Tong et al. 2013). Using a metal compass (static pressure) on the different parts of the body, Weinstein (1968) revealed that acuity found with two-point discrimination was three to four times lower than with point-localization, although they were highly correlated. Furthermore, they revealed that spatial acuity varies substantially over the body site, with the lowest acuity for the torso (point-localization threshold of 10 mm). However, their results only reflected responses to slow-adapting receptors (i.e., Merkel disks) and may not be extended to prevailing wearable tactile communication systems equipped with dynamic mechanical stimulators.

As a pioneer work on the vibrotactile spatial acuity on the back, Eskildsen et al. (1969) performed both two-point discrimination and point-localization tests, using an array of five mechanical vibrators (burst duration of 1 sec) attached to the back of a dentist chair (located on the back at the level of the scapula). They reported similar threshold gaps for both tests (10-11 mm) while both thresholds approximated the one found for the point-localization test with static touch. Van Erp (2005a) tested both horizontal and vertical spatial acuities by deploying linear arrays of tactors (250 Hz) taped to the users’ back and abdomen. They reported comparable discrimination thresholds for horizontal and vertical spatial acuities of 20-30 mm with a lower threshold of 10 mm around the spin and navel, only found in horizontally oriented arrays. In addition, they highlighted the role of spatiotemporal interactions by observing that the accuracy increased as burst duration or/and inter-stimulus interval increased with a stronger effect of interstimulus interval.

Recently, a research group in the University of Iceland have conducted two subsequent studies (Jóhannesson et al. 2017; Hoffmann et al. 2018b) in an attempt to systematically investigate, so-called, relative spatial acuity (i.e., whether the second stimulus was to the left or right of the first stimulus or whether it was the same one.), of the skin of lower back to vibrotactile stimulations by deploying wearable displays. In their pioneer study(Jóhannesson et al. 2017), they have explored the effect of inter-tactor distancing, using arrays of 3x3 coin cell eccentric rotating mass motors (10 mm) attached to a spongy waist-worn belt, named Vibro-sponge. They have found the relative spatial acuity increased from 64% to 91% as the center-to-center inter-tactor distance decreased from 30 to 13 mm c/c. Additionally, they compared the spatial acuity of Vibro-sponge with a tactile vest consisting of 64 (8x8) tactors. They indicated the weaker spatial acuity for tactile vest despite the bigger inter-tactor distance in the tactile vest. In their subsequent study (Hoffmann et al. 2018b), they have explored the influence of the choice of tactor type, the orientation of stimulus presentation, and the near-spin location effect. They have remarked significant differences between vibrotactile spatial acuity of different tactors, emerged from differences in the way the vibration is generated. They also found strong spatial anisotropy (direction dependencies) in vibrotactile perception, with higher accuracy for horizontal than vertical presentation direction, consistently across tactor types. Furthermore, they observed that localization accuracy was lower in the spine area than more peripherally.

1.3.2 Tactile point localization

Several studies in the literature have deployed the tactile localization test that evaluates the ability to localize a point of stimulation in an array of actuators mounted on the torso (Cholewiak and Collins 2003; Cholewiak et al. 2004; van Erp 2007; Chen et al. 2008; Jones and Ray 2008; Jones 2011; Medina et al. 2018). The results of those studies are of interest for applications where cues about the external world, e.g., the location of an object in a virtual environment, are presented to the specific location of the torso. In addition, such experiments assist in determining the optimal dimension of an array of vibrators intending to convey information.

Researches that deployed one-dimension arrays of vibrators around the waist demonstrated that the localization accuracy is highly influenced by the inter-tactor spacing and the specific location of the actuator on the body. In two separate studies, Cholewiak et al. (2004) and Jones and Ray (2008) reported the localization accuracy of 92% and 98%, respectively, using an eight-tactor belt around the waist (spacing of 107 mm and 80-100 mm, respectively), yet deploying 12-tactor belt (spacing of 72 mm) resulted in the accuracy of 74%. Additionally, both studies reported the highest accuracies for tactors near the spine and navel. This higher identification ability near anatomical landmarks such as joints was primarily introduced by Weber (1834). It has also been recently shown for the point localization of both vibrotactile and static pressure stimuli presented on the upper limbs (e.g., elbow, wrist) (Gibson and Craig 2005; Cody et al. 2008). Although the results of Cholewiak et al. (2004) and Cholewiak et al. (2004) studies have suggested that the spine can be served as the body landmark, those studies that deployed a two-dimensional array of tactors on the user back have not found any superior effect of the spinal area. However, such studies have observed that in addition to inter-tactor spacing, the location of the target in an array can play a crucial role in localization accuracy. Using an array of 4x4 tactors (horizontal and vertical inter-tactor spacing of 60 mm and 40 mm, respectively), Jones and Ray (2008) have reported an average accuracy of 59% (range over 40-82%). They have indicated that participants were more accurate in identifying the correct column (87% correct) rather than the correct row (68%). Cholewiak and McGrath (2005) have utilized an array of 4x6 tactors (inter-tactor spacing of 50 mm) on a waist belt to examine the localization accuracy of the mid-lower back area. They have reported accuracy of approximately 55% (varies in a range of 40-77%) while the higher accuracy has been observed at the edge of the array than those in the center. Lindeman and Yanagida (2003) tested the localization accuracy on the whole back through a 3x3 array of tactors (spacing of 60 mm) attached to a chair. They have reported the accuracy of 84% with a comparably long burst duration of 1 second. They have also noted the lower performance in the spinal regions compared to the peripheral. With all the above-mentioned studies focusing on the point localization within an array of vibrators on the back, Al-Sada et al. (2019) have investigated the discrimination of tap stimuli on the front and back torso using a waist-worn robotic arm. They have divided the whole back into 16 cells (4x4) with an average spacing of 50-80 mm. By applying static pressure of 7.4 N on the back, they found that the accuracy varies in the range of 6.67% and 96.6%, while higher accuracies were assessed for the most top cells, and it gradually decreased by going towards the lowest row. They have also found a superior effect of the peripheral region compared to the inner regions.

1.4 Torso-based haptic technology

In general, a haptic interface uses three complimentary sub-sensory channels, kinesthetic (force feedback), tactile and thermal to influence on the human somatosensory system. Force feedback interfaces convey force or motion while the two others enable us to perceive an object's properties via skin contact (Lederman and Klatzky 2009). Although force feedback interfaces have a longer and more substantial history of research and technological advancement, they often require a bulky setup to operate actuators/sensors placed at their joints. Therefore, they are less likely to be used in a wearable and portable arrangement. Torso-worn haptic displays applying tactile or thermal cues to users have gained a lot of attention in recent years (Choi and Kuchenbecker 2012). The majority of torso-worn haptic displays, developed in the last two decades, have used miniature vibrotactile stimulators as they have become more common and affordable (Arafsha et al. 2015; Karafotias et al. 2017; Garcia-Valle et al. 2018). Additionally, vibrotactile stimulators can be easily embedded in a wearable interface, which is desirable to make a confidential and mobile stimulation system. Below, some of the recent torso-worn haptic displays will be reviewed.

As one of the pioneering studies, Rupert (2000) has developed ergonomic torso-worn tactile communication displays to counteract the danger of visual and auditory overload for military pilots in acceleration conditions, see Figure 1:7 (a) as an example (van Erp et al. 2003). Viola et al. (2018) have designed a corset-like vest (see Figure 1:7 (b)) equipped with IMU and four vibrotactile motors to provide gravitational guidance in deep-sea diving or micro-gravity. Van Erp and colleagues have employed torso-worn vibrotactile displays as the pedestrian navigation system (van Erp et al. 2003; Van Erp et al. 2005; Van Erp 2005b; van Erp 2007). Tactile displays worn on the torso can be also used as sensory substitution systems to provide spatial information about the environment to people whose visual, auditory or vestibular systems are impaired. For instance, VibroVision (Figure 1:7 (c)) was developed to help visually impaired people by projecting information about the area in front of the wearer onto her/his abdomen in the form of a two-dimensional tactile image rendered by an array of vibration motors (Wacker et al. 2016). Buimer et al. (2018) also developed a wearable sensory substitution device (SSD, see Figure 1:7 (d)) consisting of a head mounted camera and a haptic belt to convey facial expressions to visually impaired users. Torso-worn vibrotactile displays have been also used for affective communication aims including emotion regulation, enhanced emotion experience and social interaction. TapTap (Bonanni et al. 2006) is a touch-sensitive scarf, which can record, broadcast and playback nurturing human touch for emotional therapy purposes (Figure 1:7 (e)). Lemmens et al. (2009) at Philip Research Europe developed a wearable vibrotactile jacket, involving 64 vibrators (Figure 1:7.(f)), to intensify emotional immersion experiences when watching movies. They targeted to evoke different emotions (e.g., love, fear, sadness, anger, anxiety, happiness) and also evaluated immersion based on immersion questionnaires and physiological measurements. Their findings showed the promising influence of tactile stimuli to enhance immersion.

Moreover, a tactile wearable jacket has been designed to enhance immersion during watching movie and gaming (Figure 1:7.(g)). It contains a combination of vibrotactile and heat actuators to display six universal emotions along with several emotional reactions such as a hug, poke, tickle or touch (Arafsha et al. 2015; Karafotias et al. 2017). Likewise, Lentini et al. (2016) addressed the complex and broad nature of vibrotactile design space by deploying an intuitive and natural technique to shape tactile gesture (Figure 1:7.(h)). In fact, they designed a tactile gesture authoring system which can translate hand gesture into vibrotactile stimuli rendered through a haptic jacket. Indeed, users by waving their hands can feel vibrotactile cues via haptic jacket with the same stroke sequence, speed and translated intensity as well as on the selected part of the jacket. Recently, Garcia-Valle et al. (2018) employed a torso-worn display (see Figure 1:7.(l)), equipped with vibrotactile and thermal actuators to improve the level of immersion in multimodal virtual environments. Via a behavioral study, they verified that the developed haptic device has improved users' performance in an environment that involved three senses: vision, audio and haptics.

As reviewed above, most current approaches are limited to expressing motion and vibrational feedback through vibrotactile stimulation ignoring the role of sustained or distributed force in conveying realism. However, only few publications discuss the use of force stimulators to the human torso to provide physical interactions in virtual environments. For instance, the force jacket (see Figure 1:7.(m)) was made of pneumatically actuated airbags to provide strong and variable forces to the torso along with vibrotactile sensations (Delazio et al. 2018). Nevertheless, this system included a series of air tubes connected to a large air compressor and vacuum resulting in a very bulky setup (neither mobile nor portable) and confining for the users. More recently, Al-Sada et al. (2019) designed the HapticSnakes (see Figure 1:7.(n)), a snake-like waist-worn robot that can deliver different types of haptic feedback to the upper body via an exchangeable end effector attached to the waist.

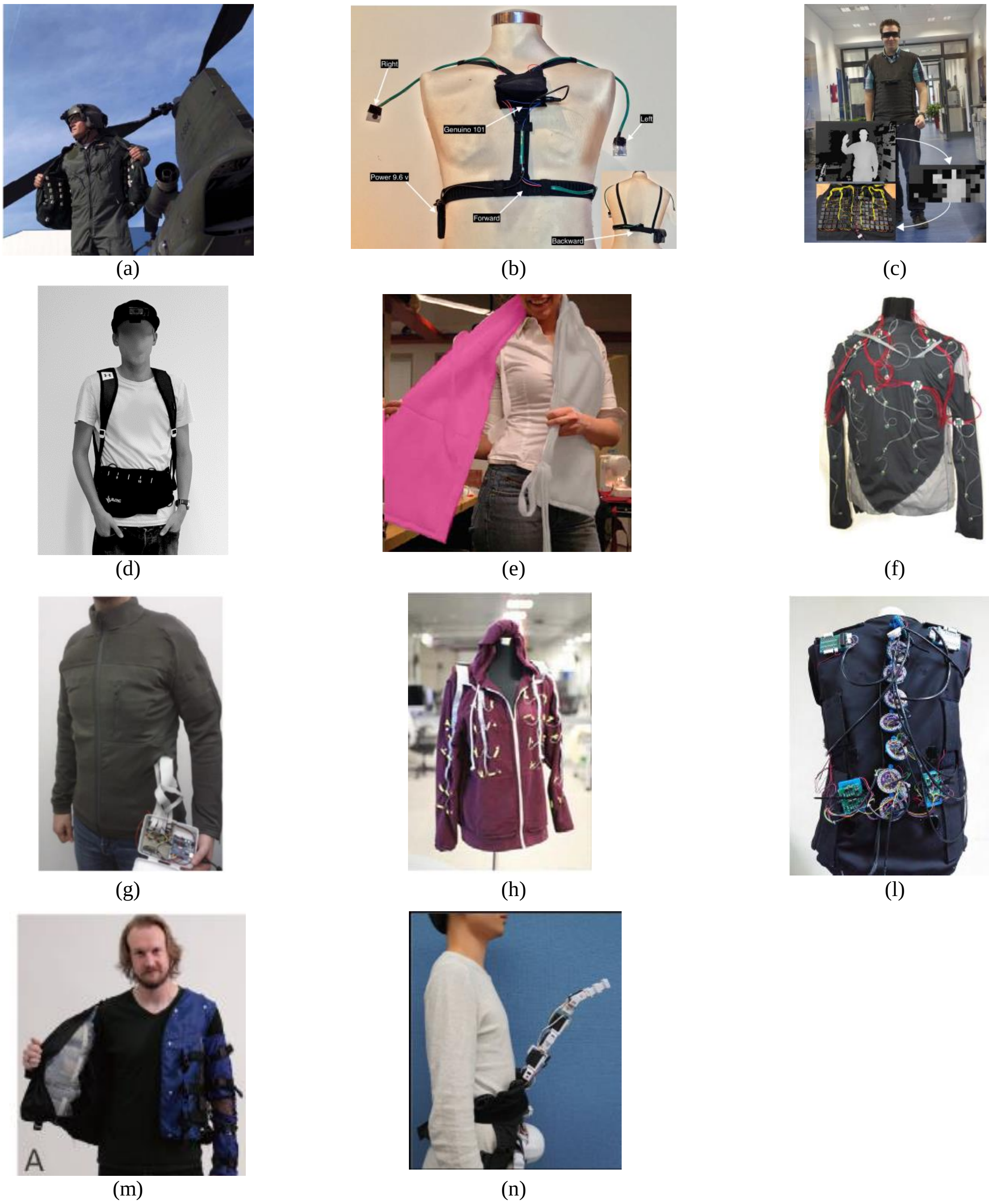

Figure 1:7 Recently developed torso-worn haptic interfaces.

(a) Helicopter pilot showing the TNO Tactile Torso Display designed for orientation and navigation in challenging environments but with a possible spin-off to sports. (b) Corset-like vest. Four vibrotactile motors were mounted on the torso (two on the front and one on the back for pitch dimension), and one per each shoulder for roll dimension (Viola et al. 2018). (c) Vibrovison vest. Depth information from an object is displayed as a vibrotactile image on the abdomen (Wacker et al. 2016). (d) Wearable sensory substitution device Person wearing the device consisted of a webcam mounted on a cap, a tablet in a mesh backpack, and a vibrotactile belt (Buimer et al. 2018). (e) TapTap prototype is a scarf with large pockets with a power supply. TapTap actuators to be mounted wherever the wearer desires. The outside of the scarf is a public color (gray), while the inside and its intimate actuators are a warm color (pink) (Bonanni et al. 2006). (f) Interior view of tactile jacket developed in (Lemmens et al. 2009). (g) Exterior view of tactile jacket developed in (Arafsha et al. 2015). (h) Interior view of tactile jacket developed in (Lentini et al. 2016) (front view). (l) Interior view of the jacket developed in (Garcia-Valle et al. 2018) (back view). (m) The appearance of Force jacket (Delazio et al. 2018). (n) Side view of the Haptic snake (Al-Sada et al. 2019).

1.5 Thesis at a glance

Chapter 2 presents a feasibility study on using a simple torso-worn vibrotactile display in experimentally inducing bodily illusions for healthy participants. **Chapter 3** describes the design, implementation, and validation of a novel torso-worn force display called "CognoVest," which provides a human-like poking sensation on the users' back. We further used CognoVest to induce altered states of BSC in a healthy population. In **Chapter 4**, we employed a fully wearable biofeedback system called FeetBack to investigate walking agency via temporal manipulation of step-related, remapped tactile feedback presented on the participants' backs during free walking. Chapter 5 evaluates and compares tactile spatial discrimination on the human back for vibrotactile and force stimulations using two different tactile perception paradigms, including tactile direction discrimination (DD) and tactile point localization (PL).

1.6 Personal contribution

1. **Chapter 2** is based on: **Jouybari A. F.**, Rognini G., Hara M., Bleuler H., and Blanke O., "*Torso-mounted Vibrotactile Interface to Experimentally Induce Illusory Own-body Perceptions*," in 2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). IEEE, 2019, pp. 6204–6209.

   Personal contribution: Technical and experimental design, software implementation, data collection, analyses, and writing.

2. **Chapter 3** is based on: **Jouybari A. F.**, Jeanmonod K., Kannape O. A., Potheegadoo J., Bleuler H., Hara M., and Olaf B. (2021) "*Cogno-Vest: A Torso-Worn, Force Display to Experimentally Induce Specific Hallucinations and Related Bodily Sensations*." IEEE Transactions on Cognitive and Developmental Systems.

   Personal contribution: Technical and experimental design, software implementation, data collection, analyses, and writing.

3. **Chapter 4** is based on: **Jouybari A. F.**, Ferraroli N., Bouri M., Kannape O. A., and Olaf B. "*FeetBack" Touch remapping of action consequences produce accurate awareness but limited (loco)motor adaptation*. In preparation.

   Personal contribution: Technical and experimental design, data collection, analyses, and writing.

4. **Chapter 5** is based on: **Jouybari A. F.**, Franza M., Kannape O. A., Hara M., and Olaf B. *Tactile spatial discrimination on the torso using vibrotactile and force stimulation.* Currently under revision in Experimental Brain Research.

   Personal contribution: Technical and experimental design, software implementation, data collection, analyses, and writing.

Chapter 2 Torso-mounted vibrotactile interface to induce bodily illusions: a feasibility study

Torso-mounted Vibrotactile Interface to Experimentally Induce Illusory Own-body Perceptions

Atena Fadaeijouybari[1,2], Giulio Rognini[1], Masayuki Hara[3], Hannes Bleuler[2,] and Olaf Blanke[1]

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[1] École Polytechnique Fédérale de Lausanne (EPFL), School of Life Sciences, Brain Mind Institute, Center for Neuroprosthetics, Campus Biotech H4, Chemin des Mines 9, CH-1202 Genève, Switzerland

[2] École Polytechnique Fédérale de Lausanne (EPFL), School of Engineering, Laboratory of Robotic Systems, Station 17, CH-1015 Lausanne, Switzerland

[3] Graduate School of Science and Engineering, Saitama University, 338-8570 Saitama, Japan

Abstract

Recent developments in virtual reality and robotic technologies have allowed investigating the behavioural and brain mechanisms that grounds self-consciousness in the multisensory (e.g., vision and touch) and sensorimotor processing of bodily signals. Yet, previous technological solutions to apply tactile stimuli for body illusion induction limit participants' movements, do not allow for stimulations in dynamic environments (e.g., the subject walking), and can hardly be integrated into real-life settings and complex, interactive, virtual reality environments. Here, we present the development and first validation of a new semi-wearable haptic system, based on vibration technology, to induce a range of bodily illusions relevant to research in psychiatry. This is a first step towards developing wearable haptic systems able to administer touch and induce specific bodily illusions under dynamic conditions and in real-life settings.

2.1 Introduction

Recent experimental evidence from neurology and cognitive neuroscience has shown how the multisensory and sensorimotor integration of bodily signals provides the basis for bodily self-consciousness (BSC) - the non-conceptual and pre-reflective representation of body-related information (Tsakiris 2010; Blanke 2012; Ehrsson 2012). Thus, when experimentally exposed to conflicting multisensory bodily cues about the location, appearance, and synchrony of one's own body signals, participants are prone to report significant alterations of their bodily experience (illusory own-body perceptions). For example, in the rubber hand illusion, synchronous stroking of a seen rubber hand and one's own real hand (hidden from view) induce illusory ownership over the fake hand and bias the perceived location of one's own hand towards the rubber hand (proprioceptive drift) (Botvinick and Cohen 1998). Through the use of virtual reality technology and by applying synchronous tactile stimuli on the participants' torso and a seen avatar, these manipulations have also been extended to the full-body (full-body illusion) (Ehrsson 2007; Lenggenhager et al. 2007). More recently, the development of MRI-compatible robotic technology has allowed performing these paradigms in MRI environments, thereby enabling precise time-delay and the investigations of the neural mechanisms of these illusions (Ionta et al. 2011).

Another important line of work has used sensorimotor (instead of multisensory) manipulations of one's bodily signals to induce systematic changes in BSC. Thus, in the tactile rubber hand illusion, blindfolded participants are guided by the experimenter to touch a fake hand while synchronously receiving the touch on their other real hand (Ehrsson et al. 2005). This results in the subjective illusion of touching one's hand (illusory self-touch) and induces a bias in the localization of the touched hand that is perceived closer to the touching hand. Recently, this sensorimotor paradigm has been adapted to the full body. Hence, Blanke et al. (2014) used a robotic system to apply sensorimotor manipulations between the hand and torso of blindfolded participants. Participants were asked to perform voluntary tapping movement with both hands by using the leader haptic device placed in front of them and received synchronous or asynchronous tactile feedback on their back. Similarly, to the tactile rubber hand illusion, in the synchronous condition, participants reported the illusory experience of touching their back (illusory self-touch). Importantly, during asynchronous stimulation, participants reported not only a reduced self-touch experience but also the illusory sensations of having someone behind them (Presence Hallucination, PH) and felt touched by someone (passivity experience), comparable to experiences reported by neurological and psychiatry patients (Llorca et al. 2016).

In spite of the recent achievements in robotic manipulation of tactile stimuli during several bodily illusions (Ionta et al. 2011; Blanke et al. 2014), haptic technology for BSC is relatively underdeveloped, compared to the advances in auditory (e.g. sound specialization, 3D audio, etc.) and visual stimulations (such as VR/AR technology, stereoscope view, etc.). For instance, the usage of the leader-follower robotic system described in the PH study (Blanke et al. 2014) is limited to the laboratory environment and to stationary conditions of participants (i.e., the participants cannot walk during stimulation), while the emerging visual (Slater et al. 2008) and auditory technologies (Tajadura-Jiménez et al. 2015) allow researchers to handle various multisensory in-congruency with small-scale, portable setups and in complex and dynamic environments. We here focus on the development of wearable and portable tactile stimulation interfaces for the human torso. This is because torso-related tactile signals have been shown to be crucial in manipulating global aspects of bodily self-consciousness and the PH in particular (Blanke 2012; Blanke et al. 2015).

In this study, we designed a new torso-mounted vibrotactile display to investigate illusory own-body perceptions, and particularly PH and passivity experiences, based on the paradigm proposed by Blanke et al. (2014) (experiment 2). We first conducted a feasibility study and deployed the novel semi-wearable setup in experimentally inducing bodily illusions for healthy participants. To characterize the new vibrotactile garment, we combined the PH experiment with additional vibrotactile perception tasks/questionnaires.

2.2 New wearable setup to induce bodily illusions

Figure 2:1a depicts a schematic view of the experimental environment deployed in the study (Blanke et al. 2014) (experiments 2 and 3). The setup comprised two robots, the leader haptic device, Geomagic Touch (formerly called as Phantom Omni), and a three-degree-of-freedom (DOF) follower robot. The position of the follower robot was controlled with the leader haptic device, causing a complete coincidence between the movements of the two devices. Participant moved the leader haptic device with the right index finger (a 3D printed finger place, Figure 2:2b, was used to fix the participant's finger at the leader haptic interface), which operated the movements of the follower robot that provides touches to the participant's back.

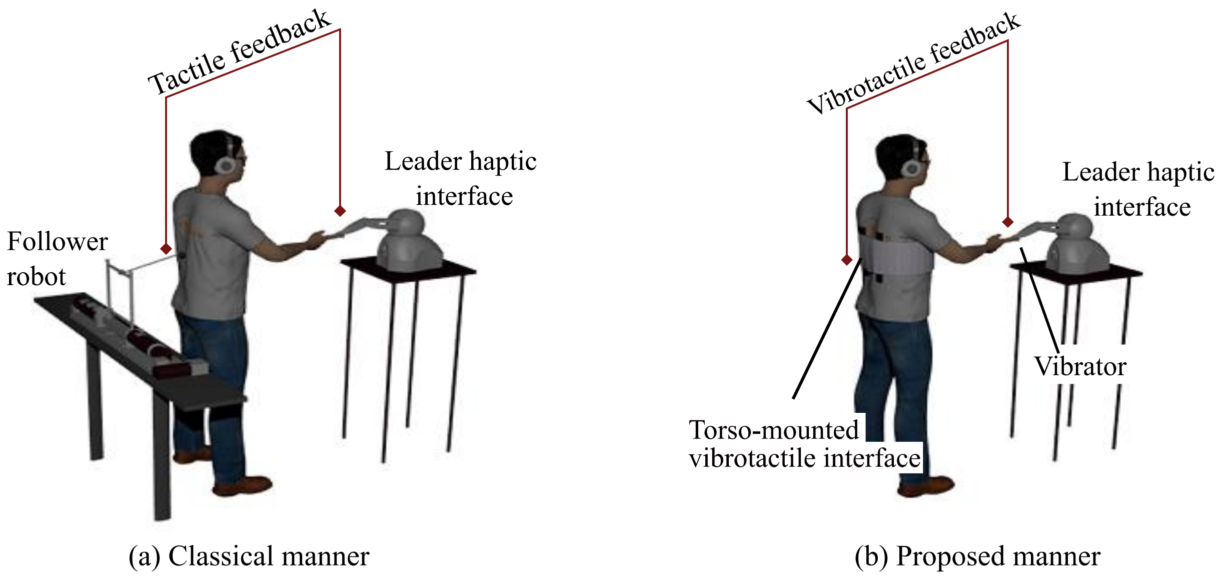

Figure 2:1 Experimental setup.

Schematic views of classical and proposed experimental setups and environments for experimentally inducing PH and relevant bodily illusions.

The experimental setup in the current study is the modified version of the two-part robotic system employed in the study (Blanke et al. 2014) (experiments 2 and 3). Figure 2:1b represents the schematic view of the proposed experimental condition. In the new experimental arrangement, the follower robot was replaced with a torso-mounted vibrotactile interface (see Figure 2:2a) to provide the vibration stimulus on the participants' back. The vibrotactile suite consists of two arrays of vibrators with a plastic-like covering. Each array had three coin-shaped, Eccentric Rotating Mass (ERM) vibrators (310-118, Precision MicroDrive; frequency: 200-250 Hz; amplitude: 0.8-1.3 g), with in-plane vibrations. An inter-vibrator distance of 8 cm was chosen to be bigger than the 2-point discrimination threshold for the back (Eskildsen et al. 1969). A pilot study confirmed that using three vibrators on each vertical array is sufficient. A chest belt was employed to locate vibrator interfaces on the participant's upper back. There were specific belts for women and men. The woman belt was especially shaped to conform to the chest, ensuring correct fit and firm support. Two vibrator arrays mounted vertically on the belt with a fixed horizontal distance of 15 cm for almost all participants (for three participants, two vibrator arrays were located closer because of their small size). This distance was chosen based on the average distance between the shoulder blades. Figure 2:2c represents the arrangement of vibrators on the back and vibrators numbering. A wireless micro-controller board embedded in 3D printed box was deployed to run vibrators through custom software.

On the leader haptic device, a single coin-shaped ERM vibrator, similar to the back vibrators, was added to the end of the finger placement to provide a vibration stimulus on the fingertip (see Figure 2:2b). The fingertip vibrator was controlled by an Arduino and worked congruently with back vibrators. In contrast to the follower robot (Blanke et al. 2014), with continuous workspace, the wearable actuator suite can only provide six discrete vibrotactile stimuli on the back. The hand exploration area was divided into 6 different smaller regions according to the vibrators' arrangement on the back to assess the spatial correspondence between continuous hand workspace and discrete back workspace. Moreover, a virtual wall with a stiffness of 0.5 N/mm was provided at the leader haptic device to administer a virtual wall, when the participant touches his/her back. Thus, depending on the region that the participant touches the virtual back with his/her index finger, the corresponding vibrator activates on the back. Custom Graphical User Interface (GUI) written in Visual C++ (Microsoft) was developed to link the leader haptic device and vibrotactile actuator suite and to control the experiment flow.

2.2.1 Setup characterization and feasibility study

2.2.1.1 Experimental design

Experimentally induction of bodily illusions: The behavioral experiment was designed to investigate the possibility of inducing the PH and passivity experiences in healthy subjects by providing vibrotactile-motor signals. Similar to our previous study (Blanke et al. 2014), the effect of synchrony (synchronous (SYNC) vs. asynchronous (ASYNC)) was investigated, while the force feedback at the fingertip of the moving hand was provided in both conditions. This was done to provide a virtual wall when participants touched their back (during SYNC or ASYNC conditions). In the original study, Blanke et al. (2014) found that the force feedback did not significantly affect inducing PH. Yet, pilot testing showed that participants tend to report higher PH when force feedback was provided. The original study (Blanke et al. 2014) also found changes in self-location depending on force feedback. In addition, to reduce habituation effects and decreases in tactile perception, we used a variable delay of 500 ± 100 ms instead of the fixed delay used in (Blanke et al. 2014).

To assess subjective changes in own body perception of participants during the experiment, a 4-item questionnaire (i.e., Bodily illusions questionnaire), adopted from (Blanke et al. 2014) (experiment 2), was proposed to participants at the end of each experimental condition.

Self-touch	"I felt as if I was poking my back."
Passivity	"I felt as if someone else was poking my back."
PH	"I felt as if someone was standing close to me or behind me."
Control	"I felt as if I had 3 bodies."

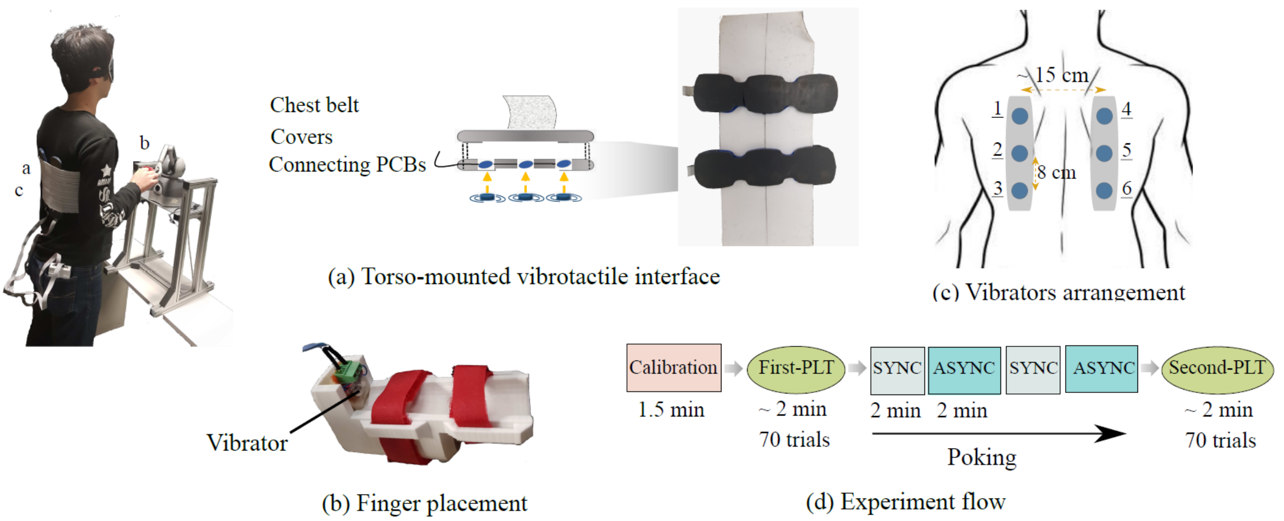

Figure 2:2 Novel experimental setups and procedures to induce PH and related bodily illusions.

Participants were asked to rate on 7 points Likert scale how strongly they agreed with each item (0 = not at all, 3 = not certain, 6= very strong). In addition, a dedicated questionnaire to assess tactile perception (called as User experience questionnaire) was used during the poking phase, after another pair of SYNC and ASYNC blocks, to assess the quality of tactile stimuli and the garment.

Uniform, vibrotactile sensation (UVS):	"I felt the same strength of vibration in the different parts of my back."
System performance (SP):	"The tactile stimuli that I felt on my back matched with my anticipation from the hand exploration task."
Comfortability:	"This semi_wearable FoP robot is comfortable to wear.

Tactile task: In order to characterize the vibrotactile setup and better understand human vibrotactile perception on the upper back, we designed and administrated a Point Localization Task (PLT). In this task, subjects received one vibrotactile stimulus at a time, and they were asked to indicate where they perceived the tactile stimuli on their back. Responses were given with a handheld keypad (prior to the PLT task, they had been informed about the arrangement of vibrators on their back (see Figure 2:2c)). That is, the PLT was used to investigate participants' absolute vibrotactile localization acuity (Jóhannesson et al. 2017). The PLT task was repeated during the experiment, once before and once after the poking task, to assess possible changes in tactile perception throughout the experiment.

2.2.1.2 Participants

Twenty-two healthy participants (15 females; age range: 18-32 years; average age (SD): 25.6 years (3.9 years)) participated in the experiment. All participants were right-handed, had no history of neurological or psychiatric disease, and were naïve to the goal of the study. In addition, participants with a wound or scar on their upper back were excluded since the former injury on the back could potentially influence sensitivity to vibrotactile stimuli. Informed consent was obtained after all instructions on the experiment were given to participants and their questions answered. All participants received financial compensation for their participation. The research was conducted in accordance with the *Helsinki Declaration*.

2.2.1.3 Procedure

Prior to the experiment, all participants were asked to wear a T-shirt and the vibrotactile interface. The experimenter helped them to properly locate the vibrator arrays on their back (two upper vibrators on each array must be located on two shoulder blades, and the rest vibrators were placed below). The experiment consists of three different sessions (see Figure 2:2d): calibration task, PLT task (the First-PLT and the second-PLT), and the poking task.

Calibration: Participants had to complete the vibrotactile calibration task while they were listening to white noise through headphones. During the calibration task, they received randomized vibrations on their back (for a constant duration of 270 ms followed with 1 s time interval between each two successive vibrations) for a period of 45 seconds, and later, they verbally answered the following question: "Did you receive uniform vibrotactile sensation all over your back and if not where was the weakest and strongest points?". Depending upon participants' responses, the experimenter applied the following modifications: 1) re-adjusting the location of vibrotactile interface on the participants' back, 2) changing the intensity of weaker or stronger vibrators (following participants request, the intensity of two upper vibrators, which were located on each side shoulder blade was decreased between 33% to 55%), 3) utilizing another chest belt on top of the vibrator belt to ensure that all vibrators were well in contact with the skin (for most of the subjects, especially medium and small size subjects the second belt was used). The calibration session was repeated until participants confirmed uniform vibrotactile perception on their back (on average, there were two calibration sessions per subject). Participants were asked to keep standing during the whole experiment to avoid any changes in calibration.

PLT: In the PLT, participants received a pseudo-random, single vibration stimulus on their back and were asked to indicate the location of the perceived vibration by specifying the number of the corresponding vibrator by a numeric keypad (see Figure 2:2c). No feedback about their performance was given to participants during the task. Moreover, to reduce task complexity, they were instructed to hold the keypad so they could see the numeric keypad buttons in a sequence matching the vibrators numbering on the back. Catch trials were added as a control trial to assess the extent to which participants responded to perceived vibrotactile stimuli rather than using other response strategies. Each of the six locations was stimulated ten times resulting in a total of 70 trials. The vibrators were turned on for 270 ms and followed with a random interval in the range of 2000 ± 250 ms. For each individual trial, participants' response was recorded by the software. During the task, participants wore headphones playing white noise to mask the sound of vibrators. The white noise intensity was adjusted for each participant in order to have complete acoustic isolation. All participants tried a training session, similar to the main task but shorter, around 1 min, to learn how to respond to vibration with the keypad. To explore any changes in tactile perception, the PLT task was repeated, along with the experiment, before (First-PLT) and after (Second-PLT) the poking task.

Poking: During the poking task, similar to the study (Blanke et al. 2014) (experiment 2), participants were asked to do poking movements using a leader haptic device and receiving vibrations on the back through the vibrotactile suite, while they were blindfolded, sound isolated, and standing in front of the leader robot. In the training session, they were instructed to put their right-hand index finger inside the finger placement and produce forth and back hand movements with the leader robot. During the experimental condition, they were allowed to freely explore the workspace (up-down, left-right) and they were guided to touch the virtual back with the frequency of 1 Hz. They were informed that the vibrator provided the touch cue during all experimental conditions depending on their hand movements, but without mentioning what type of condition was applied. Participants had their eyes open throughout the training session (different from the main experiment). The preparation session lasted around 2 minutes. Afterward, participants started to follow four random blocks: a combination of 2 experimental conditions (SYNC and ASYNC) and two questionnaires (Bodily illusions and User experiences). Each block lasted 2 minutes, and participants heard acoustic cues indicating the starting and ending of the block. After each block, participants answered the questionnaires. At the end of the poking task, participants were asked to comment on their experience and the setup freely.

2.2.2 Results and discussion

2.2.2.1 Bodily illusions

To evaluate the performance of the proposed experimental setup to experimentally induce PH and passivity experiences, we analyzed the questionnaire data and analyzed the responses as reported in (Blanke et al. 2014). According to the test for normal distribution (Shapiro-Wilk test of normality), all data derived from the questionnaire significantly deviated from the normal distribution. Hence, the significant effect of synchrony (SYNC vs. ASYNC) was analyzed using the Wilcoxon signed-rank test (signrank; Matlab R2016a) for each question. Figure 2:3a represents the average values for self-touch, passivity, and PH questions in both experimental conditions.

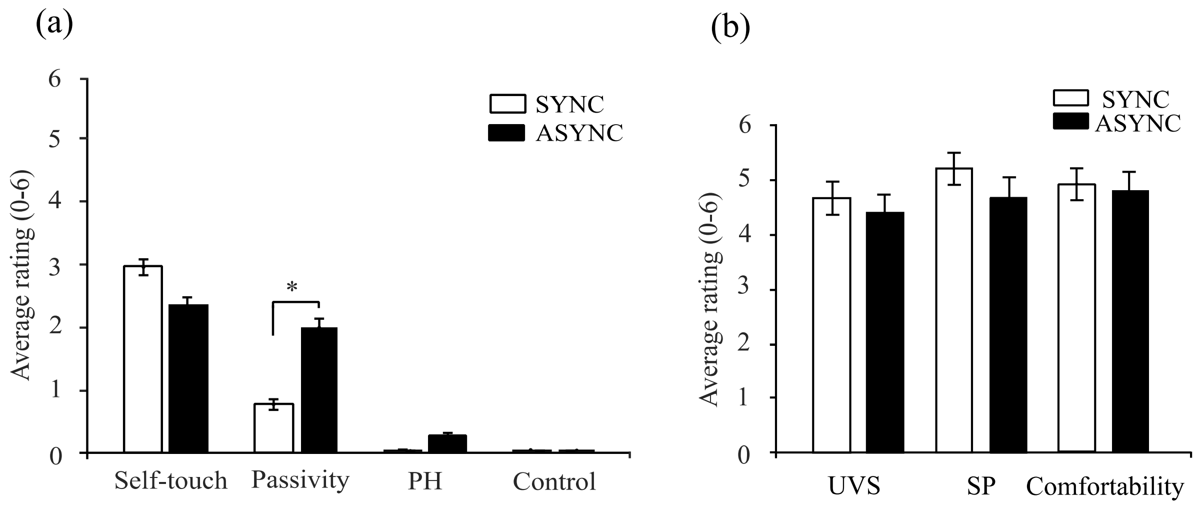

Figure 2:3 Likert scale ratings assessing subjective experience.

Following two minutes of robotic sensorimotor stimulation (a) Ratings for bodily illusions and control questions. The figure presents the average rating and standard error from the mean (SEM) for each question. Note that for the passivity question, there is a significant difference between SYNC and ASYNC conditions. (b) User experience results. Bar charts and error bars represent the average score for each statement in each condition and its standard error of the mean (SEM), respectively.

During the post-condition debriefing, five participants indicated that the tactile stimuli on their back were not comparable to human touch ("Vibration stimuli on my back was not close to human pocking stimuli"; "It was Machine who is working on my back" (3 participants), and "Vibration does not give me the feeling of self-touch and other-touch"). This demonstrates that the simple vibratory pulse was not an appropriate replacement for the natural human poking stimuli, and even providing vibratory sensation in both hand and back sides was not sufficient. Also, we believe that the perception of being touched can be improved by using an array of three by three vibrators on the subject's back, as this arrangement can provide a proper spatial matching between the hand workspace and the back sensation. Moreover, future studies using vibrators should try to personalize and further optimize this human-like poking sensation, also exploiting the multiple levels of controls allowed by vibrators such as amplitude, intensity, and waveform (Seifi and Maclean 2013), as this may enhance the PH and other illusions.

Statistical analysis revealed a significant effect of delay for passivity experiences ($p = 0.02$), where ratings were as predicted significantly higher in asynchronous condition than in the synchronous one (SYNC: $M = 0.77$, $SEM = 0.28$; ASYNC: $M = 2.00$, $SEM = 0.46$). This observation is consistent with the finding in (Blanke et al. 2014). For the self-touch question, although mean ratings in the SYNC condition were numerically higher than in the ASYNC one (SYNC: $M = 2.95$, $SEM = 0.42$; ASYNC: $M = 2.36$, $SEM = 0.42$), a Wilcoxon signed-rank test only revealed a statistical tendency in that direction ($p=0.055$). The data collected for PH and the control question were below 0.3 in both experimental conditions. Our findings reveal that with our semi-wearable, vibrotactile setup, we could induce moderate illusory passivity experiences and mild illusory self-touch but no PH. Moreover, passivity and self-touch illusions depended differently on poking conditions. Results are promising for using our wearable vibrotactile garment to induce own-bodily illusions in a controlled fashion based on synchrony manipulation. However, compared to previous work, illusions were of lower intensity, especially the PH.

2.2.2.2 User experiences

To investigate other tactile perceptions during the experimental conditions, we analyzed the data collected through the User Experiences questionnaire. Figure 2:3b shows the average ratings for all three questions. Results indicate that participants' ratings for each question did not change across different experimental conditions. These observations show that participants felt the same high level of uniformity, comfortability, and the correspondence between tactile sensation on the hand and the one on the back, across experimental conditions (SYNC vs. ASYNC). We note that all mean ratings are higher than 3 (neutral). These results imply that the present configuration of the garment allows uniform and distinguishable vibrotactile perception on the participants' back regardless of synchrony with high comfort.

2.2.2.3 Vibrotactile localization accuracy across the experiment

To assess vibrotactile spatial perception on the participants' upper back, we performed the PLT task (twice during the experiment). We only report the statistical analysis of PLT with 18 participants (a total of 22 participants), as in 4 participants, we did not have a full data set due to technical problems. There were no outliers at the group-level (Median Absolute Deviation (MAD) criteria with the factor of 3). Figure 2:4a shows the average localization accuracy (LA) in both first and second sessions. The chance level was at 14.28 %. Based on the test for normal distribution (Shapiro-Wilk test of normality), LA data for both sessions were not normally distributed. Hence, we performed the one-tail, one-sample Wilcoxon signed-rank test to investigate whether the level of performance was better than chance. We found that in both sessions, participants scored higher than chance level (both $p<0.01$). In addition, the data from the PLT test revealed that the average accuracy for the vibrotactile localization did not change significantly between both sessions (Wilcoxon sign rank test, $p = 0.81$). This observation, together with the result of the UVS question, admits that we could keep the calibration status during the entire experiment under the circumstance of the proposed experimental condition.

2.2.2.4 Vibrotactile localization accuracy over the back

Mixed model analysis was implemented to investigate whether the localization accuracy changes over the different locations on the back. We considered “Location” as the fixed effect (6 different levels corresponding to 6 vibration locations) and subject as a random effect (intercept). We found a significant variation of LA per vibrators. Figure 2:4b depicts the profile of absolute vibrotactile localization accuracy on the upper back, associated with our vibrotactile suite. These data reveal the variability of touch perception on the back when using the current display. We note that this profile depends on garment design, contact of the vibrators, and generally low tactile spatial sensitivity on the back. Future studies should further investigate this issue to further improve the induction of illusory own body perceptions.

2.2.2.5 Correlation between bodily illusions ratings and localization accuracy

We also explored the possible correlation between illusory touch ratings and vibrotactile localization accuracy. For this, we used the self-touch rating in the SYNC condition and the Passivity ratings in ASYNC condition, in which we found a similar trend as the study (Blanke et al. 2014). Spearman correlation's test revealed no correlation between self-touch rantings (SYNC) and average LA for 18 subjects ($R = -0.24$, $p = 0.3$; corr, Matlab 2016a). The same result was found for Passivity ratings and LA ($R = -0.26$, $p = 0.29$; corr, Matlab 2016a). There was also no correlation between UVS ratings and LA ($R = -0.3$, $p = 0.2$). These observations suggest that illusory own body perceptions are not driven by the tactile spatial accuracy as tested here.

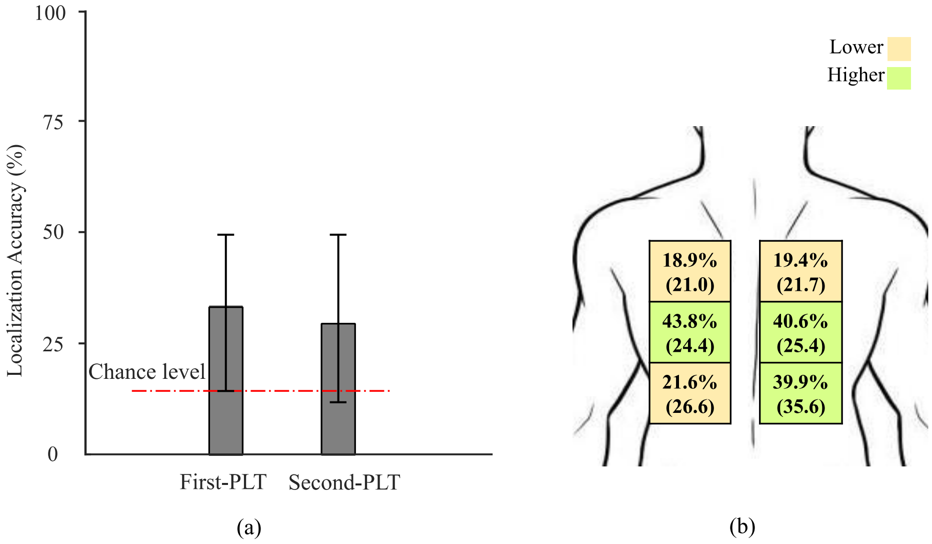

Figure 2:4 Localization accuracy for the torso-mounted vibrotactile interface.

((a) LA for both the first and second PLT tasks. The figure shows the average accuracy and standard error of the mean for each task. The red dash-line shows the chance level. (b) Average LA profile on the back. The figure depicts the profile of average LA and standard error of the mean for each vibrator location on the back.)

2.2.3 Conclusions

This paper used a portable and wearable vibrotactile display to provide personalized and well-perceived tactile stimuli on participants' upper back to manipulate BSC. Our findings revealed that with our semi-wearable, vibrotactile setup, we could induce illusory passivity experiences and self-touch, but no PH. In addition, illusory passivity and self-touch differently depended on poking synchrony. In addition, we have proposed possible technological improvements so that future work could improve the wearable technology and possibly enhance the tested bodily illusions by also further testing the involved tactile system on the participants' back. Finally, we note that the lead part of our robotic system, non-wearable in the present system, could be made wearable by integrating standard state-of-the-art motion-sensing technology and a vibrator on the user's fingertip. This would make our system fully portable and wearable, paving the way to the development of wearable haptic systems able to administer touch and induce bodily illusions under dynamic conditions and in real-life settings.

Chapter 3 CognoVest: a torso-worn force display to induce bodily illusions

Cogno-vest: A Torso-Worn, Force Display to Experimentally Induce Specific Hallucinations and related Bodily Sensation[2]

Atena Fadaei J.[1, 2], Kenny jeanmonod[2], Olivier A. Kannape[2], Jevita Potheegado[2], Hannes Bleuler[1], Masayuki Hara[3, *], and Olaf Blanke[1, *]

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[1] École Polytechnique Fédérale de Lausanne (EPFL), School of Life Sciences, Brain Mind Institute, Center for Neuroprosthetics, Campus Biotech H4, Chemin des Mines 9, CH-1202 Genève, Switzerland

[2] École Polytechnique Fédérale de Lausanne (EPFL), School of Engineering, Laboratory of Robotic Systems, Station 17, CH-1015 Lausanne, Switzerland

[3] Graduate School of Science and Engineering, Saitama University, 338-8570 Saitama, Japan

[*] These two authors contributed equally to this work.

Abstract

Recent advances in virtual reality and robotic technologies have allowed researchers to explore the mechanisms underlying bodily aspects of self-consciousness, which are largely attributed to the multisensory and sensorimotor processing of bodily signals (bodily self-consciousness, BSC). One key contribution to BSC, that is currently poorly addressed due to the lack of a wearable solution concern realistic collision sensations on the torso. Here, we introduce and validate a proof-of-concept prototype of the torso-worn force display, the CognoVest, that provides mechanical touch on the user's back in a sensorimotor perception experiment. In a first empirical study, we characterized human finger poking (N=28). In order to match these poking characteristics and meet the wearability criteria, we used bi-directional, push-pull solenoids as a force actuator in the CognoVest. Subsequently, and based on an iterative design procedure, a body-conforming, unisex, torso-worn force display was prototyped. Finally, we conducted a behavioral study that investigated BSC in 25 healthy participants by introducing conflicting sensorimotor signals between their hands and torso (back). Using the final reiteration of the CognoVest, we successfully replicated previous findings on illusory states of BSC, characterized by presence hallucinations (PH) and passivity symptoms, and achieved higher illusion ratings compared to static conditions used in prior studies.

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3.1 Introduction

Wearable haptic displays for the torso have been gaining importance in recent years in a variety of applications, ranging from virtual environments (Garcia-Valle et al. 2016; Garcia-Valle et al. 2018) to navigation (Rupert et al. 1994; Ertan et al. 1998; Gemperle et al. 2001; van Erp et al. 2003; van Erp 2007; Paun 2018; Viola et al. 2018), affective stimulation (Bonanni et al. 2006; Johnson and Higgins 2006; Cha et al. 2009; Cosgun et al. 2014; Arafsha et al. 2015; Lentini et al. 2016; Karafotias et al. 2017; Paun 2018), rehabilitation (Wall and Weinberg 2003) as well as sensory-substitution (Johnson and Higgins 2006; McDaniel et al. 2008; Wacker et al. 2016; Buimer et al. 2018). Torso-worn haptic displays range from precise, focal applications to broad surfaces and convey haptic information without competing for audio-visual attentional resources while offering a hands-free solution (Rognini and Blanke 2016). Torso-worn tactile stimulators can easily be used in a portable, wearable arrangement (e.g., in the form of an actuator vest), and the information provided is mostly processed automatically, imposing relatively low attentional loading on the user (Rupert et al. 1994).

Preliminary works in the field of torso-based haptic displays focused on navigation and spatial orientation purposes as the human torso is often referred to as the location and central reference frame for the human body (Karnath et al. 1991). In two seminal studies, Rupert et al. developed and tested different vibrotactile torso-worn displays to facilitate orientation awareness for pilots in unusual acceleration environments (Rupert et al. 1994; Rupert 2000). van Erp (2007) deployed a torso-worn vibrotactile display as a pedestrian navigation system. They also carried out a series of systematic experiments to determine vibrotactile perception on the torso in humans. Several studies have been published on the use of torso-based haptic displays as a tactile-visual sensory substitution system to aid visually impaired people. The VibroVision vest, developed by Wacker et al. (2016), comprised an array of 16 x 8 vibrators and could convert visuospatial information into a 2D vibration image on the abdomen. Similarly, the Tactile Vision Substitution (TVS) system was designed to capture visual information from the surrounding environment using a video camera and to deliver feedback to the skin of the back, abdomen, or thigh via an array of actuators (Johnson and Higgins 2006).

In addition, previous studies have demonstrated that vibrotactile actuators are able to transmit physical information either as a simple cue to indicate contact location in virtual environments or a complex one to convey an object's physical properties. For instance, Israr et al. (Israr and Poupyrev 2010; Israr and Poupyrev 2011a) used a two-dimensional array of vibrotactile actuators mounted on the back of a chair to create static and dynamic haptic sensations derived from movie and game scenes. Lindeman et al. (2006) designed TactaVest, a torso-based vibrotactile interface, to deliver feedback about collisions with virtual objects in military simulations. Previous studies have also demonstrated the application of torso-based tactile displays for the communication of affective touch. Lemmens et al. (2009) developed a wearable vibrotactile jacket involving 64 vibrators, intended to intensify the emotional immersion experience while watching movies. Arafsha et al. (2012) designed the Emojacket for enhancing immersion while watching movies and gaming experience, containing a combination of vibrotactile and heat actuators to display several universal emotions, along with several emotional reactions such as a hug, poke, tickle, or touch. Lentini et al. (2016) designed a tactile gesture authoring system able to translate hand gestures into vibrotactile stimuli rendered through a haptic jacket.

Researchers in cognitive neuroscience have recently highlighted the crucial role of the processing of somatosensory signals from the torso for global aspects of Bodily Self Consciousness (BSC), a crucial brain mechanism of self-consciousness based on perceptual mechanisms associated with the integration of multisensory and sensorimotor bodily signals (Blanke 2012; Park and Blanke 2019). In these studies, participants were exposed to a large variety of different conflicting combination (spatial and/or temporal mismatch) of torso-based touch feedback (e.g., stroking/tapping on the chest/back) and other sensorimotor bodily signals (e.g., visual stimuli and motor action). As the conflicting spatio-temporal feedback prevents normal multisensory integration of bodily signals, participants experienced different illusory own-body perceptions, affecting both self-location and self-identification.

So far, torso-worn haptic displays have rarely been used for investigating global BSC. Ehrsson (2007) and Lenggenhager et al. (2007) studied out-of-body and full-body illusions by providing participants with an image of their filmed body or a virtual body on a Head-Mounted Display (HMD) while an experimenter stroked their torso with a stick. As a result of multisensory stimulation, participants reported that they are located outside their physical bodies, self-identified with the virtual body, and had the impression of looking at themselves from this perspective. A significant limitation of such manual touch-feedback is the inherent variability in both-touch location and timing and its effects on replicability.

Recently, Blanke et al. (2014) used a robotic system to apply sensorimotor manipulations between the hand and torso of blindfolded, sound-isolated participants. Participants were asked to perform poking movements with both hands by using the front haptic device placed in front of them while receiving tactile stimuli on their back from another robotic device synchronously or asynchronously with their hand movements. In the synchronous condition, participants reported the experience of touching their own back (illusory self-touch). Interestingly, in the asynchronous condition, they reported a reduction in self-touch sensations as well as the impression that someone else was behind them (presence hallucination, PH) and touching them (passivity experience). It has been argued that such robot-induced experiences are similar to symptomatic PH reported by neurological and psychiatric patients (e.g., Parkinson's disease and schizophrenia, respectively) (Llorca et al. 2016).

Despite recent progress in robotic control for inducing different types of illusory own-body perceptions, the use of such a system is limited to the laboratory environment in which participants remain stationary. Therefore, to investigate the different facets of global BSC, more versatile haptic technology is required that allows us to manipulate tactile stimuli on the torso, together with other sensory modalities, in a complex and dynamic environment. In our previous research (Jouybari et al. 2019), we partly replicated the results of (Blanke et al. 2014) using a custom-made torso-worn vibrotactile garment, reporting an effect of synchrony for passivity experiences (“It was as if someone else was touching my back."), but failed to significantly modulate self-touch (“I felt as if I was touching my back with my finger") and PH as observed in (Blanke et al. 2014). We concluded that a simple vibratory stimulus might not be sufficient in substituting collision-type touch stimuli. However, to provide mechanical touches or simulate collisions in virtual environments, it has been shown that force feedback may enhance immersion (Huang et al. 2017; Jadhav et al. 2017). In a recent study, Shim et al. (2019) further observed that participants recognized tactile patterns presented on their wrist more accurately while presented via poking than vibrotactile stimuli. However, to the best of our knowledge, most torso-worn displays described in the literature provide vibrotactile feedback, whereas few publications discuss the use of force stimulators to the human torso to provide physical interactions in virtual environments. The force jacket was made of pneumatically actuated airbags to provide strong and variable forces to the torso along with vibrotactile sensations (Delazio et al. 2018). Nevertheless, this system included a series of air tubes connected to a large air compressor and vacuum, resulting in a very bulky setup (neither mobile nor portable) and confining for the users. More recently, Al-Sada et al. (2019) designed the HapticSnakes, a snake-like waist-worn robot that can deliver different types of haptic feedback to the upper body via an exchangeable end effector attached to the waist. One shortcoming of their approach is that the end effector movements can be limiting for the user's hands and body mobility, especially in VR environments, as they use a hand controller while their vision is occluded. Their design also introduced an unavoidable delay since the robotic arm was required to move to different points to apply feedback.

A promising solution could be integrating light force actuators into torso-worn garments allowing users to wear them on a regular basis with minimum motion constraints. Yet, due to the large morphological differences in the torso area (within and between-subject variability), forming and fitting the torso-worn haptic display to the user‘s body is another crucial design challenge (Mortimer and Elliott 2017). Therefore, design features should preferably enable the actuator positions to be adjustable on the user‘s skin. However, previous studies have not addressed this problem adequately, and little attention has been paid to the garment design.

This study focuses on the technical design, implementation, and validation of CognoVest as a proof-of-concept prototype torso-worn force display. Extending our previous work (Jouybari et al. 2019), we here address the complexity of designing a body-conforming, torso-worn, haptic display and propose a technical approach, including robotics, fashion design, and 3D printing technologies: CognoVest is a novel, portable, torso-worn force display developed to provide human-like poking stimuli on the user's back and investigate robotically-induced altered own-body perception, including PH, by extending the paradigm proposed by Blanke et al. (2014) (experiment 2) to a wearable system.

The remainder of the paper is organized as follows: In section II, we describe the design concepts, realization, and validation of CognoVest. Section III describes the experimental scenario and results for the own body perception experiment. Section IV discusses the results and examines possible limitations. Finally, section V presents our conclusions.

3.2 Novel wearable setup to induce bodily illusions

A schematic view of the stationary experimental setup, used in the study (Blanke et al. 2014) (experiments 2 and 3), is represented in Figure 3:1(a). The setup consists of a haptic device (Geomagic Touch, 3D Systems), i.e. the front haptic interface, and a three degree-of-freedom (DOF) robot, i.e., the back robot. The front haptic interface controls the position of the back robot, which causes complete conjunction between the movements of the two robots. Participants manipulated the front haptic interface using their right index finger (via 3D printed finger support) to control the position of the back robot, which in turn provides touch-cues to the participant‘s back.

The novel experimental setup is illustrated in Figure 3:1(b). In the experimental arrangement, the back robot has been replaced with a torso-worn force display (Figure 3:1(b)), called CognoVest, to provide the mechanical touch on the participants' back. The same front haptic interface as in the study (Blanke et al. 2014) is used. To assess the spatial correspondence between the continuous hand workspace and discrete back workspace (as a limited number of actuators was employed on the torso-worn display side), the hand exploration area (160 W x 120 H x 120 D mm) was divided into nine square sections, according to the arrangement of the nine on-off actuators embedded in the CognoVest. Each square was around 30 x 30 mm, while the effective depth (i.e., the depth threshold that, if exceeded, activates one of the actuators, depending on the level of height or width) was considered at the mid-depth. Depending on the participant's finger poking position in the front robot's workspace, the corresponding actuator was activated on the back (see Movie S1). The actuator remained operating until the participant's finger departs that actuator's specific area. In this section, we describe the design concepts, implementation, and characterization of CognoVest.

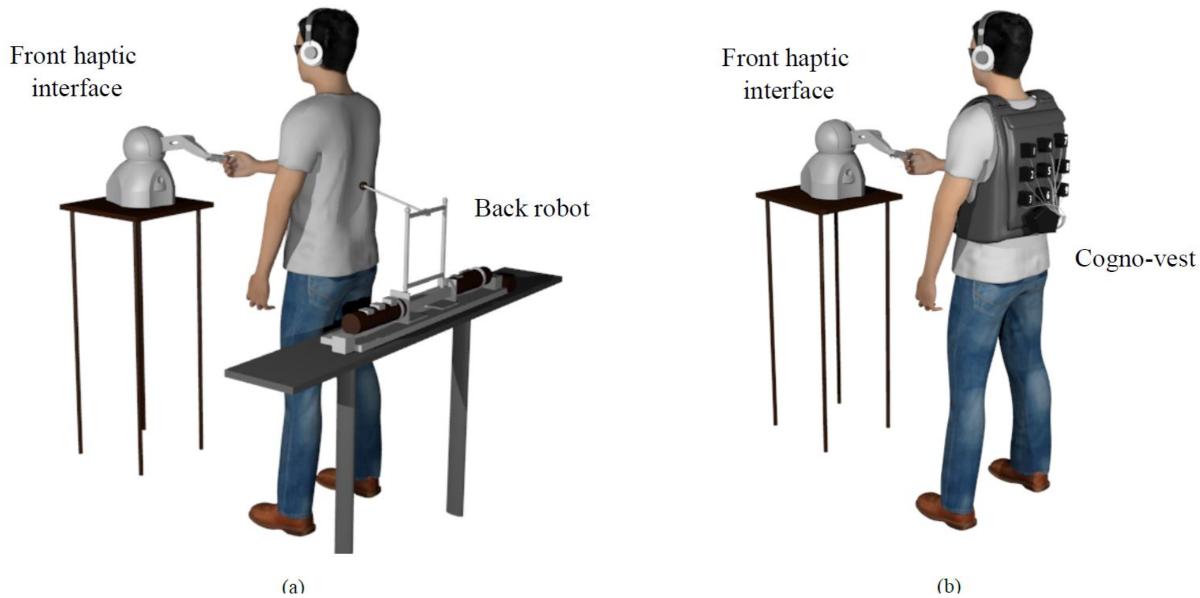


Figure 3:1 Schematic views of setups for experimentally inducing PH and relevant bodily illusions.

(a) Classic setup: the setup comprised two robots, the front haptic interface, Geomagic Touch, and a three-degree-of-freedom (DOF) follower robot. (b) CognoVest setup: In the novel setup, the torso-worn force display replaced the robotic arm.

3.2.1 Finger poking characterization

In order to induce the intended bodily illusions, the actuator garment should provide force characteristics comparable to those of human-finger poking, i.e., the act of prodding someone with your index finger, as if to get their attention. Prior to actuator selection, we, therefore, characterized human finger poking with N=28 participants (14 females, age: 27.6±5.1 years) and quantified peak poking force (F_{PP}, poking duration (T_{PD}), and poking interval (T_{PI}) (see Figure 3:2(b)). These parameters were also used in the solenoid evaluation tests and to determine the proper driving parameters. Figure 3:2(a) illustrates the experimental environment. The testbed included a 3D-axis force sensor (OMD-10-SE-10N, OptoForce) attached to a base plate and fixed on a desk in front of the seated participant; in this study, we only used force data in the z-axis. Participants were asked to touch the force sensor as if they were poking someone's back. They were completely free in producing finger poking, and no instruction was provided by the experimenter. We gave them tens of seconds to become familiar with the task after we recorded data for 1 minute. Figure 3:2(c) represents the sample result for one of the participants, while Figure 3:2(b) shows the zoom-in in the range of 0-3 s. The results for 28 participants showed that peak poking force and poking duration were F_{PP} = 2.15 ± 0.28 N and T_{PD}= 0.22 ± 0.03 s, respectively. Participants performed finger poking with a time interval of T_{PI} = 0.6 ± 0.07 s.

The present study is a proof-of-concept and experimental use-case for the novel torso-worn force display and its feasibility for use in a sensorimotor perception experiment. We, therefore, decided to use simple on-off force actuators to produce the poking-like sensation. Compared to other types of linear servo actuators (e.g., voice coil motor), on-off actuators have fewer parameters to be adjusted; they can be implemented with a simpler control system and motor driver resulting in a lighter setup that is important for wearable and portable haptic interfaces. Additionally, bi-directional push-pull solenoid actuators were included, building on the finger poking characterization experiment results, as they can provide mechanical touch perpendicular to the skin. The solenoid (1), that best matched human finger poking, had a starting force of 5 N (12 VDC), a shaft length of 5.5 mm, and weighed 39 g.

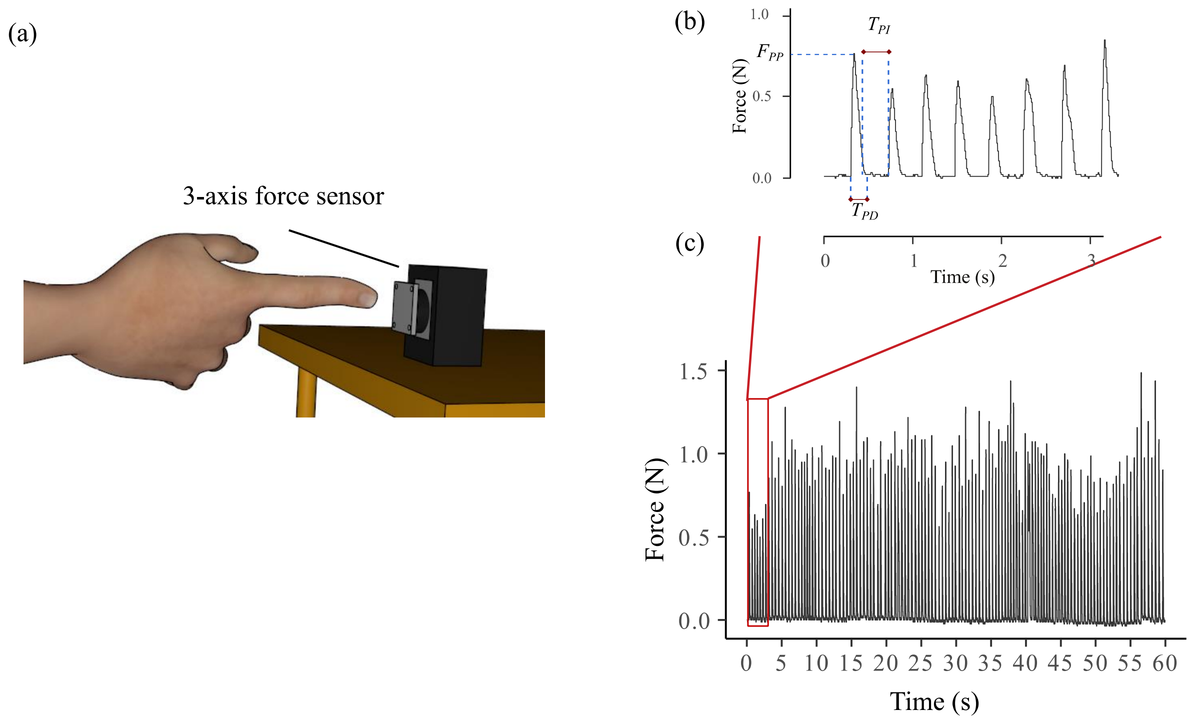


Figure 3:2 Finger poking characterization experiment's setup and result.

(a) Experimental environment including a 3-D axis force sensor fixed on the table. (c) Results of finger poking experiment for one of the participants during one minute (b) with special zoom-in in the range of 0-3 s. The plot (b) also contains an illustrative view of quantitative parameters used to describe finger poking results (peak poking force (F_{PP}), poking duration (T_{PD}), and poking interval (T_{PI}).

3.2.2 CognoVest

3.2.2.1 Electronics and Software Development

In a previous study (Jouybari et al. 2019), we reported that an array of 3 by 3 tactile actuators on the back is sufficient to create the sensation that the entire back is covered with actuators. This is due to the poor tactile spatial acuity of the human back (Jóhannesson et al. 2017) and explains the limited number of solenoid actuators used, in our case 9. Solenoids were placed at the center-to-center distance of 60 mm, which approximates the tactile localization threshold of the human back (Lindeman and Yanagida 2003; Jones and Ray 2008). As a result, the dimension of the back workspace is approximately two times larger than that of the hand. Yet, according to our previous study with the vibrator setup and the initial user testing experience with the current setup, the matching ratio of 1:2 between the hand and the back workspace seems natural to participants, and, indeed, they are not able to perceive the difference. This observation points to the poor tactile spatial discrimination on the human back.

Figure 3:3(a) presents the system architecture. The actuators are controlled using an Arduino Mega 2560, which connects via a Bluetooth module to a host PC. The controller board can be fully portable (battery-powered) or tethered for more extended studies. The sampling time for the front haptic interface is 1 ms. However, the host PC reads the finger's position data only every 60 ms, and sends the processed position data in terms of the solenoid activation status (solenoid ID) every 100 ms (this value was adjusted to avoid jittering behavior of solenoids, especially at the border of two squares) to the controller board.

A customized GUI was implemented in the Qt platform (free and open-source platform to create GUI) to provide a convenient interface for controlling haptic stimulations by the solenoids and handling experiments with the CognoVest.

3.2.2.2 Garment Design

We designed a new actuator brace for solenoid actuators by considering the following design criteria, suggested by our previous study (Jouybari et al. 2019) and literature (Lindeman et al. 2004; Mortimer and Elliott 2017):

- It should keep actuators snug against the skin, even during walking and movement.
- It should be as light as possible and comfortable to wear, possibly for longer periods of usage.
- It should be adjustable and unisex.

We named our solution CognoVest (see Figure 3:3(b)). CognoVest is a Y-harness brace with stretchable straps wrapped around the shoulder, chest, and lower back, securing garment positioning on the users' torso. To support the wearable hardware, the back part of the brace, taken from the Mil-Tec Military-style Lightweight vest, covers the entire back. This piece of fabric is made of durable polyester nylon and integrated laser-cut loops, which facilitate mounting solenoid actuators on the back (see Figure 3:3(d)). As a result, CognoVest is unisex, lightweight (the overall weight, including actuators and controller board, is 1 kg), and allows for unimpeded, free breathing. The stretchable material and Velcro fasteners make it size adjustable and body-conform.

3.2.2.3 Solenoid boxes

The actuators were placed in custom 3D printed boxes so that they could be fixed to the wearable garment. These mechanically distance-adjustable, 3D printed boxes (see Figure 3:3(c)) were designed to account for the irregular surface of the human back, especially on the spinal cord and lower back areas. The experimenter can manually adjust the distance of each solenoid with the participants' back to ensure that there is contact between the tactile display and the user 's back. A 20 mm silicone tube was used (hardness: 60 shore A, inner diameter:12 mm, outer diameter: 14 mm) to extend the solenoid actuator tips, mainly for actuators located on the spinal cord (actuator 4-6) and lower back areas, where higher curvature can be found, depending on the participants' back-morphology.

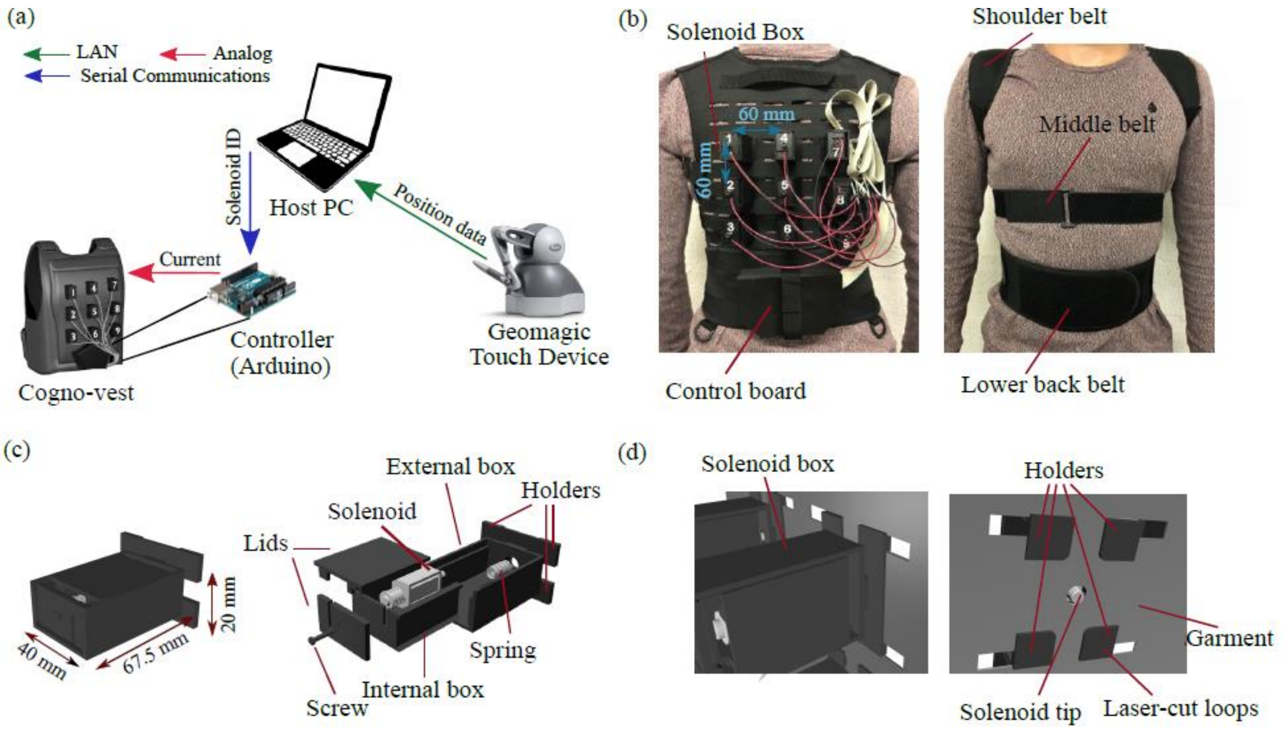


Figure 3:3 CognoVest components.

(a) System architecture. (b) CognoVest on the participant, back view (left) and front view (right). (c) Mechanically-adjustable box, box dimension (up-left), box components (right). (d) Mounting solenoid boxes on the wearable garment, exterior view (left) and interior view (left).

3.2.2.4 System Evaluation

In order to compare the performance of the integrated solenoid actuators to that of their datasheet, we tested one solenoid actuator under various environmental and parametric conditions, as shown in Figure 3:4(a): *Solenoid* (upper figure: only solenoid), *Solenoid-Tip* (middle figure: solenoid with elastic tip), and *Solenoid-Box* (lower figure: only solenoid inside the 3D printed box). In each condition, we sent a square pulse signal (pulse width = 250 ms, pulse duration = 5.25 s) to the solenoid. The activation duration was chosen based on the results of finger poking duration (T_{PD}). We measured the provided impact force, activation delay (ActD: the time interval between command sending and solenoid activation), and deactivation delay (DeactD: the time interval between command sending and solenoid deactivation) at different stroke lengths of 0, 1, 2, 3, 4, and 5 mm (end of the stroke).

The solenoid's impact force profile, ActD, and DeactD are shown in Figure 3:4(a) and Figure 3:4 (b). Figure 3:4 (b) indicates a gradual increase in the impact force profile with increasing stroke length for all three conditions. This observation suggests that in order to get a stronger touch sensation, each solenoid‘s position needs to be adjusted to (approximately) 60-80% of the maximum stroke length. Moreover, the new arrangements did not reduce the impact force, although its dependency on the stroke length changed.

We also observed that delayed activation of 50 ms followed by a longer, variable deactivation delay, even for the *Solenoid* condition (Figure 3:4 (c)). While ActD is constant (around 50 ms), the deactivation delays increase with stroke length. However, it is worth noting that both ActD and DeactD were lower than the average human finger poking time interval; hence their influence should be negligible in the self-poking procedure.

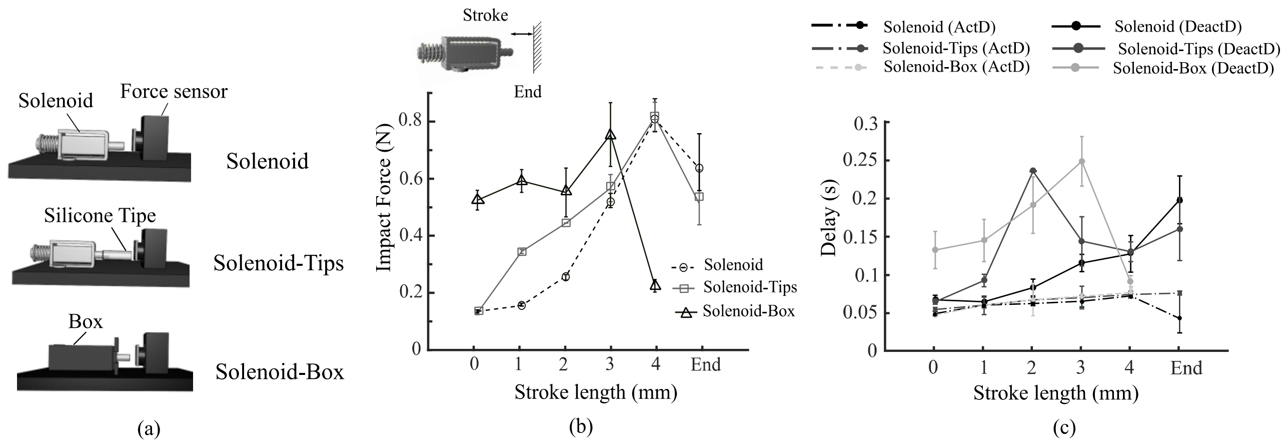


Figure 3:4 Solenoid characterization experimental setup and results.

(a) Schematic view of solenoid characterization setup in three different experimental arrangements. (b) Provided impact force by solenoid at different stroke lengths in three experimental conditions. (c) Solenoid activation and deactivation delays as a function of stroke length in three experimental conditions.

To conclude, the new arrangement of solenoids improves the force profile; however, it leads to bigger delays to follow the deactivation command. To compensate ActD and DeactD, we deployed a linear estimation that calculates the front robot position for the next 100 ms (approximate mean of ActD and DeactD) with the current velocity and position.

3.3 Own body perception experiment

3.3.1 Participants

We recruited 25 healthy participants (12 female) aged between 18 and 32 years (mean age: 26 ± 3.9 years). Participants were all right-handed, reported no previous neurological or psychiatric conditions, and were naïve to the purpose of the study. All participants gave written informed consent before participating, and the research was conducted in accordance with the Helsinki Declaration.

3.3.2 Experimental design

We designed a behavioral study to investigate the feasibility of inducing PH in healthy participants by providing tactile-motor signals from the prototyped CognoVest. As in previous studies (Blanke et al. 2014; Jouybari et al. 2019), we explored the effect of synchrony (synchronous (SYNC) vs. asynchronous (ASYNC)) in providing self-generated tactile stimuli on the participant's back. In the SYNC condition, participants receive poking sensations on their back immediately after touching the virtual wall in the front robot workspace. In contrast, in the asynchronous condition, a systematic delay was introduced between when participants touched the virtual wall and when they received force sensations on their back: to reduce the habituation effect and related potential changes in tactile perception of our participants, a variable delay of 500 ± 100 ms was used in the asynchronous block. There was no force feedback at hand for both SYNC and ASYNC modes.

We used a 4-item bodily illusion questionnaire to estimate subjective changes in altered own body perception during the experiment. The questionnaire was adapted from (Blanke et al. 2014) (experiment 2) and given to participants at the end of each experiment block. The statements used in the questionnaire can be seen below:

Self-touch: "I felt as if I was touching my back with my finger."

Passivity: "It was as if someone else was touching my back."

PH: "I felt as if someone was standing close to me or behind me."

Control: "It was as if I had two bodies."

We asked participants to report the degree of their agreement on a 7-point Likert scale for each item (0 = not at all, 6= very strong). In addition, we asked all participants to write down a short description (at least two lines) about any observation that they may have had during the experiment.

3.3.3 Procedure

Participants wore the CognoVest over a fitted T-shirt. They were blindfolded and received noise-canceling headphones (WH-1000XM3, Sony) to eliminate the sound of solenoid activation during the experiment. The experiment consisted of two main blocks (see Figure 3:5), namely the calibration task and the poking task.

3.3.3.1 Calibration

In the calibration task, the experimenter activated each solenoid actuator individually (in a random sequence) to ensure that there was contact with the back. The experimenter manually adjusted the solenoid position at different stroke lengths until receiving verbal confirmation from participants that they felt a mechanical touch from each solenoid. The calibration session lasted around 10 minutes. Participants were asked to stand during the whole experiment to avoid changing solenoid position.

3.3.3.2 Poking task

Following (Blanke et al. 2014) (experiment 2), we asked participants to produce poking-like hand movements with the front robot in order to receive mechanical touch on their back (synchronously or asynchronously) through the CognoVest (see Movie S2).

The experiment started with a training session in which participants performed the poking task (synchronous), first with their eyes open and then closed. We instructed participants to place their right-hand index finger inside the finger placement and generate forward and backward hand movements with the front robot at a frequency of approximately 1 Hz, while also instructing them to freely explore the entire workspace (up-down, left-right; adopted from study Blanke et al. (2014) (experiment 2)). The training session lasted around 2 minutes. During the subsequent poking task, participants were sound-isolated and blindfolded. In this way, they completed two blocks of SYNC and ASYNC (one block of each), equally distributed among participants. Each block lasted 2 minutes, and an acoustic cue was presented at the beginning and the end of each block. After each block, participants were asked to complete the questionnaire and, at the end of the poking task, to comment freely on their experience and the experiment.

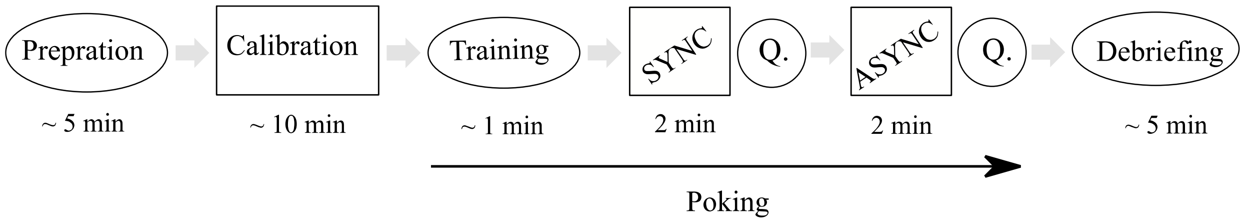


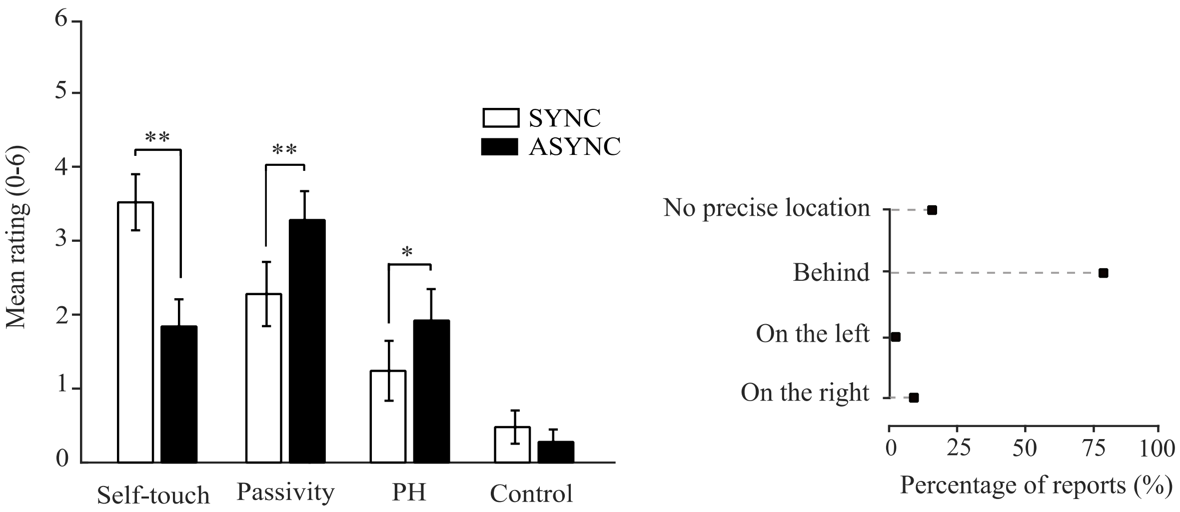
Figure 3:5 Experiment flow.

In the preparation session, the experimenter helped participants to properly wear the CognoVest on a thin T-shirt. Then she manually calibrated the position of each single solenoid, ensuring that there is actual contact between solenoids and the participant's back (Calibration). Subsequently, participants started to complete two blocks of the poking task (followed with the bodily illusion questionnaire) after getting familiarized with the task. At the end of the poking task, participants commented on their experience and the setup freely (Debriefing)

3.3.4 Results

The questionnaire data of the CognoVest experiment were collected from 25 participants. As the questionnaire data were not normally distributed (Shapiro-Wilk test for normality), we analyzed the effect of synchrony (Sync vs. Async) with the one-tailed Wilcoxon signed-rank test for each questionnaire item. The mean values for Self-touch, Passivity, PH, and Control questions in both SYNC and ASYNC conditions are presented in Figure 3:6(a). We report first that the average ratings for all three experimental items (*Self-Touch*, *Passivity*, *PH*), in both conditions are significantly higher than those of the *Control* question.

Second, for all three experimental questions, we found a significant effect of synchrony (*Self-touch*: $z=3.7$, $p < 0.01$, *Passivity*: $z=-2.5$, $p < 0.01$, *PH*: $z=-1.8$, $p = 0.03$). As hypothesized based on (Blanke et al. 2014; Jouybari et al. 2019), participants gave higher ratings for the *Self-touch* question in the synchronous than asynchronous condition (SYNC: M=3.5, SEM= 0.4; ASYNC: M = 1.8, SEM = 0.4), while for *Passivity* experience and *PH* questions, their ratings were higher in the asynchronous condition (*Passivity*, SYNC: M= 2.3, SEM = 0.4; ASYNC: M=3.2, SEM=0.4; *PH*, SYNCH: M = 1.24, SEM = 0.4; ASYNC: M=1.9, SEM=0.4).



(a) (b)

Figure 3:6 Results of bodily illusions questionnaire.

(a) Mean ratings for bodily illusions and control questionnaire items. The bar charts and error bars depict the average scores and standard error of the mean (SEM) for each question (**: $p < 0.01$, *: $p < 0.05$). (b) Participants' reports on the location of presence in the asynchronous condition.

In addition, we asked participants who gave *PH* ratings > 0 to specify the location of the perceived presence. Figure 3:6(b) represents the percentage of reports on the location of the perceived presence in asynchronous conditions, indicating that participants mainly perceived the presence behind their body.

3.4 Discussion

While the majority of prior studies have used vibrotactile stimulus for substituting collision-type stimuli on the users' torso in virtual environments, employing force feedback actuators may enhance the level of immersion. However, compared to vibrotactile devices, force feedback interfaces demand higher considerations in the interface design and handling procedure, as their perceptions depend upon the actual physical contact with the skin. With higher morphological changes in the torso area, maintaining physical contact with the skin of the torso is problematic. As a solution, we prototyped CognoVest, a unisex, body-conforming torso-worn force display. We further validate its performance in providing realistic collision sensations in a sensorimotor perception paradigm.

Our results demonstrate that the CognoVest can be used to experimentally induce illusory self-touch and passivity experiences as well as presence hallucinations (PH) of mild to moderate intensity in a healthy population. Despite the substantial inter- and intra-subject variability in torso morphology, the CognoVest was able to reliably provide mechanical touches on the back. To our knowledge, this is the first study to investigate the design, implementation, and application of an untethered, torso-worn force display.

Our results further replicate and extend prior findings (Blanke et al. 2014) on the robotic induction of bodily illusions in a healthy population by providing a sensorimotor mismatch between the right hand and the back. In our previous study (Jouybari et al. 2019), we were able to induce illusory passivity experiences via a vibrotactile interface but were not able to modulate self-touch and PH. However, the present force display allowed us to also modulate illusory self-touch and

PH. Compared to the study (Jouybari et al. 2019), we have observed stronger passivity experiences reported by participants. These results imply that force stimulation is more effective in inducing bodily illusions than vibrotactile stimulation and are in line with prior studies (Jadhav et al. 2017; Cao et al. 2018), which have shown the importance of rendering realistic force stimuli to simulate collisions or physical interactions in virtual environments.

3.4.1 Study limitations

We note, however, that compared to the study by Blanke et al. (2014), participants gave slightly lower ratings across all questionnaire items in both synchronous and asynchronous conditions. The observed decrease in illusory ratings may be explained by the forces that can be applied by the solenoids as seen in the evaluation test, which revealed that the maximum provided force is substantially smaller than the average poking force obtained from the human finger poking experiment. Indeed, providing such weaker touch sensations on the back, which has low spatial tactile acuity and density of touch receptors, likely reduced the level of immersion and may lead to weaker induction and modulation of robot-induced illusory own body perceptions.

We speculate that smaller synchrony-dependent modulation might be due to additional temporal delays in solenoid activation and deactivation commands. In spite of implementing linear estimation to reduce ActD and DeactD, some participants still reported the feeling of time delays at deactivation moments during the synchronous condition. Given that the present experiment aimed at investigating the effects of temporal mismatch in a somatosensory-motor stimulation paradigm between the hand and back, unexpected alterations in the temporal delay are likely to negatively influence participants' responses. We argue that future applications may resolve these technical limitations by deploying a more reliable solenoid actuator, which can guarantee time precision and ensure a sufficiently strong poking force.

3.5 Conclusion and future works

In this paper, we addressed the complexity of designing a body-conform force display by following an iterative design procedure to prototype CognoVest: a novel, torso-worn force display to provide mechanical touch cues on participants' back. Further, we evaluated CognoVest's potential for 1) providing touch cues and measuring tactile perception, but also 2) the induction and modulation of altered states of bodily self-consciousness.

Our findings demonstrate that the CognoVest is capable of successfully inducing PH and passivity experiences during asynchronous stimulation as well as self-touch during synchronous stimulation in a healthy population. Based on these findings, we propose technological improvements, leading to the induction of higher illusory ratings. We are confident that the prototype CognoVest, described here, may pave the way for future user-friendly, torso-worn force display technology to provide personalized, realistic touch sensations in virtual environments.

We are currently employing the CognoVest in tactile spatial resolution tests to quantitatively evaluate its performance while worn on the user's body. We believe that the results of such research would provide more practical information on the design and handling of force feedback stimulators.

Although we successfully demonstrate that inducing an illusion is possible with the current solution, future work should concentrate on the use of proportional force actuators (e.g., voice coil motor), instead of On-Off actuators, to simulate approaching speed and variable force during poking movements and to create a more realistic poking sensation on the back. In addition, the handling procedure may be standardized by implementing automated distance-adjustable boxes to uniformly adjust solenoid distance from the body in a more precise and efficient manner.

Moreover, the front robot, not portable in the present study, can be replaced by currently existing motion-sensing technology in combination with a finger-based haptic stimulator. This would make the system fully portable and wearable, and allow us to perform experiments on tactile perception and BSC outside of the laboratory setting. With respect to clinical translation, this equates to placing the device also in the patient‘s home or in clinics to facilitate the study of specific hallucinations such as the PH (or other bodily illusions) in ecological settings (i.e., close to daily life situations). It is also of interest to employ the portable CognoVest in a mobile setting, allowing us to investigate bodily illusions during human locomotion.

Chapter 4 Investigating gait agency through manipulating step-related remapped tactile feedback

“FeetBack” touch remapping of action consequences produces accurate awareness but limited (loco)motor adaptation

Atena Fadaei J.[1,2], Nathanael Ferraroli[1,2], Mohammad Bouri[3], Olivier A. Kannape[1,2 *], and Olaf Blanke[1,2 *]

In preparation.

[1] École Polytechnique Fédérale de Lausanne (EPFL), School of Life Sciences, Brain Mind Institute, Center for Neuroprosthetics, Campus Biotech H4, Chemin des Mines 9, CH-1202 Genève, Switzerland

[2] Laboratory of Cognitive Neuroscience, Brain Mind Institute, Faculty of Life Sciences, Swiss Federal Institute of Technology (EPFL), Lausanne, Switzerland

[3] REHAssist Group, EPFL, Station 9, STI IMT MED, Lausanne Switzerland

[*] These two authors contributed equally to this work.

Abstract

Previous studies on the sense of agency (SoA) have mainly focused on investigating performance-related auditory or visual cues and neglected the importance of tactile action consequence on human action awareness. The present study aims to explore the limit of human consciousness in free walking conditions by systematically manipulating touch action consequences. To this aim, we develop the FeetBack system that remaps the foot rolling sensations onto the skin of the users’ torso during free gait movements. Our findings are in line with prior results of auditory or visual gait agency that delayed feedback changes SoA for walking in a systematic manner even when presented in the form of remapped tactile feedback. We also observed a general impact of tactile remapped feedback on the participants’ stride time deviation; nevertheless, this was not specific to the delay or systematic as in prior studies. These findings are of interest both for our understanding of the sense of agency but also of translational value for sensory augmentation and substitution in clinical populations.

4.1 Introduction

A large portion of the movements we perform over the day is neither immediately goal-directed nor does it result in a consciously “desired” outcome. For instance, we may adjust our posture after being stationary for an extended period of time, we may shift our weight to maintain our balance, or we may just be walking without any particular target or goal. At the same time, we are in control of these actions and perceive them as our own; in other words, we perceive a sense of agency (SoA) for these actions (Jeannerod 2003). The vast majority of research on SoA has, however, focused on goal-directed actions and predominantly investigated brief upper-limb movements directed at specific target locations and the related SoA (Nielsen 1963; Daprati et al. 1997; Franck et al. 2001; van den Bos and Jeannerod 2002; Farrer et al. 2003; Tsakiris et al. 2005; Shimada et al. 2010). SoA research may also include mediated action outcomes such as the occurrence of a tone after a button-press (Sato and Yasuda 2005; Repp and Knoblich 2007; Sato 2008; Knoblich and Repp 2009) an approach also applied to investigate intentional binding (Suzuki et al. 2019). Thus, these studies studied the SoA by focusing on the immediate action-outcome of such goal-directed actions rather than conscious monitoring of movement details. Recent studies have also investigated the SoA for continuous and partially automated movements such as drawing (Fourneret and Jeannerod 1998; Slachevsky et al. 2001; Knoblich and Kircher 2004; Salomon et al. 2011) or locomotion (Kannape et al. 2010; Menzer et al. 2010; Kannape and Blanke 2013). These studies have further demonstrated that participants unconsciously and automatically adapt their movements to (spatially or temporally) deviated feedback of their movements. In the present study, we investigated how remapped, tactile locomotion feedback would modulate participants' SoA and gait behavior (Menzer et al. 2010; Kannape and Blanke 2013).

In many previous studies, the SoA has empirically been assessed via motor awareness (MA) paradigms where participants are exposed to manipulated sensory (visual and auditory) consequences of their ongoing movements and asked to judge if the sensory feedback matched the expected sensory consequence of the executed movements (Aarts et al. 2005). Such work used paradigms that included continuous upper-limb movements. For instance, hand drawing and reaching movements studies that introduced angular biases in visual feedback revealed dissociations showing that participants consciously self-attributed movements with the angle of deviation up to 6.5-15, although they corrected their movements to compensate for spatial deviation (Franck et al. 2001; Slachevsky et al. 2001; Farrer et al. 2003; Jeannerod and Pacherie 2004; Kannape et al. 2010). Similarly, studies that provided temporally manipulated visual feedback (hand movements) showed that participants only become aware of temporal biases beyond 150-200 ms (Franck et al. 2001; Farrer et al. 2008; Kannape et al. 2010; Shimada et al. 2010). These studies also revealed that participants automatically corrected their hand trajectories while unconsciously compensating for the spatial or temporal deviation.

Despite these insights, there is arguably a cognitive bias in the studies mentioned above. Participants achieve their task of reaching a target (location or button press) may override contradictory sensorimotor evidence (Kannape and Blanke 2012). One way to avoid such a "task-completion bias" is to study SoA for continuous movements such as walking or locomotion. Locomotion is cyclic, more rarely immediately goal-directed, and generally considered a highly automatic and unconscious action (Grillner and Wallen 1985; Armstrong 1988). Yet, as discussed in the following, it also presents an interesting alternative for studying our sense of agency. Menzer and colleagues (Menzer et al. 2010) investigated the SoA with different auditory feedback conditions during free walking (using 20 random delays between 0-1800 ms; linked to their footfalls). The authors reported a systematic sinusoidal modulation of the SoA: SoA strongly depended on the delay and was highest for trials when auditory and locomotor events were subjectively in phase (i.e., no delay, half-cycle delay, and full-cycle delays). In other words, whenever the (auditory) footfall coincided with an actual footfall, participants judged the feedback to correspond to their own movement, even if the sound and the heel strike were left-right reversed. Kannape and Blanke (2013) extended these data and measured SoA for locomotion using visual feedback. In these studies, participants continuously walked on a treadmill and watched an individually mapped, life-size virtual body perform their own movements either in real-time or with a randomized delay (10 random delays of 0-1500 ms). As before, there was a systematic and predictable relationship between SoA judgments and the extent of the temporal delay, but this time with a U-shaped pattern; SoA was highest for trials during which visual feedback and walking phase were “synchronized” (i.e. no-delay or a full-cycle delay) but lowest for trials with left-right reversed feedback (half-cycle delay). Furthermore, both gait agency studies demonstrated highly systematic gait adaptations, which were disassociated from walking-related SoA.

While such auditory and visual stimuli clearly delineate SoA for locomotion, the most fundamental and immediate consequence of our movements concerns the sense of touch, particularly in the case of locomotion (Thomas and Whitney 1959). Ground reaction forces are the most evident sensory consequence of walking. In fact, while the presence of visual or auditory walking consequences is intermittent and dependent on many environmental factors (e.g., floor texture, shoe type, the direction of gaze, being in front of reflective surfaces, etc.), we always touch the ground during walking cycles. Although the integration of audio-visual feedback into the sensorimotor control has been widely investigated for both upper-limb movements or gait movements (for review see (Kannape and Blanke 2012)), there appears to be no individual study investigating the effect of tactile action consequence on SoA or potentially accompanying motor adaptation. The lack of studies investigating the impact of tactile action is certainly due to the fact that the spatiotemporal manipulation of the actual sense of touch at the effector carrying out the action is impossible (or would require the use of anesthesia in healthy participants or investigations of neurological patients). However, additional artificial tactile feedback (i.e., vibrations) could be provided using, for example, recent wearable biofeedback systems (i.e., providing artificial tactile feedback, mainly in the form of simple vibration during walking). For instance, Winfree et al. (2013) employed a shoe-based vibrotactile feedback system and reported improved gait in patients with Parkinson's disease. Crea et al. (2017) provided gait-synchronized vibrotactile feedback to the thigh skin of patients with lower leg prostheses, reporting significant improvement in temporal gait symmetry immediately after training. Afzal et al. (2015) developed a portable rehabilitation biofeedback device that provides correcting vibrotactile feedback at the level of the foot to improve gait symmetry in stroke patients. Ling et al. (2020) provided the missing foot sensation of hemi-paraplegic patients during gait via distinct vibratory feedback on their back. After a three-week clinical test, they found significant improvements for the push-off movement. However, they observed decreased performance as participants were asked to recognize more number of focalized vibrators on their back; identifying five vs. three vibrators on the back required a higher attentional load. Alternatively, Shokur et al. (2016) presented continuous vibratory sensations (tactile illusion) via forearm haptic display and induced realistic illusion of walking in fully paraplegic patients in an immersive virtual reality environment. Their approach included reproducing the tactile/proprioceptive cues, describing bipedal walking by remapping the foot rolling sensations onto the skin of the patient’s forearm. While these studies demonstrated the effectiveness of vibrotactile biofeedback for gait rehabilitation, they neither addressed how augmented or remapped tactile feedback affects SoA nor whether such artificial tactile feedback is integrated into the sensorimotor control loop as expressed in gait adaptation.

Here we wanted to determine if participants display SoA for remapped tactile biofeedback and how it compares to previous work using auditory or visual feedback. We also investigated whether such remapped tactile feedback impacts online sensorimotor control and gait adaptation. To this aim, we developed a robotic FeetBack system that provided non-invasive, walking-related, remapped feedback during free walking. For this, we adapted previous paradigms for conscious gait monitoring via auditory (Menzer et al. 2010) and visual (Kannape and Blanke 2013) cues to touch sensation. The present fully wearable, portable tactile remapping system aims to introduce a specific range of temporal delays between participants' footsteps and step-related tactile cues provided onto the skin of their back. Based on previous gait monitoring studies, we predicted systematic modulations in SoA and participants' walking speed as a function of temporal delay.

4.2 FeetBack system

4.2.1 Remapped tactile sensation

In this study, we deliver somatosensory information originated from free gait movements of participants onto the skin surface of their back via using FeetBack system (see Figure 4:1). To provide remapped tactile sensation, two linear arrays of vibrators were mounted on the sides of the back, each informing about the movement of the corresponding side leg. To induce a movement sensation on the back, inspired by the work of (Shokur et al. 2016), we used the vibrotactile apparent movement (VAM) illusion. VAM can be invoked through activating two or more vibrators, sequentially with specific timing parameters such as duration of stimuli (DOS) and stimuli onset asynchrony (SOA). As a result, the stimulation point is perceived as if it is moving continuously from one position to another, although the physical stimulating points are discrete (Burtt 1917; Sherrick and Rogers 1966). To link participant gait movements to the artificial back sensations, different scenarios were evaluated: 1) representing the rolling of the foot on the floor (feedback on stance) versus the swinging of the leg when the body is balancing 2) delivering VAM upward vs. downward on the back. According to primary user testing experience, tactile presentation of the foot rolling in an upward direction on the back seemed more feasible to users. We further considered a fixed VAM duration of 855 ms (e.g., the time of presenting the vibrotactile apparent motion with each linear array of vibrators) for all participants that approximates the span of the rolling of each foot on the ground. Therefore, VAM timing parameters (DOS = 150 ms, SOA = 85 ms) were chosen considering the results of the primary study on vibrotactile apparent movement (for more details see 7.1) and confirmed via a user study.

4.2.2 Wearable gait measurement system

To measure the stride time (time elapsed between the first contact of two consecutive footsteps of the same foot), pressure-sensitive insoles have been used (HD-FSR 002 by IEE S.A., Contern, Luxembourg.; Figure 4:1) as they are flexible and thin enough to be placed in a shoe without causing discomfort or hindering the user. Additionally, compared to other plantar pressure sensors, resistive pressure sensors are less susceptible to noise. Each insole contains eight force-sensitive resistors (Locations: 2 at the heel, 1 at lateral mid-foot, 3 at the ball of the foot, 2 in the front) capable of recording a pressure range from 100 mbar to 6 bar. To accurately capture the temporal gait parameters, pressure insoles were provided in two sizes (medium and large) and employed depending upon subjects' feet sizing. To read the changes in pressure on the sensors of the flexible insole that are represented by changes in resistance, each insole is connected to an ankle box including the readout electronics (Eight Wheatstone bridges, one for every sensor, and an analog-to-digital converter is used to read the sensor signals). The ankle box is attached to the shank by Velcro straps. Pressure data is sent to the main box (mounted on the back) using SPI (Serial Peripheral Interface) through a shielded cable. The box is closed by using a lid (not shown), held in place by magnets.

The mainboard is served as the central computing unit as it collects all data gathered by sensors and communicates (receive/send; sampling time of 10 msec) with the host PC through the Wi-Fi connection. It includes a BeagleBone Black

(BBB, a single-board computer marketed by the Beagle-Board.org Foundation) as the computing unit, an Inertial Measurement Unit to record acceleration and gyroscope information (not used in the current study), a Wifi module (TP-LINK WLAN-N-USB adapter) to communicate with the host PC, and lastly a battery (power bank, 3000 mAh) to make the whole system fully portable.

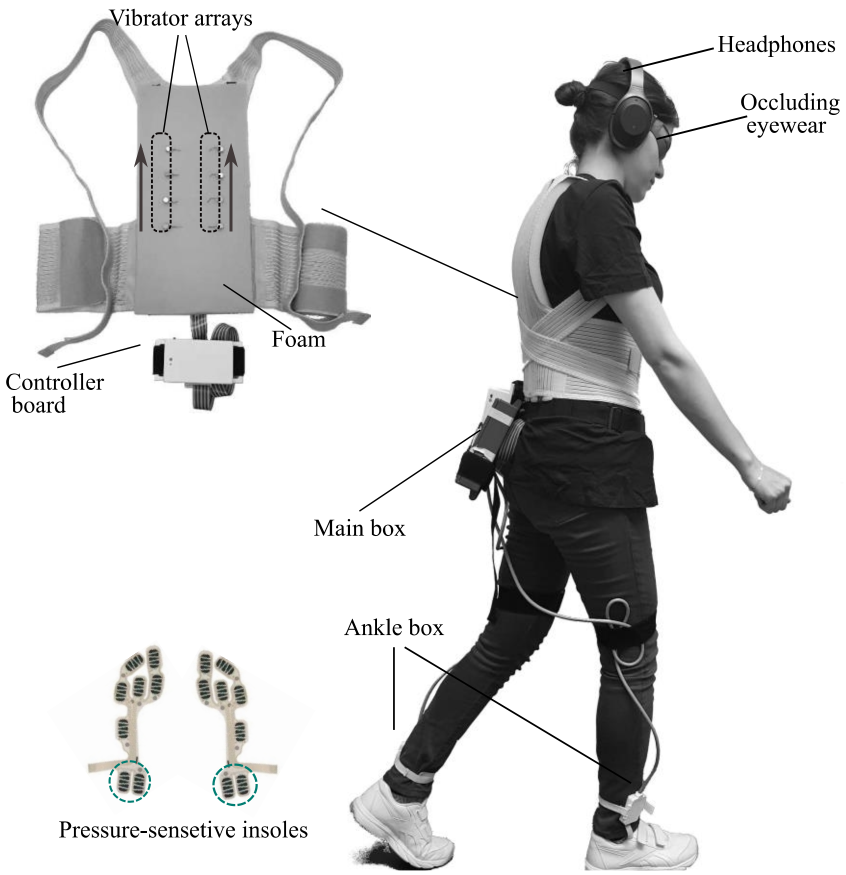


Figure 4:1 FeetBack system on the user and its components.

FeetBack system remaps the foot rolling sensation under the user's feet (lateralized feedback on the stance) onto the skin of the back. It includes two main parts: a wearable gait measurement system and a torso-worn vibrotactile display. The wearable gait measurement system detects the user's step. It consists of pressure-sensitive insoles under the user's feet, two ankle boxes, and the main control board attached to the participants' lower back. Only two force-sensitive sensors that are located at the heel (specified with dashed circles) were used to detect heel-strike. The vibrotactile display provides moving sensations (i.e., VAM) on the participant's back and includes two vertical vibrator arrays attached to foam, a torso-worn vest, and the controller board. Feedback on the stance was provided from down to up (solid black arrows).

4.2.3 Torso-worn vibrotactile display

To provide VAM on the participants back, two vertical arrays of coin-shaped, eccentric rotating mass (ERM) vibrators (310-003, Precision MicroDrive; body diameter: 10mm; body length: 3.4 mm; weight: 1.1 gr) with a horizontal distance of 110 mm were attached to a 20mm-thick foam (Softpur polyurethane foam) by using snap fasteners (see Figure 4:1). There were four vibrators in each array (inter-tactor distance of 40 mm). Female and male sides of fasteners were respectively glued to vibrators and foam. Vibrator foam was fixed to a fully elastic, posture-corrector brace by using velcro straps. The posture-corrector firmly keeps vibrators against the skin while allowing the user to move conveniently. The

ERMs are controlled by a haptic motor driver (DRV2605, Texas Instruments) on 5 V (DC), resulting in a vibration frequency of 175 Hz and an acceleration of 1.3 G. Haptic drivers are controlled with an STM32F407 microcontroller, which connects via a Bluetooth module (HC-05) to the host PC. The controller board (Figure 4:1) can be fully portable (battery-powered) or tethered for more extended studies.

A customized GUI was implemented in the Qt platform (free and open-source platform to create GUI) to provide a convenient interface for controlling the experiment flow. It received the pressure data from the gait measurement computing units via the Wi-Fi connection and provided live plotting of data together with other functionalities allowing the experimenter to monitor the data streaming and quickly detect any technical problems that occurred during the experiment. Besides, it allowed manual adjustments of vibrator parameters (e.g., intensity, DOS, SOA) as well as sending activation commands to vibrotactile display for presenting apparent motion stimuli.

4.3 Methods

4.3.1 Participants

A total of 29 healthy participants with normal or corrected-to-normal hearing (18 female, aged between 21 and 36, M = 26.86, SD = 4.6) were recruited in the experiment. They were all right-handed with no history of known orthopedic, metabolic or neurological impairment or painful condition that might alter walking. They were also asked to have any back-scarring as it could potentially induce sensitivity to the tactile stimuli. All participants were unaware of the purpose of the study and gave written informed consent before participating in the experiment. The research was conducted in accordance with the Helsinki Declaration.

4.3.2 Paradigm

The experiment was conducted using a within-participants repeated measures design. There was one block to familiarize the participants with the setup, during which we exposed participants with non-delayed tactile feedback (Familiarization; see Figure 4:2). There were two baseline blocks: one prior to the main experimental block (pre-baseline: without any tactile feedback, B_{Pre}), which was repeated after the main experiment (post-baseline: without tactile feedback, B_{Post}). Familiarization and pre-baseline blocks allowed us to establish points of reference for stride time alterations for the main experimental part. The post-baseline was carried out to assess any influence beyond the main experiment on subjects' gait (e.g., habituation, fatigue, etc.). The main experimental part consisted of trials with undelayed and different delayed feedback (i.e., delay as a with-in participant variable), including eleven different levels of delay (ranging from zero to 1500 ms with a time step of 150 ms). We also included catch trials (i.e., presenting a completely noisy (variable delay) tactile sensation, to assess the extent to which participants responded to perceived tactile feedback on their back rather than using other response strategies. Each condition was repeated ten times resulting in a total of 1200 trials per participant. All delay conditions were presented randomly during the main experimental part, in a total of four blocks. SoA was assessed at the end of each trial, and participants were asked to respond ("yes," "no"). Based on previous work (Menzer et al. 2010; Kannape and Blanke 2013) we asked the following question:" Did the feedback you felt on your back exactly correspond to the walking you just performed?". The ratio of "yes" responses was analyzed and reported. Participants' stride time values were recorded to capture any alterations in participants' walking pattern, influenced by the different feedback conditions.

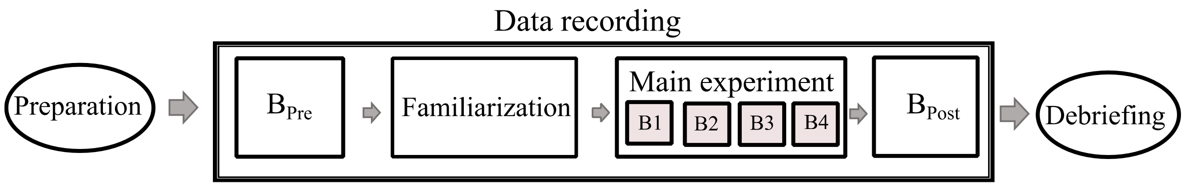


Figure 4:2 Experimental flow.

In the preparation, experimenters helped participants to wear the FeetBack setup. Then, participants were asked to walk for a few turns to get familiar with the rectangular walking path. The experiment consists of pre- and post-baselines (B_{Pre}, B_{Post}), a familiarization block, and the main experimental part. In baseline blocks, participants were asked to walk for three turns while receiving no tactile feedback on their backs. In the familiarization block, they received non-delayed feedback while walking for three turns. The main experimental part consists of four blocks. In each block, participants had to complete different trials in which feedback was presented either in real-time (60 ms) or randomly delayed by up to 1,500 ms. They had to respond to the agency question (yes/no) after each trial.

4.3.3 Procedure

The experimental flow is demonstrated in Figure 4:2. Following the signing of the informed consent form, participants were asked to put on a thin-fit T-shirt. Then, they were assisted in wearing the torso-worn vibrator and wearable gait measurement system properly. Three different sizes (i.e., 37, 40, 43 in European shoe sizing) of the same brand shoes (running shoes from Decathlon), including the proper size shoe soles (i.e., Medium for 40 and any sizes below it and Large for sizes above 40), were provided. Participants also wore occluding eyewear (SKLZ Court Vision Basketball Dribbling Goggles), preventing them from seeing their legs while walking. This helped to minimize the visual contribution to the task. They were also asked to keep their heads up when walking. In addition, they received white noise through noise-canceling headphones (WH-1000XM3, Sony) to attenuate potentially distracting ambient sounds and to mask any acoustic cues that might be related to activation of vibrators or participants' footsteps. The headphone also played auditory notifications (single or multiple beeps) at the start and termination of baseline and trial sessions.

After donning the experimental equipment, participants were asked to walk on a rectangular walking path of 4 x 20 m (marked on the floor with red tape) in a large open space for as many turns as they want. This allowed participants to familiarize themselves with the experimental setup and walking path. Experimenters also checked whether pressure data were correctly acquired and recorded by the software in the course of familiarization. Participants were instructed to walk (counterclockwise) at normal and relaxed speed throughout the whole experiment (as if they were "taking a stroll along a foot-path"). They were also asked to make a curve at corners so that their walking speed does not change. Participants were asked to walk for three turns (non-stop) along the rectangular path in baseline conditions. On the other hand, in the Main experimental part, participants were free to initialize each trial via the handheld wireless device. Two other buttons were assigned as "response" buttons. Participants were instructed not to initiate trials on their approach to the turn at the end of the hallway but rather to wait to initiate the next trial until the commencement of their walk down the length of the space (to minimize any potential effect of turning on the stride time). Individual trials lasted for 7 s allowing each participant to take on average 6.3 footsteps (±0.7 steps; SD). Participants were informed that trials would be presented in four blocks while they have the opportunity to be seated and take a drink of water. All participants completed a training session of 5 minutes (including three different delays of zero, 300 ms, and 600 ms, each repeated three times) to get familiar with the task and the questionnaire before starting the main block. At the end of the experiment, participants were asked to comment freely on their experience and the experiment.

4.3.4 Data analysis

SoA rates for each delay were computed as the ratio of yes responses. One of the participants that responded yes to three of the catch trials was excluded. Two other participants were also excluded, as they gave "yes" responses for more than 90% of highly out-of-phase trials (e.g., 1/2 Cycle delay); they were considered nonresponsive to this experimental variable. Therefore, in this article, we present the results for 26 participants (17 female, aged between 22 and 36, M = 27, SD = 4.5).

To calculate the temporal threshold, we considered agency response for trials with 0-ms to 600-ms delays. Two participants that had an SoA of 50% for ND trials were excluded. Four other participants were also excluded as they never reached the 50% threshold for delays [0-ms 600-ms]. Hence, we report the temporal threshold for 20 participants.

Commencement of the gait cycle was considered at the heel strike as detected by the two force-sensitive resistors located at the heel (Figure 4:1, specified with dashed circles), using a personalized threshold. Stride time was calculated as the time interval between two successive heel strikes of the same foot. Stride time was separately calculated for each leg, while only complete cycles (for each leg) were included in the average for each trial, and cycles shorter than 900 ms or longer than 1500 ms were rejected. The stride time calculation was processed online via the GUI and recorded for statistical analysis. For the final analysis, the average stride time for the left and right leg was employed as the stride time of each trial. We further excluded trials with the stride time that deviated >3 SD from the median (Median Absolute Deviation criteria with the factor of 3). On average, 0.73 of 110 trials (per participant) were rejected.

Moreover, to compare stride time alterations in baselines and intervention conditions, mean stride time (M_{ST}) and the stride time coefficient of variation (CV_{ST}; i.e., the ratio of the standard deviation over the absolute mean) were calculated for each individual participants across conditions. In order to diminish between-participants variability, stride time deviations (DEV_{ST}; i.e., the difference between trials' stride time and average stride time in the main experimental part for each participant) were used to assess stride time modulation in the main experimental part condition.

4.3.5 Statistical analysis

All analyses were performed in R (R Core Team 2020) running in the RStudio environment (RStudio Team 2020). The normality of the residuals together with linearity and homogeneity of variance was checked, and none of such assumptions were violated. For SoA and DEV_{ST} data, the significant effect of the delay was assessed by performing separate two-way repeated-measures ANOVA by considering delay (11 levels) as independent variables. All post-hoc comparisons were conducted using Tukey's honest significant difference test (Tukey HSD). In all analyses, significance was reported for p-values smaller than 0.05.

To assess whether there were any statistically significant differences in M_{ST} and CV_{ST} between conditions, two-way repeated-measures ANOVA was performed by considering Condition (B_{Pre}, B_{Post}, familiarization, main) as a factor. We further examined the effect of presenting tactile feedback on the participants walking by collapsing data into feedback (including familiarization, and main experimental blocks) versus no-feedback (including B_{Pre}, and B_{Post} blocks) groups. A simple paired t-test was used to assess the significant effect of presenting tactile feedback.

Since a non-significant p-value provides insufficient evidence neither in favor of the null hypothesis (H_0) nor toward insensitive data (Dienes 2014; Quintana and Williams 2018), separate Bayesian analyses were conducted to facilitate the interpretation of the data. For each analysis, different models were calculated by considering independent variables (similar to the frequentist statistic designs explained above). Different models were compared to an H_0 (model only including the intercept). For each model comparison, a Bayes factor (BF_{10} or showed as BF in the present study) was reported, which shows evidence for the H_1 (alternative hypothesis) relative to the H_0 (Wagenmakers et al. 2018), e.g., BF = 5 means that the data are 5 times more likely under H_1 than under H_0. As the Bayes factor deviates from 1, which indicates equal support for H_0 and H_1 hypothesis, more support is gained for either H_0 or H_1. A BF below 1/3 provide compelling evidence toward the null hypothesis (with 1/10 < BF <1/3 = moderate evidence; BF < 1/10 = strong evidence). A BF between 1 and 3 is considered as inconclusive as it shows inadequate evidence in either direction, and a BF greater than 3 is considered compelling evidence towards an alternative hypothesis (with 3 < BF <10 = moderate evidence; BF > 10 = strong evidence). All Bayesian analyses were performed in JASP 0.13.1 (Wagenmakers et al. 2018).

To fit harmonic function to both SoA and stride time deviation data, nonlinear regressions function in R (nls(); nonlinear least squares) was used to determines the coefficients of the parameters in the model (SoA rating: cosine function; stride time deviation: sine function). The linear and nonlinear models for SoA and DEV_{ST} data were compared in R with ANOVA. the Aikake and Bayes Information Criteria (AIC and BIC, respectively) (Burnham and Anderson 2004; Rodriguez 2005).

Temporal thresholds were determined by fitting a cumulative Gaussian to the agency responses for trials with 0-ms to 600-ms delays with the published psignifit toolbox (Wichmann and Hill 2001a, 2001b) for MATLAB (MathWorks, Natick, MA). This toolbox enforces bootstrapping algorithms and weighs the individual data points based on the number of valid trials per stimulus intensity. All thresholds reported here reflect the 50% point of subjective equality.

4.4 Results

4.4.1 Sense of agency

Statistical analysis showed that SoA significantly differed as a function of delay (repeated-measures ANOVA; $F(10, 250) = 16.07$, $p < 0.001$, BF> 100). A cosine model showed that the SoA modulation was regular as a function of the delay (see Figure 4:3). The cosine model has a significantly lower residual sum of squares (i.e., the variability not explained by the model; $F(2, 282) = 51$, $p<0.001$) compared to the linear model (38% reduction). Using BIC and AIC, we compared the goodness of fit for the linear and nonlinear models and found smaller AIC and BIC for the cosine model (AIC = 152, BIC= 170.9) compared to the linear model (AIC = 236, BIC= 247), showing that the cosine model is better at capturing the SoA rating data.

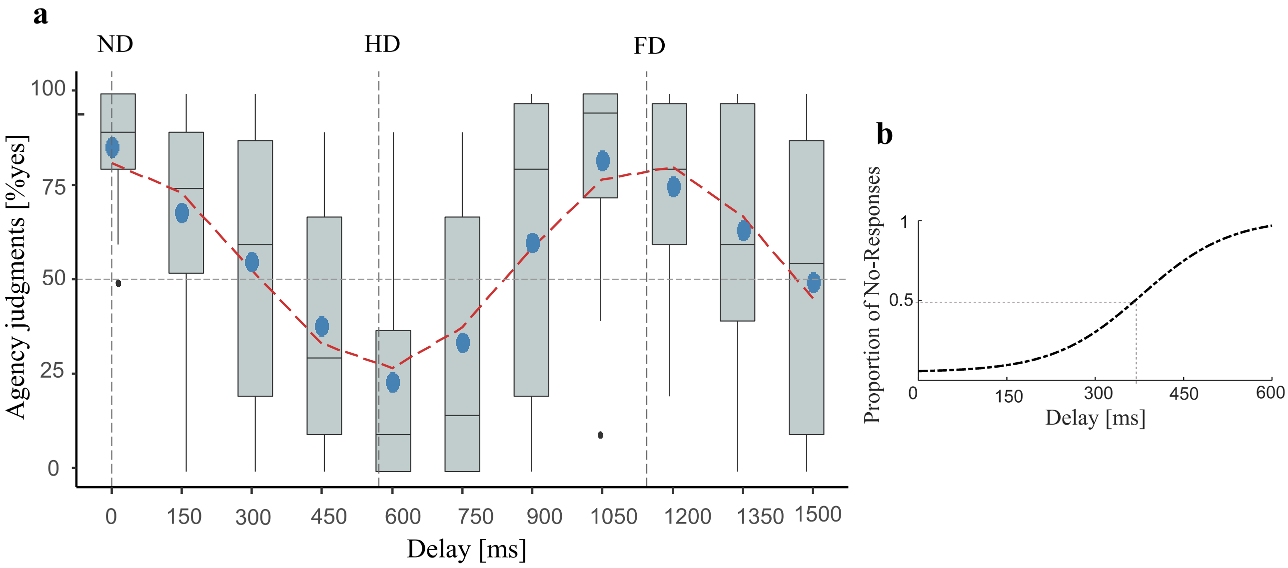


Figure 4:3 Sense of agency results.

(a) SoA as a function of delay. ND corresponds to non-delayed trials, HD to a mismatch of a half-cycle step, and FD to a full step cycle. The cosine function (dashed line) confirms the regularity of SoA modulation (y-axis) as a function of the delay (x-axis). Blue circles show the population's mean SoA ratings. Participants judged the majority of trials as self-attributed for temporally synchronous feedback (ND, FD). SoA judgment decreased by increasing delays until 600 ms, which correspond to a half-step cycle delay. At HD trials, participants receive tactile feedback left-right reversed, so they had the lowest self-attribution ratings. The figure also represents the Box plot of SoA judgment across delays. Each box plot shows the median (50th percentile; dark bar), values to the 1.5 interquartile range (whiskers), 25th to 75th percentile range (box), and outliers. Boxplots clearly show higher intersubjective variabilities for trials that are neither temporally nor spatially congruent. (b) Temporal thresholds were determined by fitting a cumulative Gaussian (cf. Data Analysis). The temporal threshold for the remapped tactile walking agency was estimated as 378 ms.

As illustrated in Figure 4:3a, for non-delayed trials (ND: i.e., step-related tactile sensations were received in synchrony with their actual stepping), participants self-attributed 85±3% of trials. As predicted, self-attribution rapidly decreased with increasing delay. We calculated a temporal threshold of 378 ms (50% point of subjective ambiguity; 378± 239 ms; including the 60 ms intrinsic delay of the system; see Figure 4:3c) so that for delays above 378 ms, the majority of movements were judged as misattributed. The lowest self-attribution in SoA judgments was observed between 300-900 ms with the minimum at 600 ms (22 ± 6%), which is close to the half-cycle delay (the population's half-step cycle is 571.4 ms). In trials with half-cycle delay, the actual movement and the remapped-tactile sensation were, on average, separated by half a step-cycle delay (HD) and were therefore maximally out of phase so that the moving tactile feedback was presented left-right reversed concerning the ongoing walking of the participant (i.e. left foot on ground and right foot providing feedback on the back). SoA judgments increased again for larger delays peaking in trials with 1200 ms delay that matched the participants' step-cycles (1144 ± 9.1 ms). SoA for trials with a full step-cycle delay (FD) was high (78 ± 4%) and approximated the SoA for ND trials.

Post-hoc analysis showed that the SoA for FD trials was not significantly different from the SoA for ND trials ($t = 1.4$; $p = 1.0$). Estimated BF (0.18) suggested moderate evidence toward the null hypothesis (SoA are similar between ND and FD) than the alternative one-sided hypothesis. Furthermore, boxplots in Figure 4:3a indicate that between-subject variability in SoA was lower for trials with rhythmically synchronous feedback (ND, HD, FD) compared to those neither temporally nor spatially congruent (e.g., ¼ cycle, ¾ cycle, 5/4 cycle).

4.4.2 Gait analysis

In the main experimental blocks, participants' gait period was, on average, 1145.7± 98.7 ms (range: 986-1379 ms), compatible with physiological data in healthy participants (Blanc et al. 1999). We looked at the stride time data to see whether stride time deviation changed systematically as a function of the delay. Statistical analysis showed a significant effect of delay on the stride time deviation (repeated-measures ANOVA; $F(10,170) = 2.75$, $p < 0.01$). However, the estimated BF was 1.08 showing an absence of evidence in either direction (null model or delay effect model). We fitted a sinusoidal model to stride time deviation data and found that a sinusoidal model has a significantly lower residual sum of square ($F(2, 282) = 4.53$, $p = 0.01$) compared to the linear model. This reduction is about 3% compared to the linear model. We further used the BIC and AIC to compare the goodness of fit for the linear and nonlinear models. We found slightly smaller AIC and BIC for the sinusoidal model (AIC = 2105.46, BIC= 2123.74) compared to the linear model (AIC = 2110.52, BIC= 2121.49); showing that the sinusoidal model was only slightly better at capturing the stride time deviation data (the difference in the goodness of fit between the two models is small). Overall, our results showed that stride time deviation only weakly depends on delay. As illustrated in Figure 4:1, participants walked faster than the average walking speed for trials with rhythmically synchronous feedback (i.e., ND, HD, and FD trials) and walked slower for those neither temporally nor spatially congruent (e.g., ¼ cycle, ¾ cycle, 5/4 cycle). Post-hoc analysis showed that there was no significant differences between participants' stride time deviation in ND, HD and FD trials (ND-HD: t=0.59, p= 1; ND-FD: t=0.34, p= 1; HD-FD: t=0.24, p =1). However, estimated BF values (ND-HD: BF = 4.1; ND-FD: BF = 4.45; HD-FD: BF= 4.56) suggested moderate evidence toward the alternative one-sided hypothesis (SoA are different between ND and FD; ND and HD; HD and FD) than the null hypothesis.

We further analyzed stride time data in the familiarization and two baselines to investigate whether participants' walking characteristics (M_{ST}, CV_{ST}) are influenced by presenting tactile feedback or change in different conditions. Statistical analysis showed that M_{ST} and CV_{ST} did not significantly differ between feedback and no-feedback conditions (M_{ST}: $F(1, 51) = 0.38$, p=0.54; CV_{ST}: $F(1,51) = 0.30$, p=0.58). Estimated BFs (M_{ST}: BF= 0.18; CV_{ST}: BF = 0.17) suggested moderate evidence toward preferring the null hypothesis (similar mean population M_{ST} or CV_{ST} between feedback and no-feedback) compared to the one-sided alternative hypothesis. In addition, we found that particpants' M_{ST} and CV_{ST} (M_{ST}: $F(3,75)$= 0.29, p=0.83; CV_{ST}: $F(3,75)$= 1.63, p=0.18) did not significantly change across blocks (baselines, familiarization and the main experimental part). Estimated BF for the effect of the block on the CV_{ST} was inconclusive (2.1) and suggested the absence of evidence in either direction (null hypothesis or alternative hypothesis). However, for the mean stride time data, we estimated BF as 3.25, suggesting moderate evidence toward preferring the block model compared to the null model.

We further performed a post-hoc Bayesian analysis on the block effect. We found strong evidence that the M_{ST} was similar in the main experiment and B_{Post} blocks (t= 1.58, p = 0.7, BF = 0.08). We also found moderate evidence showing that M_{ST} and CV_{ST} were different in B_{Pre} and B_{Post} (M_{ST}: t= 0.28, p = 1, BF = 4.54; CV_{ST}: t= 0.14, p = 1, BF = 4.7); in familiarization and main experiment (M_{ST}: t = 0.7, p = 1, BF = 4.3; CV_{ST}: t= 0.63, p = 1, BF = 4.12); in familiarization and B_{Post} (M_{ST}: t= 0.89, p = 1, BF = 3.73; CV_{ST}: t= 1.2, p = 1, BF = 3.3). We showed that estimated BF for other comparisons were inclusive and suggested the absence of evidence in either direction (null hypothesis or alternative hypothesis; M_{ST}: B_{Pre}-main experiment: t= 1.16, p = 1.0, BF = 2.27; B_{Pre}- main experiment: t = 1.86, p = 0.4, BF = 1.06; CV_{ST}: B_{Pre}-familiarization: t= 1.34, p = 1.0, BF = 0.2.16; B_{Pre}- main experiment t= 1.97, p = 0.3, BF = 0.89).

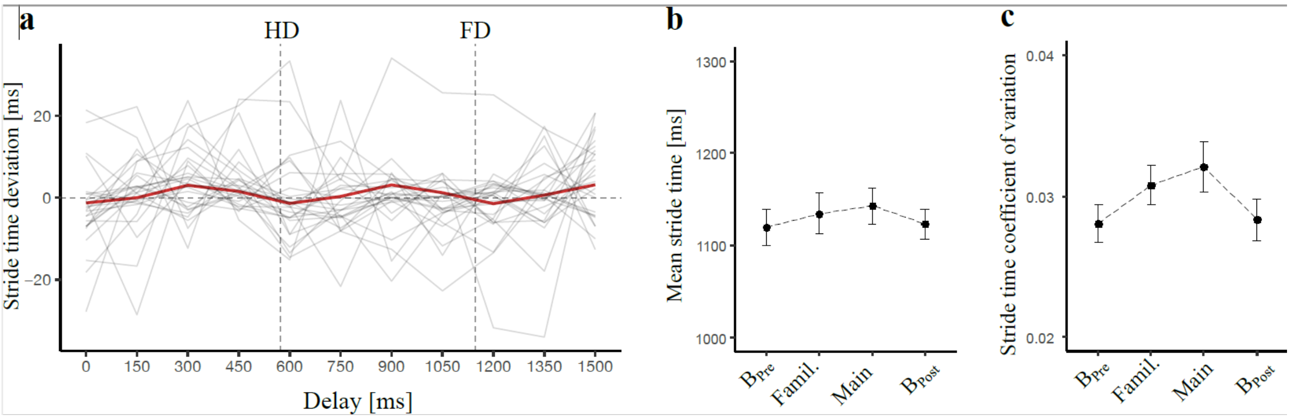


Figure 4:4 Gait movements.

(a) Gait adaptation. Variation of stride time deviation (DEV_{ST}) is weakly systematic. (b) Mean stride time (M_{ST}) across different conditions. Famil. And Main are abbreviations for familiarization and main experiment blocks. (c) Stride time coefficient of variation (CV_{ST}) across different conditions.

4.5 Discussion

In the present study, we employed a fully wearable sensory feedback system to investigate walking agency via temporal manipulation of step-related, remapped tactile feedback presented on the participants' back during free walking. We demonstrated that participants had robust SoA for remapped tactile feedback during walking. Participants rated trials with small delays as well as trials with delays matching their stride-time (that is, trials with much longer delays approaching an FD) as self-generated, corroborating previous findings in gait studies using visual and auditory feedback (Menzer et al. 2010; Kannape and Blanke 2013). Feedback lateralization mattered as temporally synchronous trials, but left-right reversed were not perceived to correspond to the ongoing movement. As compared to previous work with auditory and visual feedback, we only observed very moderate sinusoidal modulations in the present participants' stride time. We discuss these findings with respect to the possible effect of cognitive workload induced by the tactile remapping technique. We conclude by indicating potential clinical applications of our FeetBack system in gait rehabilitation and neuroprosthetics.

4.5.1 Remapped feedback systematically modulates SoA

We show that tactile motor feedback, in the form of remapped tactile sensation, modulates the SoA for free walking. Our findings illustrate that SoA depends on two main variables as tested here. (1) The temporal delay of the remapped tactile feedback as well as (2) the periodicity of each participant's walking cycle. Our results demonstrate that SoA modulation follows a cosine pattern. Participants rated undelayed trials as self-generated, but this score decreased with increasing delay, reaching its lowest value for delays of half a step-cycle (HD; feet left-right reversed). Larger delays, on the other hand, led to an increase of self-attribution, peaking for trials with a full-cycle delay (FD). For these latter trials, participants reported high SoA ratings (approximately 85%), which were comparable to ND trials (i.e., heel-strike feedback that coincided with their ongoing gait but was actually delayed by a full cycle). Similar observations have also been made in previous auditory and visual gait agency studies (Menzer et al. 2010; Kannape and Blanke 2013).

We also note that analogous with prior studies (Menzer et al. 2010; Kannape and Blanke 2013), SoA did not reach 100% in either ND and FD trials. This is most likely due to a combination of the intrinsic delay of our system that was 60 ms introduced by wireless communication and vibration system, lapses, or another perceived mismatch. Self-attribution of gait feedback became weaker as the temporal conflict between the remapped tactile sensation and the participants walking phase became more distinguishable (e.g., temporally out-of-phase trials), closely following the results for visual gait agency (Kannape and Blanke 2013) where SoA was lowest for trials with left-right reversed feedback (HD). This deferred from the data of Menzer et al. (2010), who measured SoA for auditory consequence of walking and did not report the feedback lateralization effect. Simply because the auditory consequence of left or right foot-steps are not distinguishable.

In the present study, we observed significant intersubjective variability in SoA ratings, which has not been reported for auditory and visual gait agency. We also found higher (378 ms) and noisier (i.e., higher intersubjective variability; SD = 239 ms) temporal threshold for remapped tactile gait awareness compared to those reported in the auditory (~200 ms) and visual (~210 ms) gait paradigms (and auditory or visual agency studies in general; for review, see (Kannape and Blanke 2012)). It has previously been suggested that the SoA is supramodal and effector-independent and should accordingly demonstrate comparable thresholds across a range of action-consequence mappings, which also corresponds to more recent work on proposing an abstracted action system (Liu et al. 2020). While the general cosine pattern qualitatively supports the supramodal and effector-independent hypothesis, the current data suggest that larger conflicts may be necessary in case of remapped tactile feedback.

Do the natural heel-strike and the remapped feedback complement each other, or do they create an additional multisensory conflict? Previous gait awareness studies (Menzer et al. 2010; Kannape and Blanke 2013) cancelled out naturally occurring visual and acoustic feedback using white-noise and by obstructing the view of their leg movements with blinkers respectively. In other words, gait feedback was substituted with experimentally controlled feedback in the same modality and relative location. In the current study, participants still perceived the actual ground reaction forces at each heel-strike, as it was not possible to remove the physical somatosensory action consequence. This leads to conflicting intra-modal, but spatially remapped information in the present experiment. Although participants were instructed to base their decision on the remapped tactile sensations on their back, the actual heel-strike and related tactile feedback on the foot may have still interfered with the present SoA judgments. In terms of the central monitoring framework (Frith and Done 1989) SoA has been argued to depend on a comparison of internal representations and predictions about our movements with the feedback we continuously receive about those movements (reafferent signal, but also with our intended or desired state; see (Blakemore et al. 2002)). Receiving both feedback cues concurrently, but either synchronously or with an experimental temporal conflict, may hence introduce noisier feedback, which may impair the central monitoring mechanism. Such uncertainty may explain the higher temporal thresholds for remapped feedback. Another explanation or contributor could be that the processing of the remapped feedback was perceived as a secondary or dual task and this may have also affected SoA. Participants were exposed to two tactile inputs while walking, likely requiring more perceptual and cognitive resources. The effect of cognitive workload on the SoA was previously investigated by (Kannape and Blanke 2013; Kannape et al. 2014). These authors found that a secondary cognitive task performed while walking suppressed gait synchronization across all tested delays and affected gait agency for selective temporal delays. Much earlier studies have also shown that a secondary perceptual, motor and cognitive task (dual tasking) influences the control of posture and gait (for review see (Woollacott and Shumway-Cook 2002) and (Yogev-Seligmann et al. 2008)), such as an increase in stride time and increased gait variability (Hoang et al. 2020). Similarly, in the current study, participants showed higher stride time variability and increased stride time when received remapped feedback (see Figure 4:4b and Figure 4:4c), although these differences did not reach to the significant level. Yet, here, we did not use any subjective or objective (physiological) measure to assess the cognitive workload imposed by the remapped technique. Previous studies have shown that, in the context of dual task walking, gait variability in young adults seems to be task-dependent; for instance, texting on a mobile phone is most challenging vs. visual task or performing arithmetic operations (Mirelman et al. 2014; Schabrun et al. 2014; Plummer et al. 2015). Future experimental investigations are needed to estimate the cognitive load imposed by the processing of remapped tactile feedback.

4.5.2 Effect of the remapped feedback on the gait

Although we observed a small overall effect of delayed remapped tactile feedback on participants' stride time deviations, this was not found to be specific to the tested delays and was not systematic as reported in prior visual and auditory gait awareness studies (Menzer et al. 2010; Kannape and Blanke 2013). Our results are instead in line with those studies on rhythmic stimulation, which found no change in walking speed or cadence of healthy adults when they were asked to walk at their preferred speed (Baram and Miller 2007; Hausdorff et al. 2007; Baram and Lenger 2012; Wittwer et al. 2013; Zhang et al. 2020). While in the visual gait study, participants had a stable baseline for walking velocity due to using the treadmill, in the present study, it is harder to detect adaptation as the baseline for walking speed is variable (with-in and between participants). It is also plausible that the adaptation in the auditory gait paradigm was simpler as participants received spontaneous auditory feedback as opposed to the concurrent tactile feedback employed in the present study; our participants might have perceived higher mental effort to detect the mismatch between the continuous, remapped feedback and gait cycle (Kannape and Blanke 2013; Kannape et al. 2014). The cognitive load induced by remapped feedback will be discussed below.

4.6 Conclusion

To conclude, the present study is the first study investigating the contribution of haptic feedback on the SoA in healthy walkers. Extending previous studies on auditory and visual gait awareness, we demonstrated that delayed haptic feedback modulates SoA in a predictable way even when it is presented in the form of remapped tactile feedback. Participants had the highest self-attribution for (re)synchronized trials (ND and FD) and gave the lowest SoA rating for trials with left-right reversed feedback. Although our findings are in-line with an effector-independent and supramodal mechanism for SoA, we observed a higher intersubjective variability in SoA ratings and limited gait adaptation to the delayed remapped feedback, compared to previous studies. This may be due to the combination of the natural heel-strike and the remapped tactile feedback leading to a noisier sensory input. Furthermore, processing the combined feedback may also create a cognitive load resulting in higher intersubjective variabilities and the suppression of gait synchronization. Finally, our results demonstrated the potential of using FeetBack system to enhance the gait awareness system for patients with peripheral or central sensory loss in feet or cognitive disorders.

Chapter 5 Tactile spatial discrimination on the torso using vibrotactile and force stimulation

Tactile spatial discrimination on the torso using vibrotactile and force stimulation

Atena Fadaei J.[1, 2], Matteo Franza[1, 2], Olivier A. Kannape[1, 2], Masayuki Hara[3], and Olaf Blanke[1, 2].

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[1] Laboratory of Cognitive Neuroscience, Center for Neuroprosthetics, Faculty of Life Sciences, Swiss Federal Institute of Technology (EPFL), Geneva, Switzerland

[2] Laboratory of Cognitive Neuroscience, Brain Mind Institute, Faculty of Life Sciences, Swiss Federal Institute of Technology (EPFL), Lausanne, Switzerland

[3] Graduate School of Science and Engineering, Saitama University, Saitama, Japan

Abstract

There is a steadily growing number of mobile communication systems that provide spatially encoded tactile information to the humans' torso. However, the increased use of such hands-off displays is currently not matched with or supported by systematic perceptual characterization of tactile spatial discrimination on the torso. Furthermore, there are currently no data testing spatial discrimination for dynamic force stimuli applied to the torso. In the present study, we measured tactile point localization (PL) and tactile direction discrimination (DD) on the thoracic spine using two unisex torso-worn tactile vests realized with arrays of 3x3 vibrotactile or force feedback actuators. We aimed to, firstly, evaluate and compare the spatial discrimination of vibrotactile and force stimulations on the thoracic spine and, secondly, to investigate the relationship between the PL and DD results across stimulations. Thirty-four healthy participants performed both tasks with both vests. Tactile accuracies for vibrotactile and force stimulations were 60.7% and 54.6% for the PL task; 71.0% and 67.7% for the DD task, respectively. Performance correlated positively with both stimulations, although accuracies were higher for the vibrotactile than for the force stimulation across tasks, arguably due to specific properties of vibrotactile stimulations. We observed comparable directional anisotropies in the PL results for both stimulations; however, anisotropies in the DD task were only observed with vibrotactile stimulations. We discuss our findings with respect to tactile perception research as well as their implications for the design of high-resolution torso-mounted tactile displays for spatial cueing.

5.1 Introduction

As the human torso provides an extensive skin area to convey tactile information, torso-worn haptic displays deploying tactile spatial cues have gained increasing attention in recent years (Rupert 2000; Lemmens et al. 2009; Arafsha et al. 2015; Lentini et al. 2016; Wacker et al. 2016; Buimer et al. 2018; Garcia-Valle et al. 2018). Moreover, while providing tactile information on the torso, a person's active body parts, such as hands and fingers, remain fully available for daily living activities. Accordingly, the torso has been considered as one of the most available and practical candidate sites for wearable and mobile tactile communication systems (Cholewiak et al. 2004; Kristjánsson et al. 2016) and may also be particularly suited for applications in cognitive and clinical neurosciences (Rognini and Blanke 2016). However, to effectively convey spatially encoded tactile information and make use of this information, more data about the tactile spatial resolution of the torso are required. Surprisingly, we lack such information: even though psychophysical research on tactile spatial acuity was launched in the nineteenth century by Ernst Heinrich Weber (1834), since then, only a handful of studies has studied tactile perception on the torso. In the present study, we described new systems and focused on assessing tactile spatial discrimination of the human torso.

Tactile point localization (PL) evaluates a person's ability to localize the point of tactile stimulation in an array of stimulators mounted on the torso. Previous studies that used a linear one-dimensional array of vibrators around the waist reported PL accuracies within the range of 74% (12-tactor with 72 mm spacing) to 98% (8-tactor with 107 mm spacing). It was noted that accuracy tended to increase by increasing inter-stimulator spacing and at locations closer to the body midline (i.e., navel, spine) (Cholewiak et al. 2004). The higher localization ability in proximity to specific anatomical reference points, such as the body midline (e.g., navel and spine) and joints (e.g., wrist), was first described by Weber (1834) and was recently confirmed for the localization of both vibrotactile and static pressure stimuli presented on the upper limbs (e.g., wrist) (Cholewiak and Collins 2003; Oakley et al. 2005). However, studies employing two-dimensional arrays of vibrators (e.g., 4x4 array) have not found higher PL accuracy for midline regions and rather observed that PL accuracy changes depending on the location of the target within the array (Lindeman and Yanagida 2003; Cholewiak and McGrath 2005; Jones and Ray 2008). For instance, accuracy was found to vary strongly (from 40 to 82%) depending on the position of the vibrator in the 4 x 4 array (Lindeman and Yanagida 2003; Cholewiak and McGrath 2005; Jones and Ray 2008).

Several other studies have investigated the spatial acuity for tactile cues applied to the torso and measured the capability of discriminating two nearby tactile stimuli presented on the skin surface. Although classical studies used the two-point discrimination test (Weber 1834), more recent studies have questioned the validity of this measure as it is vulnerable to several possible confounds (e.g., two-point discrimination may be based on intensity rather than spatial cues). Alternatively, they suggested a task in which two successive stimuli are applied at nearby locations, and participants' have to judge whether the two stimuli were delivered in the same location or not (Johnson and Phillips 1981; Johnson 1994; Stevens and Patterson 1995; Tong et al. 2013). For instance, Eskildsen et al. (1969) presented successive vibrotactile stimuli via a horizontal array of five vibrators on the back and reported a discrimination threshold at 10 mm on the back (at the level of the scapula). Van Erp (2005a) measured tactile direction discrimination (DD) using two successive tactile stimuli on the torso, defined as the ability to discriminate whether a second tactile stimulus was to the left or to the right of a first tactile stimulus. They used a linear array of vibrators (11 in horizontal and 14 in the vertical direction). Using this method, they determined the tactile spatial acuity threshold at 20-30 mm on the torso, with better DD accuracy (approximately 10 mm) only for horizontal array locations near to the body midline (i.e., navel and spine). They also highlighted the role of spatiotemporal factors by observing that the accuracy increased as the burst duration and/or inter-stimulus interval increased. Finally, Jóhannesson et al. (2017) explored the impact of inter-stimulator distancing on tactile DD accuracy (so-called relative spatial acuity; three-alternative force choice task [AFC]), using arrays of 3x3 vibrators on the lower thoracic region of the back. They reported that accuracy increased from 64% to 91% as an inter-stimulator spacing increase from 13 to 30 mm. Taken together, while PL and DD measure two different aspects of tactile spatial discrimination, previous studies often directly compared the results of these two tasks. To the best of our knowledge, there is no study investigating the degree of agreement or disagreement between the results of tactile localization and direction discrimination (as an indicator of tactile spatial acuity). Here, we investigate PL and DD on the torso in the same subjects, using 3x3 arrays of tactile stimulators.

The majority of torso-worn tactile displays developed in the last two decades have commonly adopted miniature affordable vibrotactile stimulators in commercial and experimental frameworks (Arafsha et al. 2015; Karafotias et al. 2017; Garcia-Valle et al. 2018). For instance, Van Erp and colleagues have employed torso-worn vibrotactile displays for use as a pedestrian navigation system (van Erp et al. 2003; Van Erp et al. 2005; Van Erp 2005b; van Erp 2007). Lemmens et al. (2009) developed a wearable vibrotactile jacket to investigate the potential intensification of emotional immersion while participants watched a movie. Garcia-Valle et al. (2018) showed that using a haptic vest, which presented vibration patterns, improves immersion in multimodal virtual reality environments. Other studies have recently employed force stimulators to present collision-type touch stimuli (e.g., force, pressure, compression, etc.) on the participants' torso (Delazio et al. 2018; Al-Sada et al. 2019; Fadaei et al. 2021). For instance, a force jacket was made of pneumatically actuated airbags to provide strong and variable forces to the torso along with vibrotactile sensations (Delazio et al. 2018). In this line of research, it has been shown that the level of immersion in a virtual environment could be considerably enhanced by presenting ecologically valid touch feedback (Yoshikawa and Nagura 1997; Lopes et al. 2015; Cao et al. 2018). In addition, the processing of tactile spatial directional cues and notification has been described as more intuitive to participants when using force stimulation rather than vibrotactile as collision touch sensations are a more common haptic experience in daily life. Until now, however, research about tactile spatial discrimination on the torso has focused on performance for manually applied stimuli (Weber 1834; Weinstein 1968; Green 1982; Gibson and Craig 2005) and vibrotactile stimuli (Eskildsen et al. 1969; Jones et al. 2009; Hoffmann et al. 2018b). To the best of our knowledge, there is no study investigating tactile spatial perception on the torso for directed force stimuli. Thus, it is not known whether force stimuli are characterized by improved tactile performance (compared to vibrotactile stimuli) in spatial discrimination tasks on the torso. Indeed, force and vibrotactile stimuli present some distinct features; for instance, vibrotactile stimuli are known to spread beyond the limits of the contact area (Cholewiak and Collins 2003), while force stimuli are more focal and this might lead to better accuracy in spatial discrimination. Here, we measured performance in PL and DD tasks and investigated the spatial accuracy of focal force and vibrotactile stimuli on the torso.

Moreover, previous studies have demonstrated directional anisotropies in tactile localization and tactile spatial acuity for both static pressure and vibrotactile stimuli. These studies reported higher tactile spatial performance along the transverse (limb) axis compared to the vertical axis. In particular, for the PL task on the back, Jones and Ray (2008), using a 4 x 4 array of vibrators, observed that participants were better in the horizontal (87% correct) than vertical direction (68% correct) when using vibratory stimuli. Also, for the DD task, recently, Hoffmann et al. (2018b) found that vibrotactile DD accuracy is substantially higher in the horizontal axis compared to the vertical on the lower thoracic region, consistently across three different types of vibrators. Therefore, we also tested for any direction anisotropies in the PL and DD, using force and vibrational stimuli.

In summary, in the present study, we employed two body-conforming torso-based tactile displays (arrays of 3x3 vibrotactile stimulators: Vibrotactile vest; force stimulators: Force vest) and assessed tactile PL and DD on the skin surface of the human upper thoracic area. Using a within-participant design, we 1) evaluated tactile spatial discrimination (PL and DD) of the upper torso region, 2) examined the association between the results of PL and DD tasks, and 3) compared performance when using vibrotactile and force stimulations. Finally, 4) we searched for directional anisotropy in both tasks and both types of stimulation.

5.2 Materials and Methods

5.2.1 Participants

A total of 34 healthy participants (17 females, aged between 20 and 36 years, M = 26, SD = 4.2) were recruited for the experiment. All participants were right-handed (assessed via a 12-item Edinburgh Handedness Inventory (Oldfield and others 1971)). Pathological conditions affecting tactile sensitivity (e.g., skin alteration, chronic pain, fractures) were excluded. They provided informed consent and ethical approval that was granted by the cantonal ethics committee in Geneva. All participants received a compensation of 20 CHF/hour for their commitment to the experiment.

5.2.2 Apparatus

5.2.2.1 Vibrotactile vest

The Vibrotactile vest consists of 9 (3 x 3) coin-shaped, Eccentric Rotating Mass (ERM) vibrators (310-003, Precision MicroDrive; body diameter: 10mm; body length: 3.4 mm; weight: 1.1 gr) with an inter-tactor distance of 60 mm (Figure 5:1a and Figure 5:1c). The ERMs are controlled by haptic motor drivers (DRV2605, Texas Instruments) on 5 V (DC), resulting in a vibration frequency of 175 Hz and acceleration of 1.3 G. The haptic motor drivers were controlled with a microcontroller (STM32F407, STMicroelectronics; sampling time of 1 ms) which connects via Bluetooth to a host PC. A custom-made GUI was developed using the Qt platform (free and open-source platform to create GUI) to control vibrators and the experiment flows as well as record participants' responses (i.e., entered via numeric keypad) along with the experiment. The ERM vibrators were attached to a 20mm-thick foam (Softpur polyurethane foam) using glued-on snap fasteners. Vibrator foam was fixed to a fully elastic, posture-corrector brace using Velcro straps, allowing the experimenter to change or replace the vibrator foam easily. The Vibrotactile vest covers the whole back, and it is unisex. The front part of the brace includes elastic straps that wrap around the shoulder, chest, and lower back to ensure a snug and secure fit (see Figure 5:1b). Moreover, the specific load frequency for the ERM vibrators was tested by activating each vibrator while the Vibrotactile vest was firmly fitted to a participant's torso. The frequency of each vibrator was analyzed using real-time fast Fourier transform analysis (Audio Spectrum Analyzer dB RTA). Our test results showed that the load frequency ranged between 150 and 220, with an average of 175 Hz.

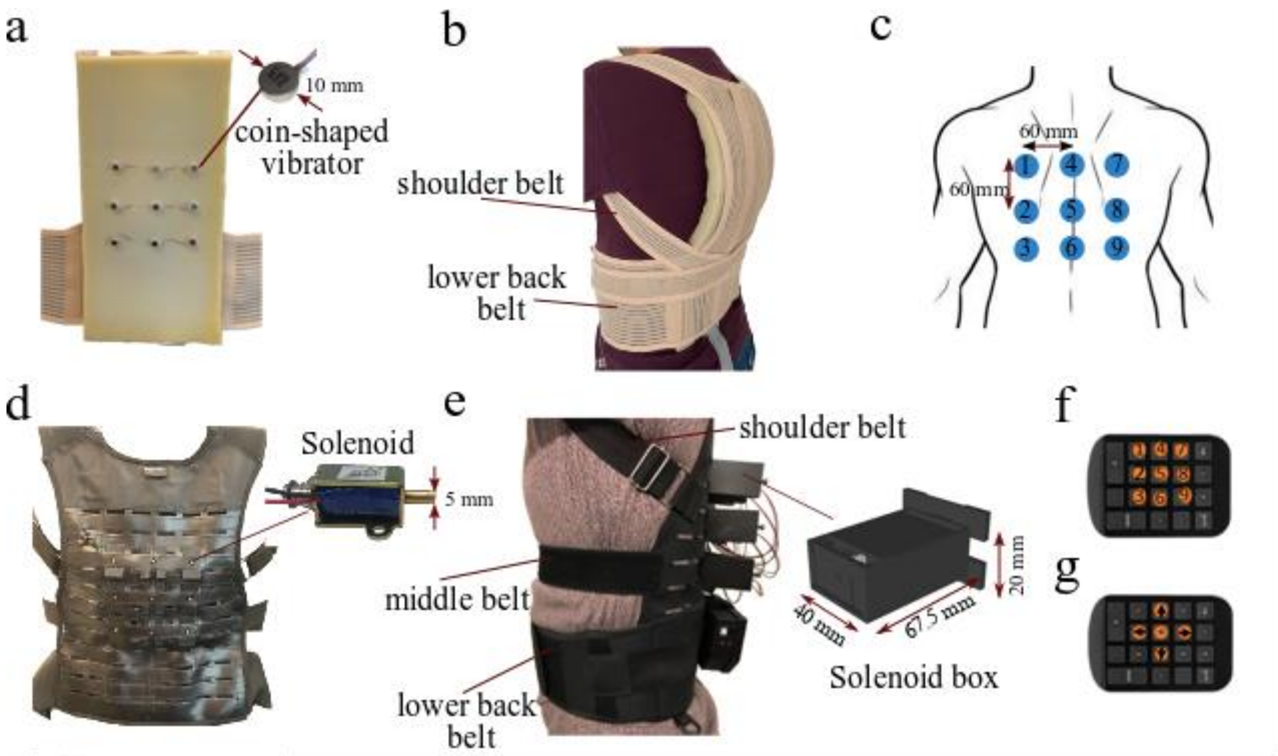

Figure 5:1 Experimental setup.

(a) Interior view of the Vibrotactile vest with 3x3 of coin-shaped ERM vibrators. (b) The Vibrotactile vest on the participant. The vest was firmly fitted on a participants' body with the lower back and shoulder belts. (c) Arrangement and numbering of stimulations for both Vibrotactile vest and Force vest. (d) Interior view of the Force vest with 3x3 push-pull solenoid actuators. (e) The Force vest on a participant. Three stretchable belts, including shoulder, chest, and lower back belts, firmly fixed the vest on the participants' torso. Solenoids were placed in a custom-made 3D-printed box. (f) A numeric keypad with marked buttons was used to respond to the PL task. (g) A numeric keypad with marked buttons was used to respond to the DD task.

5.2.2.2 Force vest

The Force vest is torso-worn and can apply focal force stimuli to the back. It was designed and prototyped in our previous study (previously named CognoVest) (Fadaei et al. 2021). It consists of nine (3 x 3) force stimulators (bi-directional, push-pull solenoid actuators; starting force: 5 N at 12 VDC, shaft length: 5.5 mm; shaft diameter: 5 mm; weight: 39 g), situated with an inter-stimulator distance of 60 mm on the back part of a tailor-made, Y-harness brace (Figure 5:1d). To overcome gender-specific morphology, the front part of the brace consists of stretchable straps that wrap around the shoulder, chest, and lower back. The back part is made of polyester nylon with integrated laser-cut loops to support the hardware (Figure 5:1e). Each force stimulator is embedded in a customized 3D-printed box, mounted on the back of the brace (see solenoid box in Figure 5:1e). The Force vest is thus unisex and can keep stimulators flush against the skin. Arduino Mega 2560 controls the driving of solenoids via Bluetooth to a host PC with a sampling time of 1 ms (similar to the Vibrotactile vest). A custom-made GUI was implemented in the Qt platform to provide a convenient interface to control stimulators with the Force vest and to facilitate the running of the experiment. It also recorded participants' responses (i.e., entered via numeric keypad). In our earlier study (Fadaei et al. 2021), the force stimulator (solenoid) performance was evaluated under various environmental and parametric conditions (e.g., the effects of the 3D printed box, elastic tips, and stroke length). The results revealed that the realistic amount of force (average) provided by the Force vest is between 0.5 and 0.8 N depending on the stroke length (the force going up as the stroke length increases until 4 mm). The load frequency of the force stimulator was assessed and analyzed in the same way as described for the vibrotactile stimulator. The results revealed that the load frequency ranged between 500 and 1000 Hz, with an average of 650 Hz.

5.2.3 Experimental design

Participants were exposed to a repeated measure design; participants wore both haptic vests (i.e., Vibrotactile vest and Force vest) and completed both the PL and DD tasks. In the experimental design for the PL task, two factors were manipulated: stimulation type (vibrotactile vs. force) and stimulator location (9 locations on the upper thoracic region). For the DD task, stimulation type (vibrotactile vs. force) and tactile orientation (three different orientation presentations, including horizontal (H), vertical (V), and double activation (DA)) were manipulated as independent within-participant variables.

5.2.4 Procedure

Participants were randomly assigned in a balanced way to the first experimental session with one of the two vests (Vibrotactile vest or Force vest). Subsequently, they performed both the PL and DD tasks in random order with a break (7mins). After, they changed the vest and were exposed to a second experimental session where they performed the same tasks in a counter-balanced order with respect to the previous session (see Figure 5:2).

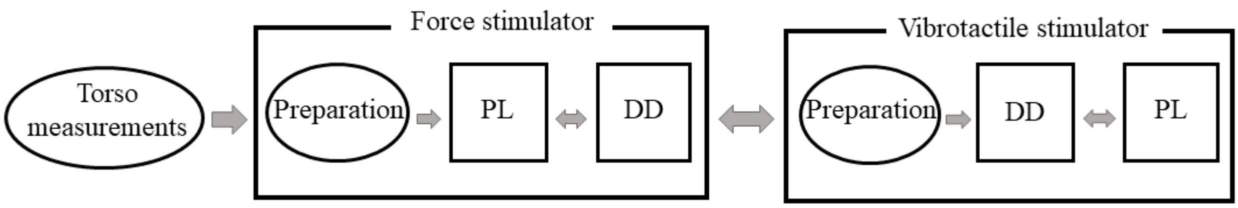

Figure 5:2 Experiment flow (simplified representation).

At the beginning of the study, participants were asked to wear a thin, fitted white T-shirt. This was done to eliminate any cloth-specific effect. Next, the experimenter performed the torso measurements, which included three measurements, namely torso length (vertical distance between the 7th cervical (C7 vertebra) and the top of the hip bone (iliac crest)), waist circumference (between the belly button and rib cage), and chest circumference (at the fullest part of the bust). Throughout the experiment, participants wore headphones playing white noise to conceal the activation noise generated by the haptic stimulators. The white noise intensity was customized for each participant to have full acoustic isolation.

Prior to each session, the experimenter helped participants to wear the haptic vests correctly. Stimulator arrays were placed centrally on the thoracic regions on the back, starting from the shoulder blades (scapula bones). Each session began with a calibration phase, where the experimenter activated each stimulator (i.e., vibrotactile or force) individually (with a duration of 250 ms and in a random sequence) to ensure that the participant could feel all stimuli by obtaining verbal confirmation. Due to the different nature of stimulators used in the Vibrotactile vest and Force vest, the calibration procedure was different for the two vests. For the Vibrotactile vest, in case of failure in perceiving the vibrotactile stimuli, the experimenter improved the perception by better fitting the vest on the participant's torso. On the other hand, for the Force vest, the experimenter manually adjusted the force stimulator (solenoid) position at different stroke lengths until receiving verbal confirmation from the participant that they felt mechanical touch by each stimulator (more details can be found in (Fadaei et al. 2021)). The calibration tasks for the Vibrotactile and Force vest lasted approximately 5 and 10 minutes, respectively. Participants completed a training session, similar to the main task but shorter (around 1 minute).

During the training session, participants learned how to respond to tactile stimulation on their back with the corresponding keypad (see Figure 5:1).

In the PL task, a series of discrete tactile stimuli were applied to the participants' back. They were instructed to indicate the location of the perceived stimulus, i.e., the position out of the total of 9 locations where the tactile cue had been applied (9 alternatives forced choice, 9-AFC). Participants responded by specifying a number that corresponded to the stimulated location by pressing a numeric keypad, as indicated in Figure 5:1f). Participants did not receive performance feedback during the task. To reduce task complexity, they were asked to keep the keypad so they could see the buttons in the same order as the stimulators numbering on the back. In each trial, stimulators were activated for 250 ms with a random inter-trial interval of 2000±250 ms. Tactile point activations (each of 9 different locations) were repeated 20 times, resulting in a total of 180 trials. To reduce potential fatigue, the task was divided into two blocks, each one including 100 trials and lasting 3 minutes. There was also a short break of around 2 minutes between two blocks.

In the DD task, participants received two consecutive stimuli, and they were asked to determine whether the second was to the right, left, above, or below the first one or whether the same location was stimulated twice (5-AFC). Considering the arrangements of stimulators on the vests (3 x 3), shown in Figure 5:1c, there are a possible 12 different horizontals (H; i.e., along with transverse axis) and vertical (V; i.e., along with longitudinal axis) presentations, and nine DA of the same stimulator. Each of the orientational combinations was repeated five times, and the DA condition was repeated six times (to assess the same number of repetitions per condition), resulting in a total of 174 trials. The location of the first stimulus and the relative position of the second were randomly arranged. Participants responded via a standard numeric keypad with five marked buttons (see Figure 5:1g) corresponding to the five possible response options, and the software recorded their responses. Similar to the PL task, stimulators were turned on for 250 ms with an inter-stimulus interval of 50 ms. The inter-trial interval was altered randomly in the range of 2000±250 ms. To avoid fatigue, the task was divided into two blocks of 87 trials, and each block lasted 4 minutes. There was a short break of approximately 2 minutes between two blocks.

5.2.5 Statical Analysis

All analyses were performed in R (R Core Team 2020) running in the RStudio environment (RStudio Team 2020). In the DD task, two participants had very low accuracy across the vests. Those data were excluded from DD analysis as, presumably, the two participants did not understand the DD procedure correctly. Thus, those analyses that involved DD data only included data from 32 participants.

For the between-stimulus comparison, the average accuracy (in percentage) of each task was considered as the response. A two-tailed paired sample t-tests were used to assess whether accuracy differed significantly between two stimulations. The chance level for PL and DD tasks were estimated at 11.11% and 20% since there were 9 and 5 possible response types in each trial, respectively. One-sample t-tests were used to compare the accuracy with the chance level.

To better understand the PL accuracy and its variation on the upper thoracic regions of the back, further analysis was conducted by considering accuracy (in percentage) at each location (location 1 to 9) as the response. To investigate the participants' ability to identify the stimulator's location along with the vertical (column) and horizontal (row) axis on the back, data were collapsed across columns (upper, middle, and lower columns) and rows (right, middle, and left rows) stimulators. Thus, a linear mixed-effect model was performed to assess the effect of vibrotactile vs. force by considering stimulation rows, columns, and interactions between them as fixed effects and the participant as a random effect, accounting for between-subject variability.

To explore orientational biases in the PL task, the number of localization errors was computed at each location for both vests. Mislocalization data were collapsed into adjacent ($N_{Adjacent}$: confusion with stimulators that are situated one gap away from the target) versus nonadjacent biases ($N_{Nonadjacent}$: confusion with stimulators that are situated at more than one gap away from the target), and horizontal (N_H: number of errors made along with horizontal axis) versus vertical (N_V: number of errors made along with longitudinal axis) biases. As inferred with the Shapiro-Wilk test of normality, mislocalization data significantly deviated from the normal distribution. Therefore, the Wilcoxon signed-rank test was employed to investigate the effect of adjacent and orientational biases.

To investigate the orientation-dependent effect in DD results, mean accuracies for horizontal (DD_H) and vertical (DD_V) trials were considered as the response. Then, a linear mixed-effect model was used by considering stimulation (vibrotactile vs. force), tactile orientation (H vs. V), and their interaction as fixed effects and subject as a random effect.

All posthoc comparisons were conducted using the Tukey HSD test. Pearson correlation coefficient was calculated to investigate the relationship between variables, and the p-values were corrected for multiple comparisons (Bonferroni correction). In all analyses, significance was reported for p-values smaller than 0.05.

5.3 Results

5.3.1 Overall accuracy

Overall accuracy results are represented in the Figure 5:3a. In both tasks, participants were significantly better than chance level (PL: vibrotactile: $t(31) = 34.78$, $p < 0.001$; force: $t(31) = 29.9$, $p < 0.001$; DD: vibrotactile: $t(31) = 25.77$, $p < 0.001$; force: $t(31) = 17.77$, $p < 0.001$). Performance in the PL task was significantly higher with the vibrotactile stimulation (M = 60.70%, SEM = 2.32) versus the force stimulation (M = 54.6%, SEM = 1.95; $t(33) = -2.92$, $p = 0.006$). For the DD task, no significant accuracy difference was found in between the two stimulations (vibrotactile: M = 71%, SEM = 1.98%; force: M = 67.7%, SEM= 2.69%; $t(31) = -1.54$, $p = 0.13$).

The tactile performance was found to correlate between tasks (PL, DD) and stimulations (vibration, force). Thus, participants' performance with vibrotactile stimulation significantly correlated with participants' performance using force stimulation in the PL task ($R = 0.50$, $p = 0.002$; brown line in Figure 5:3b) and in the DD task ($R = 0.61$, $p < 0.001$; green line in Figure 5:3b). This was also found when comparing the two tasks, revealing significant correlations between the two tasks for force stimulation ($R = 0.46$, $p = 0.007$; red line in Figure 5:3c), but for the vibrotactile stimulation, there was only a trend towards a significant correlation ($R = 0.33$, $p = 0.060$; blue line in Figure 5:3c).

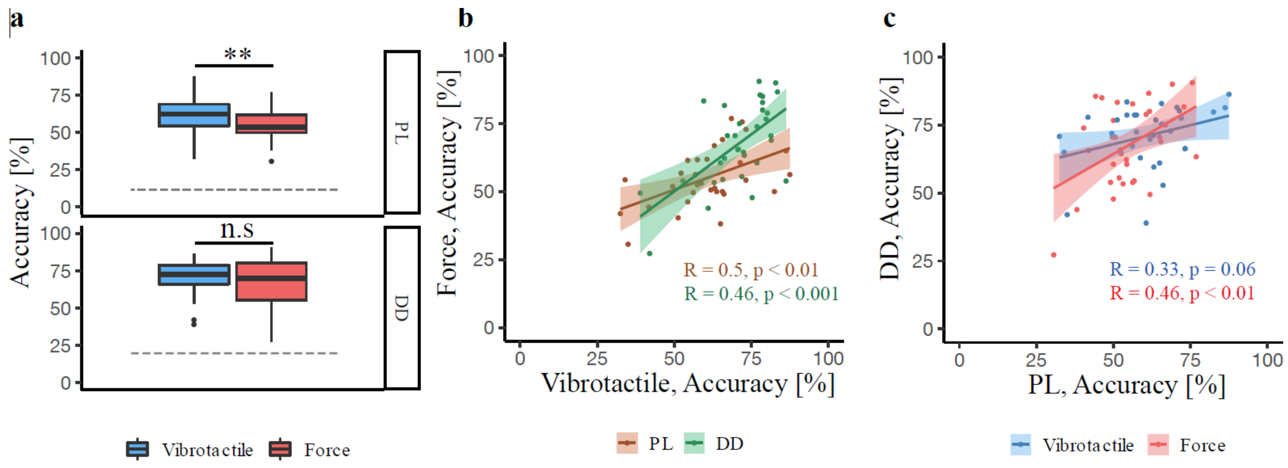

Figure 5:3 Overall accuracy results.

(a) Box plot of overall accuracy for two stimuli across tasks. PL accuracy was significantly higher with vibrotactile stimulation, while no difference was found between DD accuracies of two stimulations. Gray dash-lines represents the chance level. Each box plot shows the median (50th percentile; dark bar), values to the 1.5 interquartile range (whiskers), 25th to 75th percentile range (box), and outliers. (*p < 0.05 and **p < 0.01). (b) Scattered dot plot and Pearson correlation between accuracies with vibrotactile and force stimulations across tasks. There are positive correlations between the accuracies of two simulators for both tasks. Each point represents data from a single participant, and shaded areas show the 95% confidence interval for the regression line. (c) Scattered dot plot and Pearson correlation analysis between PL and DD accuracies of two stimulations. There is a significant positive correlation between PL and DD accuracies for force stimuli (in red) and not vibrotactile stimuli (in blue).

5.3.2 PL task

The range of localization accuracies across both types of stimulation was 52.0-71.7% for vibrotactile and 37.5%-65.1% for force stimulation, respectively. The mixed-model showed a significant main effect of stimulation ($F(1, 573) = 11.22$, $p < 0.001$), stimulation row ($F(2, 573) = 28.52$, $p < 0.001$), and stimulation column ($F(2, 573) = 8.22$, $p < 0.001$); none of the interaction terms were significant. In line with the overall accuracy findings, participants' PL accuracy was significantly higher for the vibrotactile versus force stimulation ($t(561) = -3.34$, $p < 0.001$). Figure 5:3a shows that, whereas PL performance in peripherial areas did not significantly differ (right-left columns: $t(573) = 0.90$, $p = 0.6$), performance was significantly more accurate for stimulations in peripheral than midline columns (right versus middle column: $t(561) = 2.97$, $p = 0.009$; left versus middle columns: $t(561) = 3.87$, $p < 0.001$, Figure 5:3a). In addition, as it is shown in the Figure 5:3c, stimulations located in the middle row were more accurately perceived compared to the upper ($t(573) = -6.97$, $p < 0.001$) and lower rows ($t(66) = 5.79$, $p < 0.001$). No significant difference was found between accuracies of the upper and lower rows ($t(573) = 1.18$, $p = 0.4$).

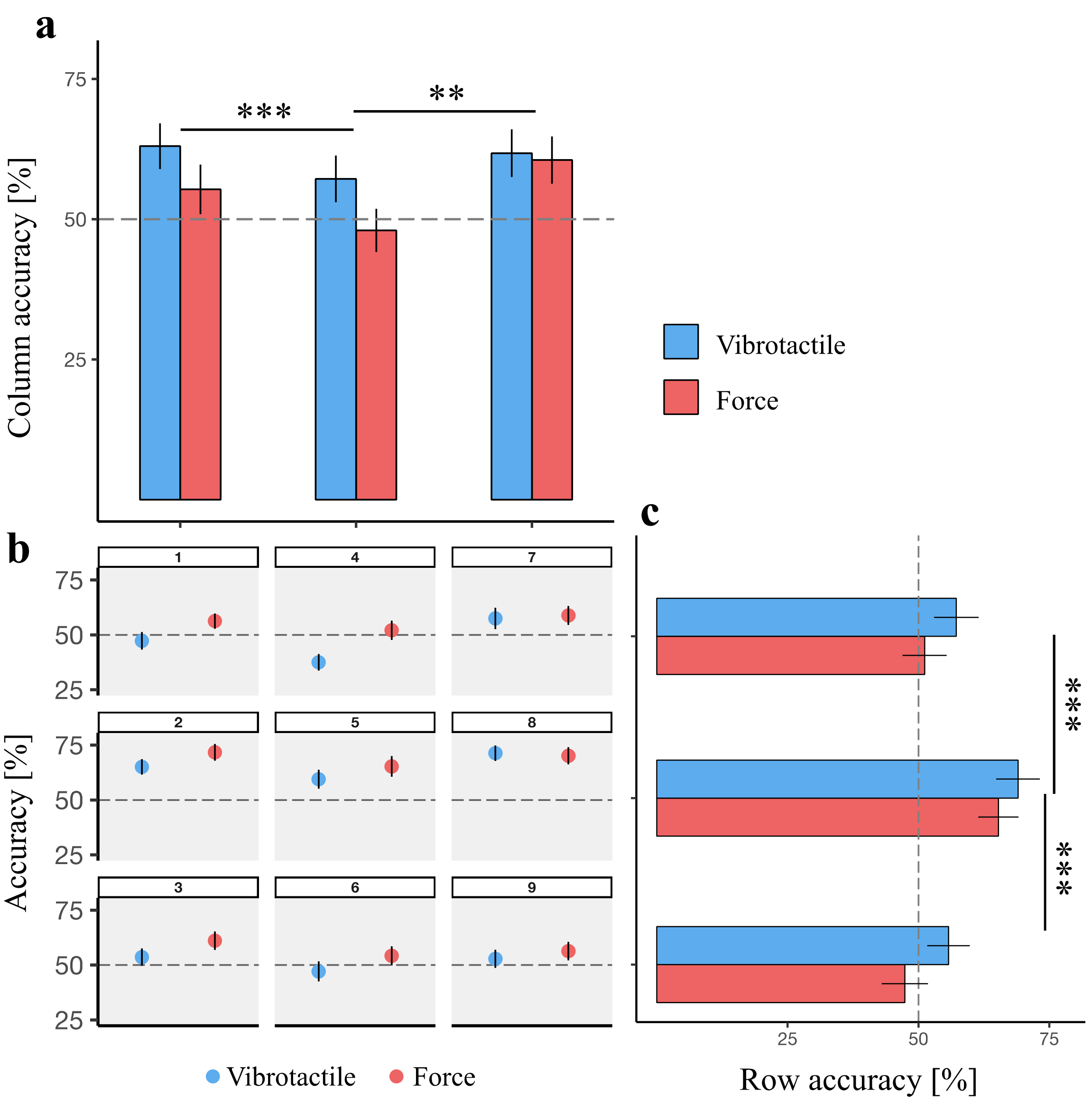

Figure 5:4 Results of the PL task.

(a) Mean PL accuracies at three columns in the array for both stimulations. (b) Mean PL accuracies at nine stimulation landmarks in a 3 x 3 array for both stimulation types. (c) Mean PL accuracies at three rows in the array for both stimulations. The dashed line shows the 50% threshold, and error bars illustrate the standard error of the mean (SEM) (*: p < 0.05, ** p < 0.01, *** p < 0 .001).

Table 1 lists localization errors in the PL task. For both stimulations, the majority of such errors were characterized by a mislocalization to an adjacent location (adjacent versus nonadjecent location: vibrotactile: z = 595, p < 0.001; force: z = 595, p < 0.001). Analyzing whether there was an axis along which localization errors predominated, we found that the number of horizontal errors was significantly lower than vertical errors, across stimulations (vibrotactile: z = 5, p < 0.001; force: z = 5.1, p < 0.001).

We further compared the number of localization errors between the two types of stimulation for different categories of error (i.e., adjacent vs. nonadjacent, and H Vs. V). Results showed no significant difference in the number of localization errors between the two stimulations (all p > 0.05).

Error of localization	Force stimulation	Vibrotactile stimulation
$N_{Adjacent}$	63.2 (2.91)	58.2 (3.21)
$N_{Nonadjacent}$	1.38 (0.36)	0.91 (0.23)
N_H	5.94 (1.1)	7.5 (1.34)
N_V	53.6 (2.23)	47 (2.30)

Table 5:1 Means of different tactile localization errors (standard error of the mean) for two vests.

5.3.3 DD task

Investigating the effect of tactile orientation and of stimulation type on the accuracy in the DD, we found a significant main effect for tactile orientation ($F(1, 93) = 37.33$, $p < 0.001$) and a significant interaction between the stimulation and tactile orientation ($F(1,93) = 8.68$, $p < 0.001$). Post-hoc analysis showed that participants were more accurate for trials presented along the horizontal axis only when using vibrotactile stimulation ($t(93)= 6.76$, $p < 0.001$; Figure 5:5) (this effect was absent for force stimulation ($t(93) = 2.24$, $p = 0.12$)).

We assessed correlation coefficients separately for vertical and horizontal levels to explore any potential relationships between orientation-related effects in DD accuracy (worse along the vertical axis) and localization errors in PL (higher vertical errors). The only significant correlation was found for the vibrotactile stimulation in the vertical axis (DD_V-N_V: $R= -0.36$, $p = 0.040$; Bonferroni corrected p-value), revealing that those participants who had higher vertical errors (N_V) in the PL task they also had low DD performance in discriminating vibrotactile stimulation in the vertical axis.

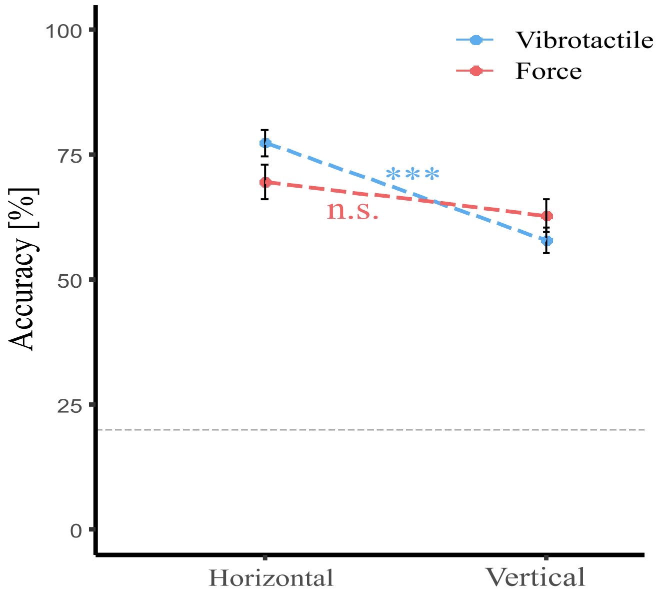

Figure 5:5 DD accuracies with vibrotactile and force stimulations.

The dash-line shows the chance level of 20%. The error bars show the standard error of the mean (SEM) (*** p <0 .001; n.s.: No significant).

5.4 Discussion

In the present study, we adapted two automatized tactile perception paradigms, namely tactile PL and tactile DD task, and measured tactile spatial discrimination on the human back. More specifically, we evaluated tactile perception over the thoracic region, using two custom-made haptic interfaces consisting of either vibrotactile or force stimulators. We found that PL and DD accuracy were slightly higher with vibrotactile stimulations than those with force stimulations. Using a within-participant design, we further demonstrate that tactile performance generalizes across tasks (PL and DD) for force stimulations but not for vibrotactile ones. Furthermore, we observed directional anisotropies in both tasks characterized by better performance for horizontal directions.

5.4.1 Overall accuracy

We observed an overall PL accuracy of 60.7% for vibrotactile and 54.6% for force stimulation in the thoracic region on the back. In the DD task, we reported an overall accuracy of 71% for vibrotactile and 67% for force stimulation. Our PL results (accuracy) are in line with earlier studies that employed a two-dimensional array of vibrators reporting PL accuracy around 60% when stimuli were applied to the participants' lower back (Cholewiak and McGrath 2005; Jones and Ray 2008). Considering the DD task, our vibrotactile accuracy was lower than in a recent study (Jóhannesson et al. 2017), where the accuracy of 91% was found, even if the inter-stimulator distance of 30 mm was smaller than in our study (60 mm). However, the latter authors used a 3-AFC DD task (via 3x3 vibrotactile array), which has a lower degree of difficulty compared to the 5-AFC used in the current study.

5.4.2 Vibrotactile vs. force stimulation: correlation and comparison

We observed a moderate, positive correlation between performance for both stimulators across tasks (see Figure 5:3c), suggesting that the spatial discrimination processes for both stimulation modalities, as tested in the present study, rely on similar perceptual mechanisms. Load frequencies of the vibrator (175 Hz) and force stimulator (600 Hz) fall in the frequency range of the Pacinian corpuscle sensitivity (100-1000 Hz) (Vallbo et al. 1984). The relatively low tactile spatial discrimination rate (around 60%) reported for both stimulations and across tasks further points to this type of subcutaneous mechanoreceptor, with its comparatively large receptive fields. In comparison, non-Pacinian receptors embedded in the glabrous skin of the palm or fingers have shown higher tactile spatial sensitivities (Weinstein 1968).

While accuracy was higher for the vibrotactile than for the force stimulation across both tasks (mean difference, PL: 6.1%; DD: 3.3%), this difference was only significant for the PL task. We fixed the spatial parameters (i.e., body site, inter-stimulator distance) and temporal parameters (i.e., burst duration and inter-stimulus interval) between the two stimulations as they may have a profound effect on both PL and DD results (Cholewiak et al. 2004; Van Erp 2005a; Jóhannesson et al. 2017). Nonetheless, we observed greater accuracy when using vibrotactile stimulation, suggesting that other stimulus properties account for this discrepancy. These could include physical features (frequency, intensity, mass), contact area, the direction of movement with respect to the skin, and the amount of surface wave created by activating the motor. We here observed a higher accuracy with vibrotactile stimulations, which had a lighter weight (1.1 gr vs. 39 gr), slightly lower acceleration (1.3 G vs. 1.65G), and lower load frequency (175 Hz vs. 650 Hz). Considering that the combination of mass, acceleration, and frequency of the tactile stimulation contributes to the perceived force, our results corroborate previous studies (Gibson and Craig 2006; Hoffmann et al. 2018b), suggesting that the effect of physical parameters is not sufficient to account for the performance in the PL and DD tasks. For the effect of frequency, it has been found that increases in frequency above 80 Hz (i.e., Pacinian corpuscle) did not result in higher accuracy (Cholewiak et al. 2004; Cholewiak and McGrath 2005; Hoffmann et al. 2018b). Another possible explanation for the higher PL and DD accuracy with vibrotactile stimulations might also be that the contact area of the vibrotactile stimulator was twice as large as the one chosen for the force stimulator (vibrotactile: 314 mm^2, force: 78.5 mm^2). While the effect of the contact area on the PL/DD has not been systematically investigated, it would seem that due to the spatial summation of afferent signals from Pacinian corpuscles, vibrotactile thresholds (above 50 Hz) decrease as the stimulator area increases (Verrillo 1963; Gescheider et al. 2010), presumably enhancing the perceptual capabilities. In addition, we here observed that PL and DD accuracy were higher with the vibrotactile stimulator (coin-shaped vibrators), which generates motions parallel to the skin's plane, compared to force stimulators that generate force perpendicular to the skin. This observation may relate to previous findings of Hoffmann et al. (2018b), who found that DD accuracy was higher with vibrators that generate motion parallel to the skin (as in our study) compared to the perpendicular to the skin as it provides stronger surface waves traveling on the skin (see Hoffmann et al. 2018 for more details). Future work is needed to investigate how tactile perception on the back depends on these different mechanisms.

5.4.3 Association between PL and DD results

In the present study, we found a positive correlation between the PL and DD performances for the force stimulations but not for the vibrotactile stimulations. Although prior studies often directly compared the results of tactile localization (PL) with tactile spatial acuity (e.g., DD), our results suggest that extending the results of PL to DD (or the other way around) depends on the type of tactile stimuli and may not hold for vibrotactile stimulation (at least in the present study). The absent correlation between the PL and DD tasks with vibrotactile stimulations suggests that distinct and, presumably, stimulation-related driving factors are involved in the discrimination process of the vibrotactile DD task as tested by us. As discussed below, the DD task with the vibrotactile stimulation may more heavily depend on and vary with the viscoelastic properties of the participants' skin.

5.4.4 PL task

We observed that the PL accuracies for both stimulations vary over the skin surface of the back in the thoracic region (vibrotactile: 52%-71.68%, force: 37.47%-65.08%). This observation may partly be explained by garment conformity but may also reflect differences in mechanoreceptor density on the torso. The present PL performance is in line with previous studies that reported variation in tactile PL (for both static pressure and vibrotactile stimuli) across the skin surface for different body parts, also including the back (e.g., forearm, abdomen, lower back, palm, thigh, etc.) (Cholewiak and Collins 2003; Oakley et al. 2005).

5.4.5 Lower PL accuracy on the spine compared to the peripheral area

Concerning the PL performance on the spine, previous studies have yielded mixed results and further depended on the physical arrangement of stimulators. Some studies that used a one-dimensional array of vibrators supported the enhancement of PL in midline regions (close to the spine) as an anatomical body reference (i.e., as being related to the joints of the body) (Boring 1942; Cholewiak and Collins 2003; Cholewiak et al. 2004; Van Erp 2005a; Jones and Ray 2008). Others, however, did not report improved PL in midline regions when using two-dimensional arrays (Lindeman and Yanagida 2003; Jones and Ray 2008). In the present study, we observed that the PL accuracy was lower for stimulators in the midline area (column 2) than those located peripherally (columns 1 and 3). These results match the findings of previous multi-dimensional setups, suggesting that by adding dimension to the tactile display (e.g., two-dimensional array), no midline advantage is observed. Compatible with this account, earlier studies on the PL for the forearm also found increased accuracy at the edges of the arm compared to those in the center (Oakley et al. 2005; Chen et al. 2008). Based on the present data of enhanced performance for lateral stimulations, we speculate that perceptual and attentional mechanisms related to lateralized stimulations may boost performance. However, more work is needed to specifically test this hypothesis and its comparison with enhanced midline performance. We also note that structural aspects such as the higher curvature in the spinal area compared to lateralized torso locations and the consequent poorer fit of the vest and stimulators around the midline may also play an important role.

5.4.6 Directional anisotropies

In the present study, we observed directional anisotropy in PL performance in both tasks, as participants made considerably fewer localization errors in the horizontal than vertical axes (see Table 1). Using a 4x4 array of vibrotactile on the back, Jones and Ray (2008) also showed that participants were less accurate in identifying the correct row of activation than the column. These observations are also in line with earlier PL studies that reported systematic biases in the vertical axis on the skin surface of the palm, thigh (Sofia and Jones 2013), and arm (Oakley et al. 2005; Chen et al. 2008; Sofia and Jones 2013). In addition, we, here, found that the level of anisotropy in PL performance was comparable between the two tasks, suggesting that comparable mechanisms are involved in the spatial discrimination process for both stimulations. One possible explanation, as discussed above, is that the torso's lateral sides function as a perceptual reference point (as located to the endpoints of the stimulus range), affording higher accuracy in the horizontal direction. It has also been proposed that receptive fields of afferent fibers and/or neurons in the spinal cord and somatosensory cortex are oval-shaped and elongated along the longitudinal-vertical axis (Cody et al. 2008). Thus, one may speculate that stimulators in the horizontal axis would more likely activate separate adjacent mechanoreceptors, leading to fewer localization errors along with the horizontal axis. However, these argumentations do not seem to apply for our observation concerning DD results as anisotropy was only seen in the results with vibrotactile stimulations: higher DD accuracy for vibrotactile stimulation in the horizontal axis than vertical. Our observation for vibrotactile stimuli is consistent with the findings of Hoffmann et al. (2018b), who recently found the superior DD accuracy for vibrotactile stimulations presented horizontally on the lower thoracic region across different types of vibrators. We argue that anisotropy in DD results is mainly influenced by the amount of surface waves created by force and vibrotactile stimulations and how they spread on the skin. In contrast to focal force stimulation, vibrotactile stimuli spread beyond the contact area in the form of surface waves. As the skin is a highly viscoelastic tissue, its mechanical properties highly impact the spread of the surface wave from the vibration source. Some direct human and animal evidence suggested that skin stiffness is anisotropic with higher stiffness along with the vertical axis than horizontal. Therefore, surface wave from a vibrating source may propagate further along with the vertical axis and hence excite mechanoreceptors some distance from the site of the stimulation, which makes difficult the recognition of the stimulation direction. (e.g., in our case, up or down).

5.4.7 Study limitations

The present study has several limitations. Although we evaluated and compared tactile spatial discrimination using dynamic force (push-pull solenoid) and vibrotactile (coin-shaped ERM) stimulators, we only controlled for the temporal and spatial parameters between the two simulators. However, there are other parameters that we did not control with the present systems, such as physical parameters, contact area, or spread of vibration waves. Therefore, the generalization of these results to other setups has to be taken with caution. Future experimental investigations are needed to systematically investigate the effect of such individual actuator properties on spatial discrimination, which was beyond the scope of the current study. Second, the design and control of force simulators are more problematic than vibrotactile stimulators. Thus, force stimulators require actual contact with the human skin to be perceived; moreover, as reported in our previous study with a force vest (Fadaei et al. 2021), the solenoid's impact force might change in the range of 0.5-0.8 N, depending on the stroke length. Such effects could lessen the quality of force perception resulting in lower tactile perception with force stimulators. Future work may monitor the uniformity of the perceived intensity across the array of actuators by employing an objective calibration procedure, where the participants are asked to rate the intensity of each individual actuators. Finally, for the field to advance, the same experimental procedures and tasks have to be applied across participants, conditions, and different research groups, further empowered by the application of psychophysical methodology.

5.5 Conclusion

Collectively, although previous studies investigated the spatial discrimination of vibration stimuli on the back, our study is the first to investigate both localization and tactile direction discrimination of the upper thoracic spine for two different types of dynamic mechanical stimulations (vibrotactile and force) in a large group of healthy participants. Our findings suggest that designers can use force stimulators to design the torso-worn tactile interface to provide more ecological touch feedback with the (almost) similar level of tactile spatial discrimination accuracy as observed in widespread vibrotactile interfaces. We also noted that overall accuracy with both stimulations is still relatively low (around 60%), indicating that further technological improvements are required to improve torso-based tactile communication systems. Apart from technological advancement, we might speculate that long-lasting training might improve performance. Alternatively, we suggest taking advantage of multisensory-training protocols (i.e., a combination of tactile with auditory, visual, or vestibular) instead of unisensory protocols to produce greater and more efficient learning (Ghazanfar and Schroeder 2006; Shams and Seitz 2008; Proulx et al. 2012). Furthermore, our findings provide new insights into the association between the results of the PL and DD tasks on the torso, indicating that the generalization of the PL results to DD is only valid for focal force stimulations and not for vibrotactile ones which spread further away. These results suggest that studies using vibrotactile interfaces should ideally measure spatial discrimination with different measures in parallel to estimate the actual discrimination accuracy.

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Code availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Compliance with ethical standards Informed consent was obtained from all individual participants included in the study.

Consent to participate The authors have no relevant financial or non-financial interests to disclose.

Chapter 6 General Discussion

In four behavioral studies, this thesis investigated the development and validation of body-conforming, torso-based tactile interfaces that register the sense of touch in static/mobile sensorimotor experimental setups, with an emphasis on robot-induced PH and conscious gait monitoring paradigms. The findings of this thesis can be thus categorized in some conceptual parts involving interface design guidelines, quantitative knowledge on tactile spatial discrimination on the back, and experimental use-cases of torso-worn displays to investigate self-other distinction and tactile walking awareness in healthy individuals. This chapter summarizes these findings, discusses them by relating the results of different studies and suggests some possible future implications in the health and disease population.

6.1 Tactile spatial discrimination on the back via torso-worn tactile interfaces

6.1.1 Summary of scientific contributions

6.1.1.1 Wearability challenges for torso-worn tactile displays

While waist-worn tactile displays (placed at the lower torso) have been widely used in industrial and experimental (psychophysical) frameworks in the last two decades (Jones and Ray 2008; McDaniel et al. 2008; Jóhannesson et al. 2017; Hoffmann et al. 2018b), only a limited number of studies have considered using torso-worn tactile interfaces that present tactile stimuli on the upper thoraces torso (Arafsha et al. 2015; Lentini et al. 2016; Karafotias et al. 2017; Garcia-Valle et al. 2018). This is because designing a wearable tactile interface for the upper torso areas has its own challenges. One complication is the large morphological differences in the human torso area, resulting in substantial within-participant's variabilities. Another issue is significant between participants' variabilities due to gender difference or variation in potential wearers' size. Hence, forming and fitting the torso-worn haptic display to the participants' torso is challenging in assuring consistent stimulus application (Mortimer and Elliott 2017). Most previous studies neglected these limitations and have simply used single, non-adjustable vests or T-shirts for different-sized users (see Figure 1:7 in section 1.4). In the present thesis, I took the first step to provide empirical knowledge to design wearable tactile interfaces for the upper torso. I tackled this wearability issue by developing flexible, body-conforming torso-based tactile displays. In a preliminary study (Study 1) (Jouybari et al. 2019), in spite of using gender-specific chest-belts containing 3x2 vibrators, I obtained poor localization accuracy of 30.7% (on average) stemming from the impaired interface design. I noted that to deliver localized vibrotactile stimuli, the tactile interface should be made of stretchable materials. Additionally, I discovered that the ideal interface for the upper torso should be sufficiently adjustable to guarantee a correct fit, firm support, and free-breathing for different-sized users even during movements despite the huge morphological variations in the torso area.

In two subsequent studies (Study 2 and Study 3), I followed iterative design procedures, which involved several prototyping, testing, analyzing, and refining the interface. I eventually addressed these seemingly opposing requirements using modular designs where the interface's components are mainly made of stretchable materials. Both CognoVest and tactile interface in FeetBack setup are Y-harness braces with stretchable straps wrapped around the shoulder, chest, and lower back, securing garment positioning on the users' torso. The great advantage of Y-harness braces is that they are unisex, and they allow covering the whole back while keeping the front part free for breathing. The back part of the brace should be chosen based on the type of actuators employed in the interface. For instance, the back part of CognoVest is made of durable polyester nylon and integrated laser-cut loops, facilitating mounting solenoid boxes on the back. On the contrary, in the FeetBack system, vibrators were placed on a sponge which helped to provide localized tactile stimuli. According to the results presented in 0, interfaces developed in the present study (i.e., CognoVest and vibrotactile interface in FeetBack system) can provide well-perceived tactile sensations (the overall accuracies of 60.7% for vibrotactile and 54.6% for force stimulation) all over the back. Furthermore, I investigated the effects of the fitting (characterized with torso sizing measurements, e.g., torso length, waist circumference, and chest circumference) and gender variabilities on the DD and PL performance results (see section 7.2). As expected, participants' torso size and gender did not influence the PL and DD results with each vest; however, the significant effect was only found for the effect of the chest circumstance on the PL results. The findings of the present thesis are important for developing future torso-worn tactile interfaces as they provide practical insight into the design of body-conforming, torso-worn tactile displays.

6.1.1.2 Vibrotactile Vs. Force stimulator

Torso-worn haptic displays deploying tactile spatial cues to users have gained a lot of attention in recent years. Such systems have been used in a variety of applications ranging from navigation (van Erp 2007; Viola et al. 2018), sensory substitution (Buimer et al. 2018), immersion in VR (Lemmens et al. 2009), and cognitive and clinical neurosciences (Jouybari et al. 2019; Fadaei et al. 2021). In all aforementioned applications, designers should consider the spatial resolution of the human torso together with the system functionality to effectively convey spatially encoded tactile information. Despite the growing interest in using the torso-worn haptic display for mobile users, there is still a lack of comprehensive knowledge about spatial discrimination features of the torso for dynamic mechanical stimulators such as vibrotactile and force stimulators. While there are some recent studies investigating the vibrotactile perception on the torso using automated and wearable devices (Eskildsen et al. 1969; Jones et al. 2009; Hoffmann et al. 2018b), to our knowledge, there is no study that measured tactile perception for a dynamic force stimuli, particularly on the torso. For instance, it has not yet known whether force stimuli can provide an advantage, compared to widespread vibrotactile stimuli, in spatial discrimination tasks on the torso. In the present thesis (0), I focused on this issue.

To this aim, I employed two body-conforming torso-based tactile displays, realized with arrays of 3x3 vibrotactile stimulators (Vibrotactile vest); another realized with force stimulators (Force vest) and assessed tactile PL and DD on the skin surface of the human upper thoracic area. This study extends the previous knowledge on the tactile spatial discrimination on the back to different stimulations (vibrotactile, force) with different paradigms (PL, DD). Tactile accuracy for vibrotactile and force stimulators was 60.7% and 54.6% for the PL task; 71% and 67.7% for the DD task, respectively. These results are comparable with those reported in recent vibrotactile studies (Eskildsen et al. 1969; Cholewiak 1999; Van Erp 2005a; Jóhannesson et al. 2017; Hoffmann et al. 2018b). Using the within-participants design allowed me to directly compare the results of two stimulators and two tasks. Data presented in 0 showed that PL and DD performances with the vibrotactile interface (commonly used) could be extended to force stimulations (the state-of-art) and vice versa; in other words, I found a positive correlation between the two stimulations across tasks. This is presumably because the frequency of both stimulators falls in the range of Pacinian corpuscles (Vallbo et al. 1995).

Despite fixing temporal and spatial parameters between the two stimulators, which have the most effects on the tactile spatial discrimination, I found slightly higher tactile performance for vibrotactile stimuli across tasks. I speculate that the slight different performances between two stimulators are based on their difference in other characteristics such as contact area (vibrotactile: 314 mm2, force: 78.5 mm2) or direction of movement with respect to the skin (vibrotactile: parallel to the skin, force: perpendicular to skin). Future experimental investigations are needed to systematically investigate the effect of these parameters on the spatial discrimination of both vibrotactile and force stimulators. Such results would also help determine to what extent the spatial resolution of vibrotactile stimuli can be expanded to the focal force ones. It is worth noting that the comparison between PL and DD accuracies of the two stimulators presented in this article is based on the specific range of differences in the characteristics of two special force and vibrotactile stimulators used in the current study. Therefore, the generalization of these results to any other setup should be taken with sufficient caution.

Additionally, the present study results for the PL and DD accuracy are limited to the skin surface of the thoracic spine. As noted in the previous studies (Cholewiak 1999; Cholewiak et al. 2004; Myles and Binseel 2007), several potential factors are influencing the results of tactile spatial discrimination such as actuator arrangement on the skin, overall size, density, and the shape of the underlying mechanoreceptor afferent receptive fields, proximity to anatomical body landmarks, etc. that results in different performance on the different areas of the body. Therefore, the generalization of these results to other body parts or even different regions on the torso should be made with considerable caution.

6.1.1.3 Suggestions to design high-resolution tactile interfaces for the back

Studies of tactile spatial perception reveal the importance of understanding the properties of the somatosensory system and their marked variation across the body (Cholewiak and McGrath 2005; Van Erp 2005a; Jones 2011; Hoffmann et al. 2018b). Factors such as tactile anisotropies, proximity to the anchor point, spatial-temporal interactions, etc., must be considered carefully in designing and evaluating tactile interfaces. In 0, I empirically assessed the effect of the spine as an anatomical reference point to improve PL results. Using two-dimensional arrays of actuators, I did not find any superior effect of the body midline on the tactile PL task. Although this observation differs from classical studies supporting the enhancement of spatial resolution in proximity with anatomical body reference (Boring 1942; Cholewiak and Collins 2003; Cholewiak et al. 2004; Van Erp 2005a; Jones and Ray 2008), it accords well with results of those studies that investigated PL on the torso using a two-dimensional array of vibrators (Lindeman and Yanagida 2003; Jones and Ray 2008). I argue that observations in classical studies were limited to the setup using a one-dimensional (i.e., linear) array of stimulators (Cholewiak and Collins 2003; Cholewiak et al. 2004). Whereas, by adding dimension to the tactile display (e.g., two-dimension array), the efficacy of the spine in the improvement of PL may change. In the present study, I claim that torso sides, as located at the borders (endpoints) of the array, might receive a greater proportion of a participant's attentional resource than the spine, which is a passive joint located in the middle of the array. Given that no body-landmark was found on the back that improves tactile localization in the vertical axis, I propose that tactile interface designers may add arbitrary local signs that could provide perceptual reference points that the participants can use in identifying the site of the stimulation. These local signs can be as simple as point stimulations that stimulate differently than the target stimulators, and they might be located at the endpoints of the stimulus range.

In addition, I observed that participants made considerably fewer errors of localization in the horizontal axis than vertical ones (see Table 5:1), consistently across stimulators. This observation is in line with earlier studies using PL task that reported systematic biases in vertical axis on the skin surface of the back (Jones and Ray 2008), palm, thigh (Sofia and

Jones 2013), arm (Oakley et al. 2005; Chen et al. 2008; Sofia and Jones 2013), and provide further evidence for mislocalization pattern with dynamic mechanical stimulators (i.e., vibrotactile and moving force stimuli) on the thoracic spine region. In addition, I found that the effect of stimulus orientation on the DD accuracy is only significant for the vibrotactile stimulator and not for the force stimulator, as I observed higher DD accuracy for vibrotactile stimulation in the transverse than longitudinal axis. This result is in line with the findings of Hoffmann et al. (2018b), who recently found the superior DD accuracy for vibrotactile stimulations presented horizontally (transverse) on the lower thoracic region for different types of vibrators. Here, using a within-participants design, I provide further information indicating that the tactile acuity in the DD task does not only depend on the stimuli orientation but also the type of tactile stimuli. I propose that the torso-worn tactile interface designer should consider relatively bigger inter-tactor distance in the vertical axis than the horizontal (of course, both vertical and horizontal inter-tactor distance must be higher than the localization threshold) to reduce the error of localization and improve direction discrimination capabilities in the vertical direction.

6.1.2 Does visual feedback of the back enhance tactile spatial resolution?

In 0, I found that the overall accuracy with both stimulators was fairly low (around 60%), indicating that more work is required to improve torso-based tactile communication systems. Apart from technological advancement (discussed above), I might speculate that long-lasting training might improve the performance, even if a recent study (Jóhannesson et al. 2017) suggested that the tactile accuracy on the back is not affected by extensive familiarization with torso stimulator. Alternatively, the torso-worn tactile interface could be designed to provide stimuli from different modalities (auditory, vestibular, visual). Recent studies on multisensory integration found that the human brain has evolved to learn and operate in natural environments that involve a constant stream of information integrated across multiple sensory modalities (Aspell et al. 2011; Ehrsson 2012; Ronchi et al. 2018). Therefore, multisensory-training protocols, as opposed to unisensory protocols, can better approximate natural settings and, thus, produce greater and more efficient learning (Ghazanfar and Schroeder 2006; Shams and Seitz 2008; Proulx et al. 2012). For instance, studies investigating the multisensory processing of somatosensory stimuli of the ones' body demonstrated that the tactile spatial discrimination ability is constantly increased when participants can look at the stimulated body part (Kennett et al. 2001; Haggard et al. 2003; Press et al. 2004; Taylor-Clarke et al. 2004; Schaefer et al. 2006; Harris et al. 2007; Serino et al. 2009; Medina et al. 2018). These studies also showed that the additional effect of vision tended to be stronger when the tactile spatial task is more challenging and closer to the performance limit. This effect is known as a visual enhancement of touch (VET), and it has been reported for different body parts, such as fingers (Taylor-Clarke et al. 2004), hands, arms (Kennett et al. 2001; Press et al. 2004; Schaefer et al. 2006; Haggard et al. 2007; Serino et al. 2009), face, and feet (Tipper et al. 2001; Serino et al. 2009), but there is very limited knowledge on the VET for the human torso (Catley et al. 2014). To examine VET for the back, in a pilot study (N=12), I tested vibrotactile direction discrimination on the back while showing different views to healthy volunteers (for more details about the experimental design and results, see section 7.3). This pilot study aimed to investigate whether providing visual information of the participants back would boost tactile direction discrimination and if such an effect depends on the complexity of the tactile spatial discrimination task (i.e., shorter inter-tactor distance). The vibrotactile vest, presented in Chapter 4 (or 0), was used; however, in this study, the vest only included a vertical array of vibrators (12 vibrators with an inter-tactor distance of 15 mm). This decision has been made to avoid the effect of tactile direction dependencies. A within-participants repeated measures design was used by considering inter-tactor distance (four levels including 15 mm, 30 mm, 45 mm, and 60 mm plus 0 mm as the catch trial) and visual condition (three levels: Body, No-Body, Blind) as the main variables. Participant's average accuracies and response time in different conditions were analyzed.

In line with previous findings on the vibrotactile discrimination (Jóhannesson et al. 2017; Hoffmann et al. 2018b), my data from the VET study showed that participants' tactile performance and response time consistently improve as the inter-tactor distance increases. Nevertheless, I did not find any superior effect for seeing the back on the tactile accuracy and response time. As it is clear from Figure 7:7, participants' tactile performance was almost the same for different visual conditions, suggesting that tactile performance on the back does not improve by providing visual information of the back. While the results of the pilot study are in contrast with those previous studies that reported VET for human face, neck, fingers, hand, feet (Kennett et al. 2001; Press et al. 2004; Taylor-Clarke et al. 2004; Haggard et al. 2007), it corroborates well with findings of Catley et al. (2014) who tested participants in the series of experiments and reported that there is no VET for the human back. One may assume that providing an indirect view of the back may diminish the VET effect; however, previous findings on the VET for the face and neck suggested that vision of the body site, independent of proprioceptive orienting, can influence tactile detection.

A possible explanation for the lack of VET in the current study might be that in the present paradigm, participants could not see the skin of the back. Due to technical complexity, participants only saw the view of their back which was covered with the vibrotactile vest. However, in the previous VET studies, participants were exposed to the skin view of the body part (Haggard et al. 2003; Press et al. 2004; Taylor-Clarke et al. 2004; Cardini et al. 2012). Earlier studies on the arm have reported that viewing a neutral object in place of the arm does not enhance tactile acuity (Kennett et al. 2001; Cardini et al. 2012). It is possible that the covered view of the back was perceived as a neutral object rather than one's own body part. Thus, most likely, participants did not associate their back with their own body because they are not used to visualizing it. It has also been shown that VET works while looking at the rubber hand (Longo et al. 2008) or someones else's hand (Haggard 2006; Longo et al. 2008), suggesting that the VET effect seems to be related to a generic visual body image, arising from the recognition of the characteristic structural form of a hand. Observations in the current VET study support this hypothesis as, during post-briefing, 10 out of 12 participants reported that the "Body" condition was distracting ("It was weird to see the back"; "I could better concentrate when I had my eyes close or looked at the cross"). Similarly, Kennett et al. (2001) have also shown that higher VET for the human forearm can be achieved, while participants saw the magnified view of their body part compared to the normal view. Thus, the ideal VET experiment may expose participants to the realistic view of the back with sufficient detailed information of the back morphology. On the other hand, as Catley et al. (2014) speculated, it is possible that bimodal visuotactile cells, thought to be involved in visuotactile performance in hand, do not exist for the back - an area that is not usually viewed.

6.2 Torso-worn tactile displays to robotically induce Presence Hallucination

6.2.1 Summary of scientific contributions

In this thesis, I took the first step towards developing and applying torso-worn tactile displays to register touch sensations and induce specific bodily illusions in healthy individuals. In an initial attempt (Chapter 2), I adapted a robotic system and paradigm previously established by our lab (Blanke et al. 2014) that investigate self-other distinction to torso-worn vibrotactile display. My data reveal that with the semi-wearable, vibrotactile setup (the combination of Geomagic Touch device and vibrator interface), I could induce moderate illusory passivity experiences and mild illusory self-touch; however, participants gave low ratings to the PH question. Via assessing vibrotactile point localization accuracy on the back, I showed that illusory own-body perceptions are not driven by tactile spatial accuracy. Nevertheless, during post-condition debriefing, participants' reports indicated that the vibration stimuli on their back were not comparable to human poking. Although vibrotactile displays have been commonly known as effective and inexpensive tools to provide tactile stimulations in various virtual environments, the findings presented in Chapter 2 demonstrated that a simple vibratory pulse might not be sufficiently realistic to induce bodily illusion sensations as strong as reported in the previous studies (Blanke et al. 2014). Thus we claimed that providing an ecologically valid sense of touch is essential in experimental manipulation of BSC states. This corroborates previous studies that highlighted the immediate and private quality of bodily sensations, particularly the sense of touch. For instance, I can understand your visual percepts by looking in the same direction as you, but understanding your tactile sensation would require being in your skin (Haggard et al. 2003). Overall, the study presented in Chapter 2 suggests that technological advances in the experimental manipulation of BSC should be concerned with providing ecological haptic solutions that adequately resemble the human body's sensations.

In a subsequent study (Chapter 3), I present a proof-of-concept and experimental use-case for the novel torso-worn force display that provides human-like poking sensations as well as its functionally in experimentally-induced PH paradigm. I addressed the complexity of designing a body-conforming, torso-worn force display and proposed a technical approach including principles from robotics, fashion design, and 3D printing technologies: CognoVest. CognoVest includes simple, low-weight, inexpensive on-off force actuators placed in custom-made 3D printed boxes. Actuator boxes are mounted on a Y-harness brace with stretchable straps wrapped around the shoulder, chest, and lower back, securing the garment positioning on the users' torso. The behavioral study results with the novel robotic system, which included CognoVest, confirmed the induction of mild to moderate illusory experience of self-touch, passivity, and PH in healthy individuals. Comparing these results with those of Chapter 2 suggests that force stimulation is more effective in robot-induced PH systems than vibrotactile stimulation. This finding is in line with prior studies which showed that presenting force feedback to provide mechanical touches or simulate collisions in virtual environments may enhance immersion (Lopes et al. 2015; Delazio et al. 2018; Garcia-Valle et al. 2018).

Nevertheless, illusory ratings in the study presented in Chapter 3 were still relatively lower compared to findings (e.g., PH scores) in (Blanke et al. 2014). One possible explanation is that integrated force actuators (embedded in 3D printed boxes) generate lower force compared to the human finger poking (maximum impact force is around 0.8 N which is lower than the peak finger poking force of 2.15 N), which may lead to weaker induction and modulation of robot-induced illusory own-body perception. Additionally, as the evaluation test results showed, the new arrangement of the force actuators (embedded in the 3D-printed box) leads to temporal delays in following activation and deactivation commands. Although this problem was addressed in the control algorithm by implementing the linear estimation to predict events for the next 100 ms, some participants still reported the temporal delays at deactivation moments in the synchronous condition. Given that the present hallucination paradigm is synchrony-dependent, any unwanted temporal shift may negatively influence the results. Future work should address this issue using a more reliable solenoid actuator, guaranteeing time precision and ensuring a sufficiently strong poking force.

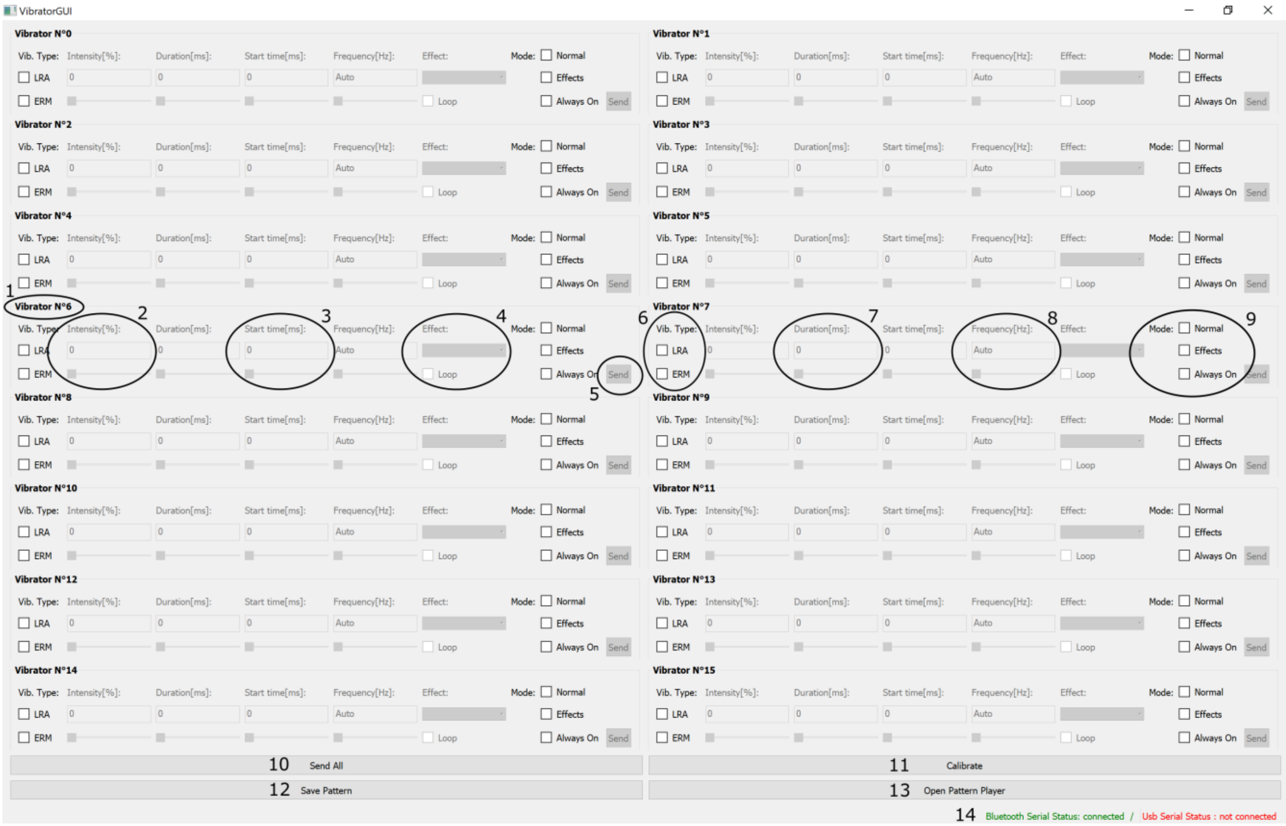

Figure 6:1 Graphic User Interface (main window) for flexible vibrotactile research platform.

(1) Vibrator ID (2) Amplitude control (3) Start time control (4) Effect selection (5) Send single command (6) Vibrator type selection (7) Duration control (8) Frequency control (9) Mode selection (10) Send the command for all vibrators (11) Send the command to calibrate corresponding to selected types (unchecked will be calibrated to ERM) (12) Opens a dialog to select XML's file location and saves the current parameters (13) Open a pattern player to replay saved setup (14) Connection status bar, indicates if USB and/or Bluetooth are connected.

6.2.2 Current and future technical improvements

6.2.2.1 More sophisticated vibrotactile sensations would be effective in modulating bodily illusions?

Chapter 2 showed that a simple vibratory pulse might not be a suitable replacement for human finger poking. While the findings presented in Chapter 3 demonstrated that using on-off force actuators is practical for robot-induced PH paradigms, future work should also consider enhancing vibration sensation quality to resemble human finger poking. Recently there has been compelling evidence on the potential of the vibrotactile stimulator in conveying rich and contextual information (Hayward 2008; Seifi and Maclean 2013; Miri et al. 2017). The high-quality tactile sensation can be achieved by adjusting multiple levels of controls allowed by vibrators (e.g., amplitude, intensity, waveform, etc.). Yet, the vibrotactile design space is really broad, interactive, and perceptually challenging (Seifi and Maclean 2013), as there is a large number of effective parameters, including vibrotactile physical parameters like frequency, amplitude, and envelope, temporal factors such as stimuli duration and pulse repetition rate, and spatial variables, for instance, body site and spacing between actuators (Choi and Kuchenbecker 2012). In addition, the effects of each of these engineering factors on affective perception can vary in function of others (Yoo et al. 2015). To address this problem, I supervised a master student project aimed to develop a flexible research platform allowing researchers to fine-tune vibrator parameters easily. We used the vibrator board presented in section 5.2.2.1, including 16 Texas Instruments DRV2605 vibrator drivers designed explicitly for haptic application. This driver was an excellent choice for us, as it is highly versatile and offers wide range of features, such as control of both ERM and LRA vibrators, open-loop frequency control for LRA, haptic waveform library (including over 100 licensed effects from Immersion for ERM and LRA, which eliminates the need to design haptics waveforms), and waveform control through various inputs. A customized GUI was implemented in the Qt platform (free and open-source platform to create GUI), which allows us to easily modify physical properties of vibrotactile actuators, including intensity, frequency, effect type (according to the haptic library list), stimulus duration, and stimulus onset asynchrony (see Figure 6:1). This platform was also used to design and fine-tune the tactile apparent movement used in Chapter 4.

6.2.2.2 Further improvements of CognoVest setup

Now that the functionality of simple on-off force actuators to provide human-like poking stimuli is proved, future work should use other types of linear servo actuators (e.g., voice coil motor), which provide proportional force stimulations to better simulate the gradual speed/force profile of finger poking. As a sensing device, the Geomagic Touch Device can detect incremental action of poking (speed and force), proportional force stimulators could provide a more convincing feeling and likely result in higher bodily illusions. Furthermore, the mechanically distance adjustable boxes can be automatized by using a combination of linear actuators and pressure sensors, allowing to uniformly adjust solenoid distance from the body in a more precise and efficient manner. This also eases the handling procedure for the researcher and allows the device to be donned and operated by an unsupervised user. However, any further improvements of setup should consider the user comfort and portability criteria by choosing light-weight electronic components and actuators. Finally, I note that our robotic system's lead part, non-wearable in the present system, could be made wearable by integrating standard state-of-the-art motion-sensing technology and a finger-based tactile display. This would make our system fully portable and wearable, paving the way to developing wearable haptic systems able to administer touch and induce bodily illusions under dynamic conditions and in real-life settings.

6.2.3 Wearable therapeutic device to down-regulate PH

According to reports in clinical populations, PH is experienced by over 40% of patients with schizophrenia and PD, mainly as early motor deficits symptoms (Fénelon et al. 2011; Llorca et al. 2016). Hallucination and particularly PH are associated with negative clinical symptoms such as psychosis, depression, early home placement, higher mortality, and dementia (Fénelon et al. 2000; Fénelon et al. 2011; Kataoka and Ueno 2015). While there are many treatment options for the motor symptoms in PD (and beyond), hallucination treatment is limited and still requires novel solutions. Recent studies from our lab have investigated the neural mechanism of robot-induced PH in healthy individuals using fMRI compatible robot (Bernasconi et al. 2020) and link that to lesions observed in neurological patients with focal brain damage associated with PH (Bernasconi et al. 2020), suggesting that both involve the similar brain mechanism. Likely, in the same way that developed setups can trick the brain into creating an alien presence, they could also train the psychotic brain to relearn the difference between self and others. In this context, researchers are interested in developing a therapeutic device that can down-regulate or reduce psychotic symptoms in actual patients. My colleagues at LNCO took the first step to control activity within the brain network, specifically associated with hallucinatory states, using real-time neurofeedback. Such results would be potentially used to control subjective mental conditions of PH and other relevant illusory states in psychosis (Dhanis et al., in preparation). Given that PH may often occur at a particular time and in specific environments (Fénelon et al. 2011), the ideal therapeutic device should be a wearable garment that patients could use either in the hospital for rehabilitation programs or at home or in any other environment during which PH occurs.

CognoVest was the first attempt to have the portable and wearable device to modulate self-other distinction and pave the way for future portable anti-hallucinatory therapeutic devices.

6.3 Step-related, remapped feedback on the torso modulate walking agency

6.3.1 Summary of scientific contributions

"Actions are critical steps in the interaction between the self and the external milieu" (Jeannerod, 2007). Previous work has shown that the SoA can be influenced by manipulating perceptual and sensorimotor cues during different phases of action execution (Fourneret and Jeannerod 1998; Frith et al. 2000; Knoblich and Kircher 2004; Sato and Yasuda 2005; Farrer et al. 2008). The sense of touch is the most fundamental, immediate consequence of the majority of human movements. Although the integration of audio-visual feedback into the sensorimotor control has been widely investigated for both body parts (Nielsen 1963; Franck et al. 2001; van den Bos and Jeannerod 2002; Daprati and Sirigu 2002; Farrer et al. 2003; Knoblich and Kircher 2004; Posada et al. 2007; Farrer et al. 2008; Shimada et al. 2010; Salomon et al. 2011) or full-body (Menzer et al. 2010; Kannape and Blanke 2013) movements, to the best of our knowledge, there is no individual study investigating the effect of tactile action consequence on the SoA and the accompanying motor adaptation. This is because the spatiotemporal manipulation of the actual sense of touch is not technically possible. In Study 3 (Chapter 4), I tackled this issue using the tactile remapping technique, which aims to reproduce tactile action consequence on a different body part, in our case, participants' back. I also aimed to investigate gait movements that, due to involving the whole body's movements, lead to explore the fundamental aspect of the global bodily self (Menzer et al. 2010). To do so, I employed a fully wearable biofeedback system to investigate walking agency via temporal manipulation of step-related, remapped tactile feedback presented on the participants' back during free walking. For the first time, I demonstrated that delayed remapped tactile feedback could influence the SoA for locomotion. Participants rated trials with small delays as well as trials with delays matching their stride-time as self-generated, similar to observations in analogous visual and auditory feedback studies. Feedback lateralization mattered as temporally synchronous trials, but left-right reversed were not attributed to the ongoing movement. I also found the temporal SoA threshold of ~378.4 ms (including intrinsic delay of 60 ms) for tactile gait awareness. The temporal threshold for tactile gait agency was much higher than the temporal acuity of the skin (~50 ms), indicating that our study was an awareness paradigm linked to the sense of agency. In addition, this observation is in line with earlier studies on intentional binding or those that asked participants to judge delays for audio-motor and visuomotor awareness paradigms (both body parts movements and gait awareness paradigms) where the observed thresholds were way above perceptual discrimination thresholds (Fourneret and Jeannerod 1998; Franck et al. 2001; Sato and Yasuda 2005; Repp 2006; Repp and Knoblich 2007; Sato 2008; Shimada et al. 2010; Kannape and Blanke 2013; Suzuki et al. 2019). Extending the finding of the earlier studies on the visual and auditory action consequence (Menzer et al. 2010; Kannape and Blanke 2013) to the tactile one, I suggest that the SoA threshold is rather independent of the sensory threshold, the type of movements, and the sensory modality tested. These findings confirm that a common and super-model neural mechanism is responsible for tactile, auditory, and visual action monitoring.

Nevertheless, the temporal threshold for remapped tactile gait awareness (378 ms) was relatively higher and noisier (i.e., higher intersubjective variability; SD = 239 ms) compared to those reported in the audio (~200 ms; (Menzer et al. 2010)) and visual (~210 ms; (Kannape and Blanke 2013)) walking SoA paradigms. This is probably because in our paradigm, participants perceived both remapped and natural heel strike as a consequence of walking, resulting in noisier feedback, impairs the central monitoring mechanism. This may also explain the observation that I did not find a systematic change in participants' stride time influenced by the delayed remapped tactile feedback, as reported in previous gait studies. The cognitive load of perceiving the second task also plays a role. To address these issues, one possible solution could be exposing participants to a longer training (for instance, in the course of weeks) before the main task, which, as previously shown it improves the performance for sensorimotor learning tasks (Shams and Seitz 2008; Proulx et al. 2012).

6.3.2 Relevance for neurorehabilitation

Altogether, Study 3 (Chapter 4) demonstrates that healthy participants have a strong SoA for remapped tactile "feetback" and highlights the importance of haptic perception in gait control and motor awareness in locomotion. These findings may have important implications for enhancing gait awareness in patients with neuropathic, sensory, and hemiplegic gait problems who suffer from sensory (touch or proprioceptive) deficits in one foot or both feet. For instance, Ling et al. (2020) employed a haptic biofeedback system that provides the foot pressure status of a paralyzed foot of hemi-paraplegic patients, in terms of discrete vibration, onto the back. They reported significant improvement for the ankle push-off, although patients needed to monitor the discrete vibratory pattern on their back. We believe that substituting heel-strike with continuous and concurrent vibrotactile sensation as in the current "FeetBack" system may provide a more realistic sensation, which may further enhance the gait performance in different patient populations while reducing the need for visual gait monitoring. In addition, our setup could be used as a sensory substitution system for neuroprosthetics to improve the prosthesis' functionality by providing bidirectional sensorimotor information. Patients with lower limb amputation often compensate for the lack of proprioceptive information by continually monitoring their prosthesis with their eyes, which entails a significant cognitive burden (Crea et al. 2017). Previous studies that used simple, gait phase-specific vibrotactile feedback presented on the thigh or forearm of amputees demonstrated considerable improvement in walking autonomy and gait temporal symmetry (Sharma et al. 2014; Crea et al. 2017; Lauretti et al. 2017). Our technique reveals a clear advantage over previous haptic-based gait biofeedback systems as it provides real-time feedback during the gait cycle on the torso as a passive body part, allowing users to use their active body parts such as hand, leg, feet, etc. for daily activities. Finally, the FeetBack system could also be used to improve gait characteristics in patients with neurological movement disorders, such as Parkinson's disease, where several studies already revealed benefits for different forms of gait feedback (Baram and Miller 2007; Baram and Lenger 2012; Baram et al. 2016).

6.3.3 Towards inducing "PH in locomotion" in healthy walkers

My colleagues at LNCO provided clinical evidence suggesting that PH in PD patients may happen when they are involved in repetitive and procedural locomotor activities such as walking, running, or cycling (Potheegadoo et al. in preparation). In this clinical study, they interviewed four patients diagnosed with PD who reported PH on a daily or weekly basis, mainly when they were walking, running or cycling alone outside their home. These patients, particularly, described that they had an impression of another agent (often shadowy and not very clear) following them (catching up or even overtaking, often, with the distance of 0-3 m behind them) which disappeared by stopping locomotor activities. These observations are comparable with findings of experimentally-induced PH in healthy and parkinsonian patients, assessed via robotically mediated sensorimotor conflicts (Blanke et al. 2014; Bernasconi et al. 2020). My colleagues, hence, argued that abnormal sensorimotor mechanisms related to gait in PD, like disclosure to robotic sensorimotor stimulation, could provoke the occurrence of PH (Potheegadoo et al. in preparation).

FeetBack experimental setup and the walking paradigm presented in this thesis could be used to investigate locomotion-related PH experience in healthy or clinical populations as it can provide real-time sensorimotor conflicts during locomotion. One possible experimental procedure to induce PH in locomotion could be conducting the same experiment as gait agency study (Chapter 4) but asking participants to rate the PH questionnaire at the end of each trial. In this way, we can examine if the somatosensory–motor conflict between the foot and torso can modulate the illusory feeling of experiencing someone behind, as it was previously shown for the hand-torso somatosensory-motor conflicts (Blanke et al. 2014). However, I would suggest exposing participants to a longer familiarization block (e.g., longer than 10 minutes walking while receiving real-time remapped tactile feedback) before completing the main experimental part and longer trial duration. The former helps participants get used to the remapped feedback, allowing them to rely more on the remapped feedback rather than their own actual foot rolling sensation on the ground. The latter would be needed as it takes some time for the sensorimotor mechanism to be disturbed.

Alternatively, foot-step related signals during locomotion is probably one of the evident sensory consequence of walking. Clinical data in neurological patients have supported this; for instance, one of the patients in (Potheegadoo et al. in preparation) had the impression of hearing footsteps coming from behind. I propose that a sensorimotor manipulation experiment to investigate PH in locomotion could also include auditory-motor conflict during walking. A similar paradigm has already been tested to investigate walking awareness in healthy walkers (Menzer et al. 2010). Considering the importance of somatosensory perception on the global aspect of BSC (Blanke 2012; Park and Blanke 2019), it seems interesting to design an experiment that includes both foot-falls sound and remapped feedback on the torso as a consequence of walking. For instance, it is possible to keep the remapped step-related tactile feedback synchronous with walking and only delay the footfall sounds. Future studies are required to investigate the possibility of inducing PH in locomotion by applying somatosensory-motor or auditory-motor conflicts during human locomotion.

6.4 Conclusion

Using a multidisciplinary approach including robotics, haptics and behavioral neuroscience, my thesis takes the first steps towards design, implementation, and verification of torso-worn tactile displays that investigate somatosensory perception and self-consciousness in healthy individuals. I prototyped two novel body-conforming torso-worn tactile interfaces, equipped with force (CognoVest) and vibrotactile (FeetBback) actuators, to provide well-perceived and ecologically valid tactile sensations on the lower thoracic region of the back. The findings of this thesis provide comprehensive knowledge on tactile spatial discrimination for dynamic mechanical stimulations. This knowledge can be used to formulate guidelines for the design of torso-based tactile displays, such as regarding tactile stimulation, garment design, arrangement of actuators on the back, and direction of stimulus presentation. The results of the experimental use-case with CognoVest that investigated the induction of PH in healthy individuals were promising and highlighted the importance of providing an ecologically valid sense of touch in experimental manipulation of BSC states. In addition, for the first time, I showed that tactile action consequence could modulate walking agency when presented in the form of remapped feedback delivered to the users' back. Outcomes of this thesis pave the way to develop future wearable haptic systems able to administer touch and induce bodily illusions under dynamic conditions and in real-life settings.

Chapter 7 Annexes

7.1 Qualitative experience of vibrotactile apparent motion

7.1.1 Overview

Vibrotactile displays have revealed their great potential in a variety of applications such as rehabilitation (Johnson and Higgins 2006), navigation (Ertan et al. 1998), affective touch (Lemmens et al. 2009), etc. In many applications, researchers require to deploy numerous vibrators to provide rich and informative touch sensations, leading to a complex and costly system. However, research into the tactile illusion phenomenon offers comparably simple, technically, and computationally economical ways to address this problem (Petkova and Ehrsson 2008; Pittera et al. 2017; Hoffmann et al. 2018a). The principal idea of tactile illusion is providing a convincing tactile sensation without rendering every single part of the phenomenon (Israr and Poupyrev 2011b). In other words, the stimulation point is perceived as moving continuously from one position to another, although the stimulating physical points are discrete. Such sparse actuation reduces the cost, size, weight, and design complexity. Therefore, vibrotactile apparent motion (VAM) has gained considerable attention in the literature. For instance, the directional tactile sensation produced via VAM can be used in various applications such as navigation (Israr et al. 2012), sensory substitution systems (Israr et al. 2012), contacts in virtual environments (Israr et al. 2012), etc.

VAM can be invoked by activating two or more tactors, sequentially with specific timing parameters. Yet, depending on the combination of control parameters, the perceived sensation can be different (Israr and Poupyrev 2011b). The authors in [35] (Sherrick and Rogers 1966) demonstrated that the variables producing robust apparent tactile motion are the duration of stimuli (DoS) and the stimulus onset asynchrony (SOA). Israr and Poupyrev (2011b) also conducted a psychometric study in which they measured the control space of apparent tactile motion between two vibrations on the forearm and on the back. They estimated SOA thresholds between no motion and motion (lower thresholds) and between discrete and continuous motion (upper thresholds). They thus reported the midpoint between the upper and lower thresholds as the optimal SOA for generating continuous apparent motion at the test duration. While prior studies on VAM were only focusing on whether the illusion was happening or not (two-alternative forced-choice), no one investigated the qualitative experience of VAM. As part of my Ph.D., I conducted a small pilot study with five healthy volunteers investigating the VAM experience quality, i.e., how "continuous" or "smooth" it was felt.

7.1.2 Experimental design and statistical analysis

A with-in participants' design experiment was conducted by considering the duration of stimuli (DoS; 100 ms, 150 ms, 200 ms) and SOA (50ms, 100ms, 150ms). We also added an intensity block to investigate the effect of intensity while DoS and SOA were fixed (DoS = 150 ms, SOA = 95 ms). DoS and SOA values were chosen in the range suggested by Israr and Poupyrev (2011b) to provide continuous VAM sensations. We also add one discrete pattern as catch trial. Overall, there were 14 different conditions (or patterns), each presented 15 times resulting in 210 trials. After each trial, subjects had to rate their feeling on a Likert scale from 0 (totally disagree) to 6 (totally agree) to whether they "*clearly felt a continuous tactile sensation on their back.*"

We used the GUI presented in 6.2.2 to create and save a set of 143 patterns. The vibrotactile vest used in FeetBack system (see Figure 4:1), which involved two vertical arrays of vibrators (each including four vibrators), was employed to present these patterns on the users' back. Trials were randomly presented on the left or right (half-half). During the whole experiment, subjects were standing in front of a computer, wearing headphones that played white noise to cover the noise of the vibrations. After each trial, the custom program running on the computer prompted them to rate the last stimuli, and the next one started once the answer was entered using a numeric keyboard.

Prior to the main experiment, participants were trained about the experimental procedure. Additionally, we ensured that they understood what was meant by "continuous" or "discrete" via showing a few examples of discrete and continuous stimulations on their back. We then helped participants to wear the vest, and we make sure that it was sufficiently tight on their torso. Next, participants completed a short training session of 20 trials to get familiar with the task and the system. The experiment flow is shown in Figure 7:1. Trials were presented in 4 blocks (in random order), starting with intensity block and following with 3 SOA blocks each at a specific DoS. In total, the experiment lasts for around 20 minutes.

Participants' scores were standardized (Standardized Score = $\frac{score-avg(score)}{std(score)}$) to avoid any effect of personal bias. As data were not normally distributed (test with one-sample Kolmogorov-Smirnov), Kruskal-Wallis tests were used to see whether there is a significant effect for intensity, DoS, and SOA. Posthoc analyses were performed using multiple comparison Tukey-Kramer to investigate the significant difference between various levels.

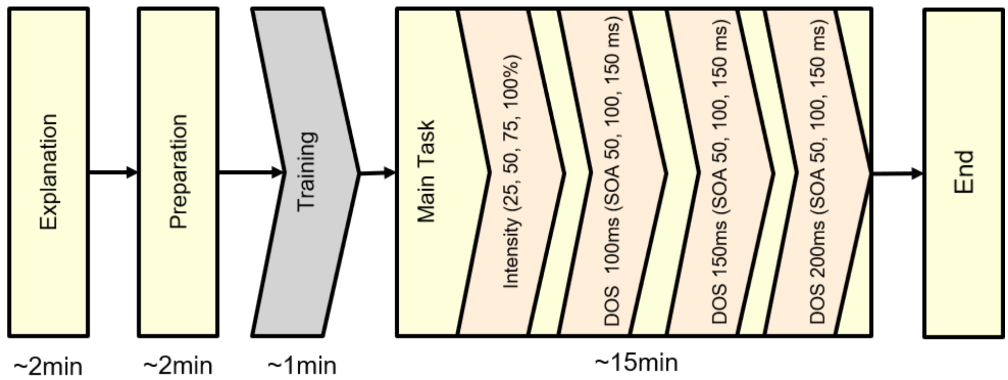

Figure 7:1 Experimental flow for the qualitative experience of the VAM.

7.1.3 Results

The Figure 7:2 represents the average participants' ratings to the qualitative experience of VAM question as a function of different levels of intensity. We did not find any significant effect of intensity on the qualitative experience of VAM ($\chi2 = 1.7$, $p = 0.08$). These findings are showing that the intensity at which VAM gets presented does not have any effect on how smooth it can be felt.

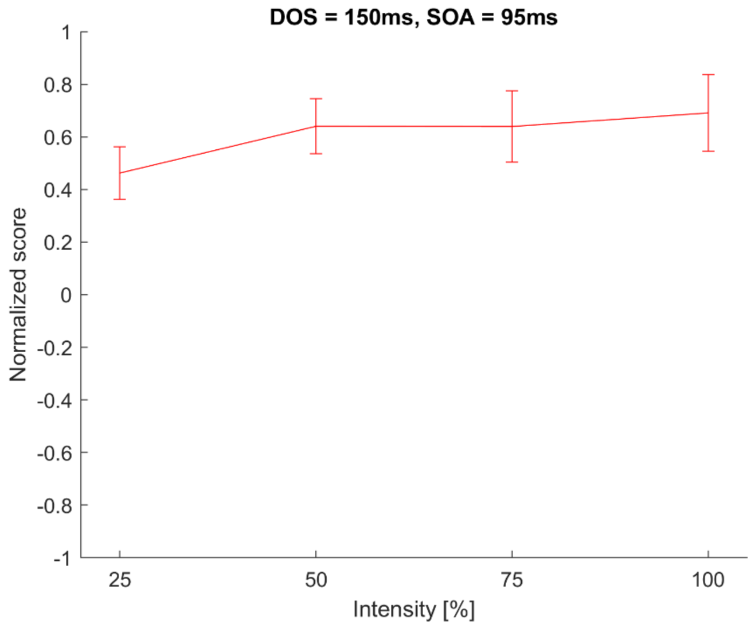

Figure 7:2 The effect of intensity on the qualitative experience of the VAM

Participants ratings to qualitative experience of touch do not change as a function of intensity.

The Figure 7:3 shows the variation of the qualitative experience of VAM as a function of the DOS and SOA. Our results showed that the qualitative experience of touch is significantly depends on the both SOA and DoS with stronger effect for SOA (SOA: $\chi2 = 14.9$, $p < 0.01$, DoS: $\chi2 = 9.27$, $p=0.01$). As it can be seen in Fig.24, for DoS of 100ms the results for SOA of 150ms is significantly lower. This can be easily explained by the fact that these timing values are clearly outside of the range were apparent motion is felt as measured in literature (Israr and Poupyrev 2011b).

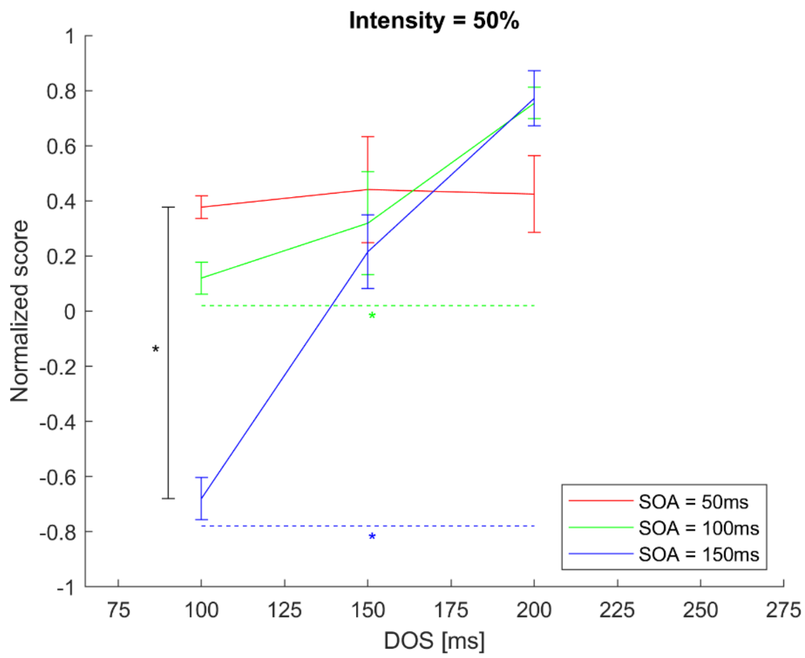

Figure 7:3 The qualitative experience of the VAM score as a function of SOA and DoS.

7.2 Investigating the effect of gender and torso sizing on the tactile spatial discrimination

7.2.1 Statistical analysis

We investigated the effects of the fitting and gender variabilities on the DD and PL performance results. Participants' torso sizings (i.e., torso length, waist circumference, and chest circumference) were measured before the experiment (explained in the procedure section). For the PL task, the overall PL accuracy was considered as the response. A linear mixed-effect model was used to assess the significant difference between the two stimulators by considering the stimulator type as a fixed factor, gender as a control variable, torso length, chest circumstances, and waist circumference as covariate and subject as a random effect.

For the DD task, the overall DD accuracy was considered as the response. A linear mixed-effect model was also used to assess the significant difference between the two stimulators by considering the stimulator type as a fixed effect, gender as a control variable, and torso length, chest circumstances, and waist circumference as covariate variables and subject as a random effect.

7.2.2 Results

Statistical analysis showed that the PL accuracy was significantly higher with vibrotactile stimulators ($F(1, 33) = 8.55$, $p < 0.01$). Furthermore, we found a significant effect for the chest circumference ($F(1, 29) = 6.98$, $p = 0.01$); suggesting that the PL accuracy improved by increasing the participants' chest circumference (see Fig. 1). This observation most likely further supports our argument that participants used torso edge as reference points with which stimuli can be associated. However, the effect of other covariant factors was insignificant (both $p > 0.2$). We also did not find any significant effect for the gender on the PL results ($F(1, 29) = 0.09$, $p = 0.77$).

For the DD task, statistical analysis revelaed no significant effect of the stimulator type ($F(1,33) = 2.81$, $p =0.1$). There was no significant effect for covarient factors (Torso length: $F(1, 29) = 3.84$, $p = 0.06$; waist circumference: $F(1, 29) = 0.11$, $p = 0.73$; chest : $F(1, 29) = 2.85$, $p =0.1$) neither for the gender factor ($F(1, 29) = 0.12$, $p =0.73$).

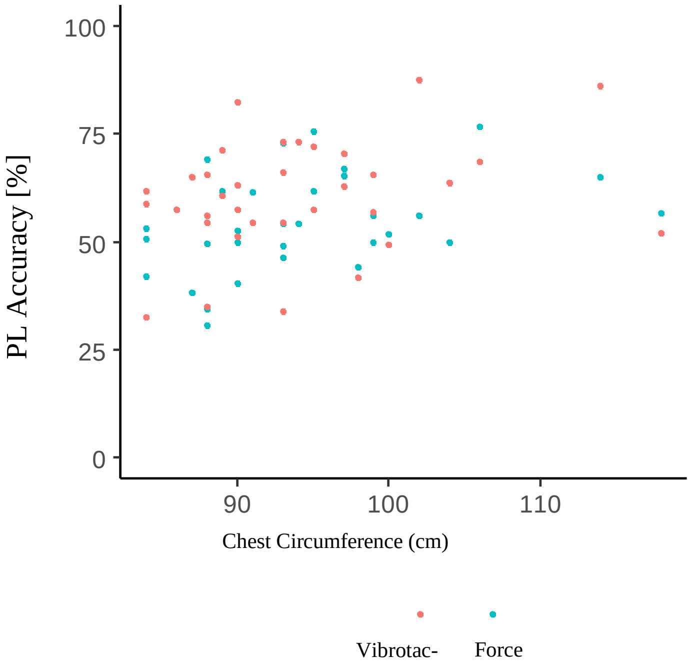

Figure 7:4 PL accuracy as a function of the chest circumference (cm).

PL accuracy as a function of chest circumference (cm). Each point shows the average PL accuracy of one participant with one of the vests.

7.3 Visual enhancement of touch on the back

7.3.1 Method

7.3.1.1 Participants

Twelve naïve healthy individuals (age 20–30, mean 23.8, 7 females), reporting normal or corrected-to-normal vision and normal touch, were recruited for the experiment. All participants were right-handed (assessed via a 12-item Edinburgh Handedness Inventory (Oldfield and others 1971)). They provided informed consent and ethical approval granted by the cantonal ethics committee in Geneva. All participants received a compensation of 20 CHF/hour for their commitment to the experiment.

7.3.1.2 Apparatus

The vibrotactile vest consists of a vertical array of vibrators (12 ERM vibrators similar to the ones used in chapter 5) with an inter-tactor distance of 15 mm, placed on the spine. The same conntroller board as Chapter 5 was used to control ERMs which connects via Bluetooth to a host PC. ERM vibrators are attached to a 20mm-thick foam using a glued-on snaps. The vibrator foam was fixed to a fully-elastic, posture-corrector brace, similar to the one used in the Chapter 4. An HD webcam (C920 HD Pro Webcam), fixed on a camera stand, was used to film participants' back. Visual information were displayed via Oculus Rift S headsets which was connected to the host PC.

7.3.1.3 Experimental design

A within-participants repeated measures design was used by considering inter-tactor distance (four levels including 15 mm, 30 mm, 45 mm, and 60 mm plus 0 mm as the catch trial) and visual condition (three levels: Body, No-Body, Blind) as experimental factors. Participants were asked to complete the vibrotactile direction discrimination task, while are exposed to one of the visual conditions.

7.3.1.4 Procedure

The experimenter helped participants to wear the torso-worn vibrotactile display and guided them to sit on a stoll chair placed in front of the camera. To ensure that if participants have uniform sensations over all actuators, participants were asked to complete a calibration task prior to the main experiment. In this task they received one single stimulus at a time and they had to answer on a 6-point Likert scale, how strong was the tactile perception (from 1 = barely noticeable, to 6 = very clear). During the calibration, participant were open-eyes and no visual information was provided. For the main part of the experiment, participants were asked to wear the head mounted display which showed real-time view of their back (filmed via a camera placed behind them) in Body condition, a picture of the same scene but only showing a cross located at their location (at the level of the torso) in No-body condition and a black picture in blind condition. They were randomly assigned in a balanced way to the first experimental session with one of the three visual conditions (Body, No-body, Blind). They were required to complete vibrotactile direction discrimination task. In each trial, participants received two consecutive stimuli, and they were asked to determine whether the second was above or below the first one, or whether it happened at the same location (3-alternative forced choice, 3 AFC). The first stimulation was always started with one of actuators 4, 5, 6, and 7 and the location of the second actuator (at which distance and which direction) was randomly arranged.

Stimulations always started with actuators 4, 5, 6, or 7. The double activation of the same stimulators (0 mm) was considered as a catch trial. Participants responded via a standard numeric keypad with three marked buttons (see Figure 1.g) corresponding to the three possible response options, and the software recorded their responses. In each trial, stimulators were turned on for 250 ms with an inter-stimulus interval of 50 ms. The inter-trial interval was altered randomly in the range of 4000±250 ms. Each condition repeated around 10 times, except for the catch trial which repeated 8 times resulting in total 144 trials. To avoid fatigue, trials were presented in 6 blocks (two repetitions of each visual condition), and each block lasted 6 minutes (approximately). Each block started with a 30 sec of visual exposure. Participants were provided with 2-3 minutes between blocks, while keeping the head mounted camera. Participants completed a training session, similar to the main task but shorter (around 2 minutes). During the training session, participants learned how to respond to tactile stimulation on their back with the corresponding keypad (see Figure 2).

Figure 7:5 Experimental setup for VET experiment.

Participant was wearing the vibrotactile interface and sit on a stoll chair, back to the camera. He had a HMD which showed different visual conditions. There was a numeric keypad on the table for capturing their responses. Participant was asked to put his chin in the chin rest in order to avoid any extra movements and probably potential fatigue.

7.3.1.5 Statistical analysis

All analyses were performed in R (R Core Team 2020) running in the RStudio environment (RStudio Team 2020). All post-hoc comparisons were conducted using the Tukey HSD test. In all analyses, significance was reported for p-values smaller than 0.05.

A linear mixed-effect model was used to analyze data from calibration experiment, by considering actuator number as fixed effect and subject as a random effect.

Average accuracies (in percentage) of each distance and visual condition were considered as the response. A linear mixed-effect model was performed to assess the effect of the visual condition on the accuracy, by considering inter-tactor distance, visual condition and interactions between them as fixed effects and the subject as a random effect, accounting for between-subject variability. The chance level for vibrotactile DD tasks were estimated at 33.3% since there were 3 possible response types in each trial. One-sample t-tests were used to compare the average accuracy with the chance level.

In addition, we analyzed trial to trial variabilities in response, to see if we can find any superior effect for the vision of the body on the trials' response variabilities. We considered participants' binary response (true/false) as the response. A linear mixed-effect model was performed by considering inter-tactor distance, visual condition and trial number, and interactions between them as fixed effects and the subject as a random effect, accounting for between-subject variabilities.

We also measured participants response time. A linear mixed-effect model was performed to assess the effect of visual information on the response time by considering inter-tactor distance and visual condition, and interactions between them as fixed effects and the subject as a random effect, accounting for between-subject variability.

7.3.2 Results and discussion

The average rating in the calibration task was 4.9 ± 0.28 (in scale 1 to 6; see Figure 7:6). We found a significant effect of actuator number on the participants rating in the calibration task ($F(11,553) = 4.38$, $p < 0.001$). However, postdoc analyses only showed significant difference for actuators 12-11 and 12-1 (1 and 12 are the uppermost and lowest actuators in the array, respectively; 12-11: $t(553) = 5.41$, $p<0.001$; 12-11 : $t(553) = 4.87$, $p<0.001$; other $p> 0.1$) which could be due to fitting problem at the lowest end of the array. These results demonstrate that vibrotactile interface used in this study can provide fairly uniform tactile sensations on the back.

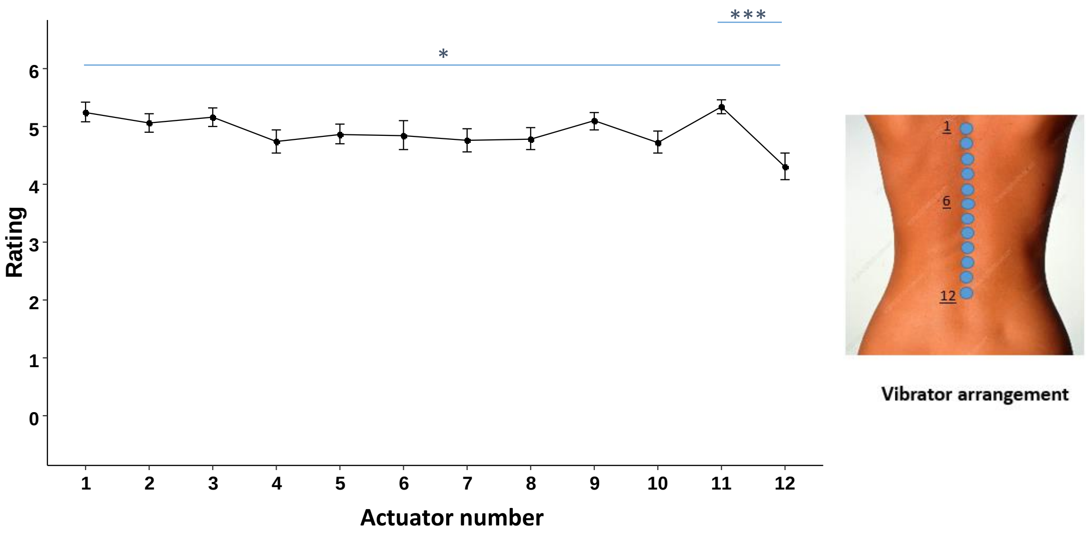

Figure 7:6 Calibration results.

Left Right plot shows the result of calibration test. Participants received one single stimuli at a time and they had to rate the intensity of stimuli in scale 1 (barely perceivable) to 6 (very clear). Right plot represents the arrangement of vibrators on the participants back and their numbering.

The overall accuracy as a function of inter-tactor distance and visual condition are shown in the Figure 7:7. Participants performance in all conditions were significantly higher than the chance level (all $p>0.1$). We found a significant effect of inter-tactor distance (F(4, 154) = 97.04, p<0.01) on the overall accuracy; however, the effect of visual condition (F(2, 154)=0.61, p=0.54) and interaction terms were not significant (F(4, 154)=0.17, p=0.9).

Investigating the trial to trial variabilities in response, we only found the significant effect of the inter-tactor distance (F(4, 4714.5)=55.2, p<0.01) on the participants' response variabilities (other p>0.2).

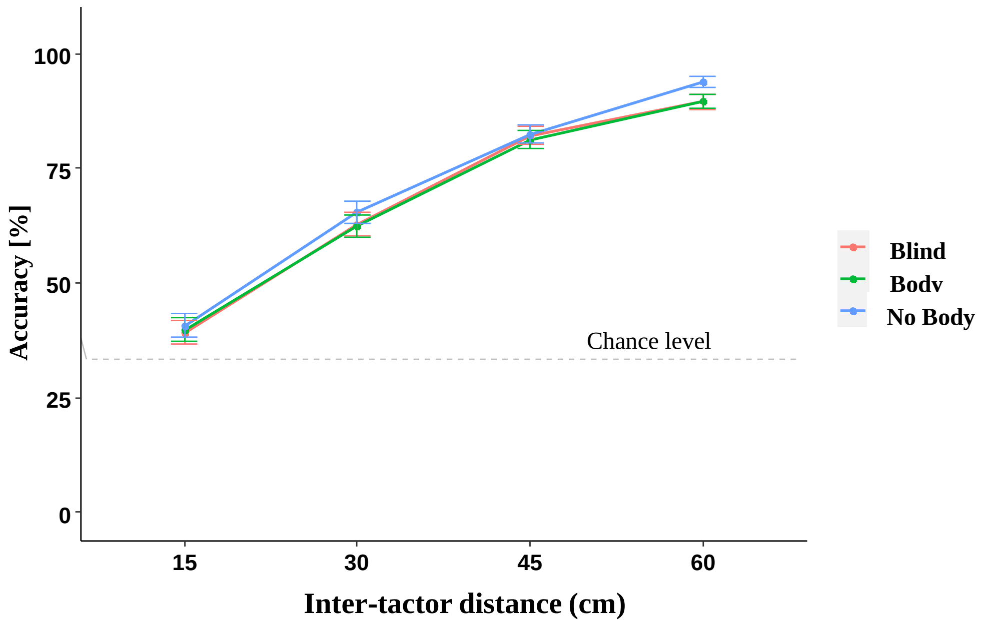

Figure 7:7 Average accuracy as a function of inter-tactor distance and visual condition.

Vibrotactile discrimination accuracy enhances as inter-tactor distance increases; however, participants performed very similarly in different visual conditions. Error bars show the standard error of the mean.

We also investigate the VET effect on the response time. Our statistical analysis showed only significant effect for the inter-tactor distance (F(4, 154) = 13.9, p<0.001), with significantly shorter response time for bigger inter-tactor distance. However, the effect of visual condition (F(2, 154) = 1.3, p=0.27) and interaction terms (F(8, 154) = 0.4, p=0.9) were insignificant. We further investigate if the visual condition can influence on the response time variabilities. Again, we only found significant effect for the inter-tactor distance (F(4, 154) = 13.15, p<0.001), while other effects were insignificant (p>0.1).

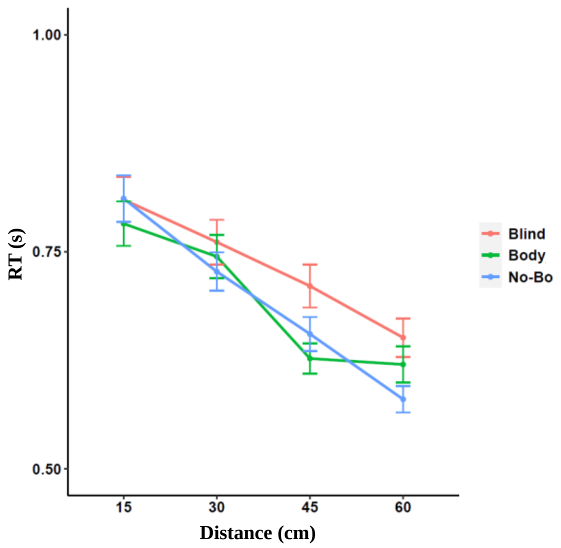

Figure 7:8 Response time as a function of inter-tactor distance and visual condition.

Participants reaction time decreases as the inter-tactor distance increases. Error bars show the standard error of the mean.

Chapter 8 References

Aarts H, Custers R, Wegner DM (2005) On the inference of personal authorship: enhancing experienced agency by priming effect information. Conscious Cogn 14:439–58.

Afzal MR, Oh M-K, Lee C-H, et al. (2015) A portable gait asymmetry rehabilitation system for individuals with stroke using a vibrotactile feedback. BioMed research international 2015:

Arafsha F, Alam KM, El Saddik A (2015) Design and development of a user centric affective haptic jacket. Multimedia Tools and Applications 74:3035–3052.

Arafsha F, Alam KM, El Saddik A (2012) EmoJacket: Consumer centric wearable affective jacket to enhance emotional immersion. 2012 international conference on innovations in information technology (IIT). pp 350–355

Armstrong DM (1988) The supraspinal control of mammalian locomotion. The Journal of physiology 405:1.

Arzy S, Seeck M, Ortigue S, et al. (2006) Induction of an illusory shadow person. Nature 443:287–287.

Aspell J, Lenggenhager B, Blanke O (2011) Multisensory perception and bodily self-consciousness: from out-of body to inside-body experience. The neural bases of multisensory processes

Azadi M, Jones L (2013) Identification of vibrotactile patterns: Building blocks for tactons. 2013 World Haptics Conference (WHC). pp 347–352

Baram Y, Aharon-Peretz J, Badarny S, et al. (2016) Closed-loop auditory feedback for the improvement of gait in patients with Parkinson’s disease. Journal of the neurological sciences 363:104–106.

Baram Y, Lenger R (2012) Gait improvement in patients with cerebral palsy by visual and auditory feedback. Neuromodulation: Technology at the Neural Interface 15:48–52.

Baram Y, Miller A (2007) Auditory feedback control for improvement of gait in patients with Multiple Sclerosis. Journal of the neurological sciences 254:90–94.

Barone VJ, Yuen MC, Kramer-Boniglio R, Sienko KH (2019) Sensory garments with vibrotactile feedback for monitoring and informing seated posture. 2019 2nd IEEE International Conference on Soft Robotics (RoboSoft). pp 391–397

Bernasconi F, Blondiaux E, Potheegadoo J, et al. (2020) Sensorimotor hallucinations in Parkinson's disease.

Biraben A, Taussig D, Thomas P, et al. (2001) Fear as the main feature of epileptic seizures. Journal of Neurology, Neurosurgery \& Psychiatry 70:186–191.

Blakemore S-J, Wolpert D, Frith C (2000) Why can't you tickle yourself? Neuroreport 11:R11–R16.

Blakemore S-J, Wolpert DM, Frith CD (2002) Abnormalities in the awareness of action. Trends in cognitive sciences 6:237–242.

Blanc Y, Balmer C, Landis T, Vingerhoets F (1999) Temporal parameters and patterns of the foot roll over during walking: normative data for healthy adults. Gait \& posture 10:97–108.

Blanke O (2012) Multisensory brain mechanisms of bodily self-consciousness. Nature Reviews Neuroscience 13:556.

Blanke O, Arzy S, Landis T (2008) Illusory reduplications of the human body and self. Handbook of clinical neurology 88:429–458.

Blanke O, Metzinger T (2009) Full-body illusions and minimal phenomenal selfhood. Trends in cognitive sciences 13:7–13.

Blanke O, Pozeg P, Hara M, et al. (2014) Neurological and robot-controlled induction of an apparition. Current Biology 24:2681–2686.

Blanke O, Slater M, Serino A (2015) Behavioral, neural, and computational principles of bodily self-consciousness. Neuron 88:145–166.

Bolanowski SJ, Gescheider GA, Verrillo RT (1994) Hairy skin: psychophysical channels and their physiological substrates. Somatosensory \& motor research 11:279–290.

Bonanni L, Vaucelle C, Lieberman J, Zuckerman O (2006) TapTap: a haptic wearable for asynchronous distributed touch therapy. CHI'06 extended abstracts on Human factors in computing systems. pp 580–585

Boring EG (1942) Sensation and perception in the history of experimental psychology.

Van den Bos E, Jeannerod M (2002) Sense of body and sense of action both contribute to self-recognition. Cognition 85:177–87.

Botvinick M, Cohen J (1998) Rubber hands "feel"touch that eyes see. Nature 391:756–756.

Brugger P, Regard M, Landis T (1996) Unilaterally Felt" Presences": The Neuropsychiatry of One's Invisible Doppelganger. Cognitive and Behavioral Neurology 9:114–122.

Brugger P, Regard M, Landis T, Oelz O (1999) Hallucinatory experiences in extreme-altitude climbers. Neuropsychiatry Neuropsychology and Behavioral Neurology 12:67–71.

Buimer HP, Bittner M, Kostelijk T, et al. (2018) Conveying facial expressions to blind and visually impaired persons through a wearable vibrotactile device. PloS one 13:e0194737. doi: https://doi.org/10.1371/journal.pone.0194737

Burnham KP, Anderson DR (2004) Multimodel inference: understanding AIC and BIC in model selection. Sociological methods \& research 33:261–304.

Burtt HE (1917) Tactual illusions of movement. Journal of Experimental Psychology 2:371.

Cao S, Li X, Yan X, et al. (2018) Overview of Wearable Haptic Force Feedback Devices and A Further Discussion On The Actuation Systems. 2018 IEEE 4th Information Technology and Mechatronics Engineering Conference (ITOEC). pp 314–319

Cardini F, Longo MR, Driver J, Haggard P (2012) Rapid enhancement of touch from non-informative vision of the hand. Neuropsychologia 50:1954–1960.

Catley MJ, Tabor A, Miegel RG, et al. (2014) Show me the skin! Does seeing the back enhance tactile acuity at the back? Manual therapy 19:461–466.

Cha J, Eid M, Barghout A, et al. (2009) HugMe: synchronous haptic teleconferencing. Proceedings of the 17th ACM international conference on Multimedia. pp 1135–1136

Chan D, Rossor MN (2002) "—but who is that on the other side of you?" Extracampine hallucinations revisited. The Lancet 360:2064–2066.

Chen H-Y, Santos J, Graves M, et al. (2008) Tactor localization at the wrist. International Conference on Human Haptic Sensing and Touch Enabled Computer Applications. pp 209–218

Choi S, Kuchenbecker KJ (2012) Vibrotactile display: Perception, technology, and applications. Proceedings of the IEEE 101:2093–2104.

Cholewiak RW (1999) The perception of tactile distance: Influences of body site, space, and time. Perception 28:851–875.

Cholewiak RW, Brill JC, Schwab A (2004) Vibrotactile localization on the abdomen: effects of place and space. Percept Psychophys 66:970–87.

Cholewiak RW, Collins AA (2003) Vibrotactile localization on the arm: Effects of place, space, and age. Perception & psychophysics 65:1058–1077.

Cholewiak RW, McGrath C (2005) Vibrotactile targeting in multimodal systems: Accuracy and interaction. 2006 14th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. pp 413–420

Cody FWJ, Garside RAD, Lloyd D, Poliakoff E (2008) Tactile spatial acuity varies with site and axis in the human upper limb. Neurosci Lett 433:103–8. doi: https://10.1016/j.neulet.2007.12.054

Cosgun A, Sisbot EA, Christensen HI (2014) Evaluation of rotational and directional vibration patterns on a tactile belt for guiding visually impaired people. 2014 IEEE Haptics Symposium (HAPTICS). pp 367–370

Craig JC, Johnson KO (2000) The two-point threshold: Not a measure of tactile spatial resolution. Current Directions in Psychological Science 9:29–32.

Crea S, Edin BB, Knaepen K, et al. (2017) Time-discrete vibrotactile feedback contributes to improved gait symmetry in patients with lower limb amputations: case series. Physical therapy 97:198–207.

Daprati E, Franck N, Georgieff N, et al. (1997) Looking for the agent: an investigation into consciousness of action and self-consciousness in schizophrenic patients. Cognition 65:71–86.

Daprati E, Sirigu A (2002) Laterality effects on motor awareness. Neuropsychologia 40:1379–86.

Delazio A, Nakagaki K, Klatzky RL, et al. (2018) Force jacket: Pneumatically-actuated jacket for embodied haptic experiences. Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems. pp 1–12

Diederich NJ, Fénelon G, Stebbins G, Goetz CG (2009) Hallucinations in Parkinson disease. Nat Rev Neurol 5:331–42. doi: 10.1038/nrneurol.2009.62

Dienes Z (2014) Using Bayes to get the most out of non-significant results. Frontiers in psychology 5:781.

Dummer T, Picot-Annand A, Neal T, Moore C (2009) Movement and the rubber hand illusion. Perception 38:271–280.

Ehrsson HH (2007) The experimental induction of out-of-body experiences. Science 317:1048–1048.

Ehrsson HH (2012) The concept of body ownership and its relation to multisensory integration. The New Handbook of Multisensory Process

Ehrsson HH, Holmes NP, Passingham RE (2005) Touching a rubber hand: feeling of body ownership is associated with activity in multisensory brain areas. J Neurosci 25:10564–73.

Van Erp JB (2005a) Vibrotactile spatial acuity on the torso: effects of location and timing parameters. First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics Conference. pp 80–85

Van Erp JB (2007) Tactile displays for navigation and orientation: perception and behaviour. Dissertation, Utrecht University

Van Erp JB (2005b) Presenting directions with a vibrotactile torso display. Ergonomics 48:302–313.

Van Erp JB, Veltman A, van Veen HA (2003) A tactile cockpit instrument to support altitude control. Proceedings of the Human Factors and Ergonomics Society Annual Meeting. pp 114–118

Van Erp JBHAV, Jansen C, Dobbins T (2005) Waypoint navigation with a vibrotactile waist belt. ACM Transactions on Applied Perception (TAP) 2:106–117.

Ertan S, Lee C, Willets A, et al. (1998) A wearable haptic navigation guidance system. Digest of Papers. Second International Symposium on Wearable Computers (Cat. No. 98EX215). pp 164–165

Eskildsen P, Morris A, Collins CC, Bach-y-Rita P (1969) Simultaneous and successive cutaneous two-point thresholds for vibration. Psychonomic Science 14:146–147.

Fadaei JA, Jeanmonod K, Kannape OA, et al. (2021) Cogno-Vest: A Torso-Worn, Force Display to Experimentally Induce Specific Hallucinations and Related Bodily Sensations. IEEE Transactions on Cognitive and Developmental Systems

Farrer C, Franck N, Georgieff N, et al. (2003) Modulating the experience of agency: a positron emission tomography study. Neuroimage 18:324–33.

Farrer C, Frey SH, Van Horn JD, et al. (2008) The angular gyrus computes action awareness representations. Cerebral cortex 18:254–261.

Fénelon G, Mahieux F, Huon R, Ziégler M (2000) Hallucinations in Parkinson's disease: prevalence, phenomenology and risk factors. Brain 123:733–745.

Fénelon G, Soulas T, De Langavant LC, et al. (2011) Feeling of presence in Parkinson's disease. J Neurol Neurosurg Psychiatry 82:1219–1224.

Fourneret P, Jeannerod M (1998) Limited conscious monitoring of motor performance in normal subjects. Neuropsychologia 36:1133–1140.

Franck N, Farrer C, Georgieff N, et al. (2001) Defective recognition of one's own actions in patients with schizophrenia. American Journal of Psychiatry 158:454–459.

Frith CD, Blakemore S-J, Wolpert DM (2000) Explaining the symptoms of schizophrenia: abnormalities in the awareness of action. Brain Research Reviews 31:357–363.

Frith CD, Done DJ (1989) Experiences of alien control in schizophrenia reflect a disorder in the central monitoring of action.

Gallagher S (2000) Philosophical conceptions of the self: implications for cognitive science. Trends in cognitive sciences 4:14–21.

Garcia-Valle G, Ferre M, Breñosa J, et al. (2016) Design and development of a multimodal vest for virtual immersion and guidance. International conference on human haptic sensing and touch enabled computer applications. pp 251–262

Garcia-Valle G, Ferre M, Breñosa J, Vargas D (2018) Evaluation of Presence in Virtual Environments: Haptic Vest and User's Haptic Skills. IEEE Access 6:7224–7233.

Geiger J (2009) The third man factor. Hachette Books

Gemperle F, Ota N, Siewiorek D (2001) Design of a wearable tactile display. Wearable Computers, 2001. Proceedings. Fifth International Symposium on. pp 5–12

Gescheider GA, Wright JH, Verrillo RT (2010) Information-processing channels in the tactile sensory system: A psychophysical and physiological analysis. Psychology press

Ghazanfar AA, Schroeder CE (2006) Is neocortex essentially multisensory? Trends Cogn Sci (Regul Ed) 10:278–85.

Gibson GO, Craig JC (2005) Tactile spatial sensitivity and anisotropy. Percept Psychophys 67:1061–79.

Gibson GO, Craig JC (2006) The effect of force and conformance on tactile intensive and spatial sensitivity. Experimental brain research 170:172–181.

Green BG (1982) The perception of distance and location for dual tactile pressures. Perception \& Psychophysics 31:315–323.

Grillner S, Wallen P (1985) Central pattern generators for locomotion, with special reference to vertebrates. Annual review of neuroscience 8:233–261.

Haggard P (2006) Just seeing you makes me feel better: interpersonal enhancement of touch. Social Neuroscience, 1:104–110.

Haggard P, Christakou A, Serino A (2007) Viewing the body modulates tactile receptive fields. Exp Brain Res 180:187–93.

Haggard P, Taylor-Clarke M, Kennett S (2003) Tactile perception, cortical representation and the bodily self. Current Biology 13:R170–R173.

Hara M, Rognini G, Evans N, et al. (2011) A novel approach to the manipulation of body-parts ownership using a bilateral master-slave system. Intelligent Robots and Systems (IROS), 2011 IEEE/RSJ International Conference on. pp 4664–4669

Hara M, Salomon R, van der Zwaag W, et al. (2014) A novel manipulation method of human body ownership using an fMRI-compatible master-slave system. Journal of neuroscience methods 235:25–34.

Harris JA, Arabzadeh E, Moore CA, Clifford CW (2007) Noninformative vision causes adaptive changes in tactile sensitivity. Journal of Neuroscience 27:7136–7140.

Hausdorff JM, Lowenthal J, Herman T, et al. (2007) Rhythmic auditory stimulation modulates gait variability in Parkinson's disease. European Journal of Neuroscience 26:2369–2375.

Hayward V (2008) A brief taxonomy of tactile illusions and demonstrations that can be done in a hardware store. Brain research bulletin 75:742–752.

Hoang I, Ranchet M, Derollepot R, et al. (2020) Measuring the Cognitive Workload During Dual-Task Walking in Young Adults: A Combination of Neurophysiological and Subjective Measures. Frontiers in Human Neuroscience 14:511.

Hoffmann R, Brinkhuis MA, Kristjánsson Á, Unnthorsson R (2018a) Introducing a New Haptic Illusion to Increase the Perceived Resolution of Tactile Displays. CHIRA. pp 45–53

Hoffmann R, Valgeirsdóttir VV, Jóhannesson ÓI, et al. (2018b) Measuring relative vibrotactile spatial acuity: effects of tactor type, anchor points and tactile anisotropy. Experimental brain research 236:3405–3416.

Huang D-Y, Guo R, Gong J, et al. (2017) RetroShape: Leveraging rear-surface shape displays for 2.5 D interaction on smartwatches. Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology. pp 539–551

Ionta S, Heydrich L, Lenggenhager B, et al. (2011) Multisensory mechanisms in temporo-parietal cortex support self-location and first-person perspective. Neuron 70:363–74. doi: 10.1016/j.neuron.2011.03.009

Israr A, Kim S-C, Stec J, Poupyrev I (2012) Surround haptics: tactile feedback for immersive gaming experiences. CHI'12 Extended Abstracts on Human Factors in Computing Systems. pp 1087–1090

Israr A, Poupyrev I (2010) Exploring surround haptics displays. CHI'10 Extended Abstracts on Human Factors in Computing Systems. pp 4171–4176

Israr A, Poupyrev I (2011a) Tactile brush: drawing on skin with a tactile grid display. Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. pp 2019–2028

Israr A, Poupyrev I (2011b) Control space of apparent haptic motion. 2011 IEEE World Haptics Conference. pp 457–462

Jadhav S, Kannanda V, Kang B, et al. (2017) Soft robotic glove for kinesthetic haptic feedback in virtual reality environments. Electronic Imaging 2017:19–24.

James W (1985) The varieties of religious experience. Harvard University Press

Jaspers K (1990) Über leibhaftige Bewusstheiten (Bewusstheitstäuschungen), ein psychopathologisches Elementarsymptom. Gesammelte Schriften zur Psychopathologie. Springer, pp

413–420

Jeannerod M (2003) The mechanism of self-recognition in humans. Behavioural brain research 142:1–15.

Jeannerod M, Pacherie E (2004) Agency, simulation and self-identification. Mind \& language 19:113–146.

Jóhannesson ÓI, Hoffmann R, Valgeirsdóttir VV, et al. (2017) Relative vibrotactile spatial acuity of the torso. Exp Brain Res 235:3505–3515. doi: https://10.1007/s00221-017-5073-6

Johansson RS, Vallbo ÅB (1983) Tactile sensory coding in the glabrous skin of the human hand. Trends in neurosciences 6:27–32.

Johnson KO (1994) The perception of two points is not the spatial resolution threshold. Touch, temperature, and pain in health and disease: mechanisms and assessments 389–403.

Johnson KO, Phillips JR (1981) Tactile spatial resolution. I. Two-point discrimination, gap detection, grating resolution, and letter recognition. Journal of neurophysiology 46:1177–1192.

Johnson KO, Yoshioka T (2002) Neural mechanisms of tactile form and texture perception. na

Johnson LA, Higgins CM (2006) A navigation aid for the blind using tactile-visual sensory substitution. 2006 International Conference of the IEEE Engineering in Medicine and Biology Society. pp 6289–6292

Jones LA (2011) Tactile communication systems optimizing the display of information. Prog Brain Res 192:113–28. doi: 10.1016/B978-0-444-53355-5.00008-7

Jones LA, Kunkel J, Piateski E (2009) Vibrotactile pattern recognition on the arm and back. Perception 38:52–68.

Jones LA, Ray K (2008) Localization and pattern recognition with tactile displays. 2008 Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. pp 33–39

Jouybari AF, Rognini G, Hara M, et al. (2019) Torso-mounted Vibrotactile Interface to Experimentally Induce Illusory Own-body Perceptions. 2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). pp 6204–6209

Kannape O, Blanke O (2012) Agency, gait and self-consciousness. International Journal of Psychophysiology 83:191–199.

Kannape OA, Barré A, Aminian K, Blanke O (2014) Cognitive loading affects motor awareness and movement kinematics but not locomotor trajectories during goal-directed walking in a virtual reality environment. PloS one 9:e85560.

Kannape OA, Blanke O (2013) Self in motion: sensorimotor and cognitive mechanisms in gait agency. J Neurophysiol 110:1837–47. doi: 10.1152/jn.01042.2012

Kannape OA, Schwabe L, Tadi T, Blanke O (2010) The limits of agency in walking humans. Neuropsychologia 48:1628–36. doi: 10.1016/j.neuropsychologia.2010.02.005

Karafotias G, Teranishi A, Korres G, et al. (2017) Intensifying emotional reactions via tactile gestures in immersive films. ACM Transactions on Multimedia Computing, Communications, and Applications (TOMM) 13:29.

Karnath H, Schenkel P, Fischer B (1991) Trunk orientation as the determining factor of the "contralateral"deficit in the neglect syndrome and as the physical anchor of the internal representation of body orientation in space. Brain 114:1997–2014.

Kataoka H, Ueno S (2015) Predictable risk factors for the feeling of presence in patients with Parkinson's disease. Movement disorders clinical practice 2:407–412.

Kennett S, Taylor-Clarke M, Haggard P (2001) Noninformative vision improves the spatial resolution of touch in humans. Current Biology 11:1188–1191.

Knierim P, Kosch T, Groschopp J, Schmidt A (2020) Opportunities and Challenges of Text Input in Portable Virtual Reality. Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems. pp 1–8

Knoblich G, Kircher TTJ (2004) Deceiving oneself about being in control: conscious detection of changes in visuomotor coupling. J Exp Psychol Hum Percept Perform 30:657–66.

Knoblich G, Repp BH (2009) Inferring agency from sound. Cognition 111:248–62. doi: 10.1016/j.cognition.2009.02.007

Koehler K, Sauer H (1984) Jaspers' sense of presence in the light of Huber's basic symptoms and DSM-III. Comprehensive psychiatry 25:183–191.

Kristjánsson Á, Moldoveanu A, Jóhannesson ÓI, et al. (2016) Designing sensory-substitution devices: Principles, pitfalls and potential 1. Restorative neurology and neuroscience 34:769–787.

Landtblom A-M (2006) The "sensed presence": an epileptic aura with religious overtones. Epilepsy \& Behavior 9:186–188.

Lauretti C, Pinzari G, Ciancio AL, et al. (2017) A vibrotactile stimulation system for improving postural control and knee joint proprioception in lower-limb amputees. 2017 26th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN). pp 88–93

Lederman SJ, Klatzky RL (2009) Haptic perception: A tutorial. Attention, Perception, \& Psychophysics 71:1439–1459.

Lemmens P, Crompvoets F, Brokken D, et al. (2009) A body-conforming tactile jacket to enrich movie viewing. World Haptics 2009-Third Joint EuroHaptics conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. pp 7–12

Lenggenhager B, Tadi T, Metzinger T, Blanke O (2007) Video ergo sum: manipulating bodily self-consciousness. Science 317:1096–1099.

Lentini R, Ionascu B, Eyssel FA, et al. (2016) Authoring Tactile Gestures: Case Study for Emotion Stimulation. World Academy of Science, Engineering and Technology, International Journal of Computer, Electrical, Automation, Control and Information Engineering 10:1911–1916.

Lieberman J, Breazeal C (2007) Tikl: Development of a wearable vibrotactile feedback suit for improved human motor learning. Robotics, IEEE Transactions on 23:919–926.

Lindeman RW, Page R, Yanagida Y, Sibert JL (2004) Towards full-body haptic feedback: the design and deployment of a spatialized vibrotactile feedback system. Proceedings of the ACM symposium on Virtual reality software and technology. pp 146–149

Lindeman RW, Yanagida Y (2003) Empirical studies for effective near-field haptics in virtual environments. IEEE Virtual Reality, 2003. Proceedings. pp 287–288

Lindeman RW, Yanagida Y, Noma H, Hosaka K (2006) Wearable vibrotactile systems for virtual contact and information display. Virtual Reality 9:203–213.

Ling J, Hong J-C, Hayashi Y, et al. (2020) A Haptic-Based Perception-Empathy Biofeedback System with Vibration Transition: Verifying the Attention Amount. 2020 42nd Annual International Conference of the IEEE Engineering in Medicine \& Biology Society (EMBC). pp 3779–3782

Llorca P, Pereira B, Jardri R, et al. (2016) Hallucinations in schizophrenia and Parkinson's disease: an analysis of sensory modalities involved and the repercussion on patients. Scientific reports 6:

Longo MR, Cardozo S, Haggard P (2008) Visual enhancement of touch and the bodily self. Conscious Cogn 17:1181–91. doi: 10.1016/j.concog.2008.01.001

Lopes P, Ion A, Baudisch P (2015) Impacto: Simulating physical impact by combining tactile stimulation with electrical muscle stimulation. Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology. pp 11–19

McDaniel T, Krishna S, Balasubramanian V, et al. (2008) Using a haptic belt to convey non-verbal communication cues during social interactions to individuals who are blind. 2008 IEEE International Workshop on Haptic Audio visual Environments and Games. pp 13–18

Medina S, Tamè L, Longo MR (2018) Tactile localization biases are modulated by gaze direction. Experimental brain research 236:31–42.

Menzer F, Brooks A, Halje P, et al. (2010) Feeling in control of your footsteps: Conscious gait monitoring and the auditory consequences of footsteps. Cogn Neurosci 1:184–92. doi: 10.1080/17588921003743581

Metzinger T (2004) Being no one: The self-model theory of subjectivity. mit Press

Mirelman A, Maidan I, Bernad-Elazari H, et al. (2014) Increased frontal brain activation during walking while dual tasking: an fNIRS study in healthy young adults. J Neuroeng Rehabil 11:85.

doi: 10.1186/1743-0003-11-85

Miri P, Flory R, Uusberg A, et al. (2017) HapLand: A Scalable Robust Emotion Regulation Haptic System Testbed. CHI Extended Abstracts. pp 1916–1923

Mortimer BJ, Elliott LR (2017) Identifying errors in tactile displays and best practice usage guidelines. International Conference on Applied Human Factors and Ergonomics. pp 226–235

Myles K, Binseel MS (2007) The tactile modality: a review of tactile sensitivity and human tactile interfaces.

Nagahama Y, Okina T, Suzuki N, Matsuda M (2009) Neural correlates of psychotic symptoms in dementia with Lewy bodies. Brain 133:557–567.

Nescio N (1991) Instructions for the Preparation of a Camera-Ready Manuscript.

Nielsen TI (1963) Volition: A new experimental approach. Scandinavian journal of psychology 4:225–230.

Nierula B, Martini M, Matamala-Gomez M, et al. (2017) Seeing an embodied virtual hand is analgesic contingent on colocation. The Journal of Pain 18:645–655.

Oakley I, Kim Y, Lee J, Ryu J (2005) Determining the feasibility of forearm mounted vibrotactile displays. 2006 14th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. pp 27–34

Oldfield RC, others (1971) The assessment and analysis of handedness: the Edinburgh inventory. Neuropsychologia 9:97–113.

Park H-D, Blanke O (2019) Coupling inner and outer body for self-consciousness. Trends in cognitive sciences

Paun S (2018) Design and characterization of a vibrotactile haptic feedback system for drone operators.

Persinger MA (1994) Sense of a presence and suicidal ideation following traumatic brain injury: indications of right-hemispheric intrusions from neuropsychological profiles. Psychological reports 75:1059–1070.

Petkova VI, Björnsdotter M, Gentile G, et al. (2011) From part-to whole-body ownership in the multisensory brain. Current Biology 21:1118–1122.

Petkova VI, Ehrsson HH (2008) If I were you: perceptual illusion of body swapping. PloS one 3:e3832.

Picard F (2010) Epileptic feeling of multiple presences in the frontal space. Cortex 46:1037–1042.

Pittera D, Obrist M, Israr A (2017) Hand-to-hand: an intermanual illusion of movement. Proceedings of the 19th ACM International Conference on Multimodal Interaction. pp 73–81

Plummer P, Apple S, Dowd C, Keith E (2015) Texting and walking: Effect of environmental setting and task prioritization on dual-task interference in healthy young adults. Gait \& posture 41:46–51.

Podoll K, Robinson D (2001) The Idea of Presence as Aura Symptom in Migraine. NEUROLOGY PSYCHIATRY AND BRAIN RESEARCH 9:71–74.

Posada A, Franck N, Augier S, et al. (2007) Altered processing of sensorimotor feedback in schizophrenia. C R Biol 330:382–8.

Pozeg P, Palluel E, Ronchi R, et al. (2017) Virtual reality improves embodiment and neuropathic pain caused by spinal cord injury. Neurology 89:1894–1903.

Press C, Taylor-Clarke M, Kennett S, Haggard P (2004) Visual enhancement of touch in spatial body representation. Experimental Brain Research 154:238–245.

Proulx MJ, Brown DJ, Pasqualotto A, Meijer P (2012) Multisensory perceptual learning and sensory substitution. Neuroscience & Biobehavioral Reviews

Quintana DS, Williams DR (2018) Bayesian alternatives for common null-hypothesis significance tests in psychiatry: a non-technical guide using JASP. BMC psychiatry 18:178.

Repp BH (2006) Does an auditory distractor sequence affect self-paced tapping? Acta psychologica 121:81–107.

Repp BH, Knoblich G (2007) Toward a psychophysics of agency: Detecting gain and loss of control over auditory action effects. Journal of Experimental Psychology: Human Perception and Performance 33:469.

Richardson M, Thar J, Alvarez J, et al. (2019) How much spatial information is lost in the sensory substitution process? Comparing visual, tactile, and auditory approaches. Perception 48:1079–1103.

Rodriguez CC (2005) The ABC of model selection: AIC, BIC and the new CIC. AIP Conference Proceedings. pp 80–87

Rognini G, Blanke O (2016) Cognetics: Robotic interfaces for the conscious mind. Trends in cognitive sciences 20:162–164.

Ronchi R, Park H-D, Blanke O (2018) Bodily self-consciousness and its disorders. Handbook of clinical neurology 151:313–330.

Rupert A, Guedry F, Reschke M (1994) The use of a tactile interface to convey position and motion perceptions.

Rupert AH (2000) An instrumentation solution for reducing spatial disorientation mishaps. IEEE Engineering in Medicine and Biology Magazine 19:71–80.

Al-Sada M, Jiang K, Ranade S, et al. (2019) HapticSnakes: multi-haptic feedback wearable robots for immersive virtual reality. Virtual Reality 1–19.

Salomon R, Szpiro-Grinberg S, Lamy D (2011) Self-motion holds a special status in visual processing. PLoS One 6:e24347.

Sato A (2008) Action observation modulates auditory perception of the consequence of others' actions. Conscious Cogn 17:1219–27. doi: 10.1016/j.concog.2008.01.003

Sato A, Yasuda A (2005) Illusion of sense of self-agency: discrepancy between the predicted and actual sensory consequences of actions modulates the sense of self-agency, but not the sense of self-ownership. Cognition 94:241–255.

Schabrun SM, van den Hoorn W, Moorcroft A, et al. (2014) Texting and walking: strategies for postural control and implications for safety. PloS one 9:e84312.

Schaefer M, Flor H, Heinze H-J, Rotte M (2006) Dynamic modulation of the primary somatosensory cortex during seeing and feeling a touched hand. Neuroimage 29:587–592.

Schneider K (1957) Primare und sekundare Symptome bei der Schizophrenie. Fortschr Neurol Psychiatr 9:487–490.

Schneider K (2007) Klinische psychopathologie. Georg thieme verlag

Seifi H, Maclean KE (2013) A first look at individuals' affective ratings of vibrations. World Haptics Conference (WHC), 2013. pp 605–610

Serino A, Padiglioni S, Haggard P, Làdavas E (2009) Seeing the hand boosts feeling on the cheek. Cortex 45:602–9. doi: 10.1016/j.cortex.2008.03.008

Shams L, Seitz AR (2008) Benefits of multisensory learning. Trends in cognitive sciences 12:411–417.

Sharma A, Torres-Moreno R, Zabjek K, Andrysek J (2014) Toward an artificial sensory feedback system for prosthetic mobility rehabilitation: Examination of sensorimotor responses. J Rehabil Res Dev 51:907–918.

Sherrick CE, Rogers R (1966) Apparent haptic movement. Perception \& Psychophysics 1:175–180.

Shim YA, Park K, Lee G (2019) Using Poke Stimuli to Improve a 3x3 Watch-back Tactile Display. Proceedings of the 21st International Conference on Human-Computer Interaction with Mobile Devices and Services. pp 1–8

Shimada S, Qi Y, Hiraki K (2010) Detection of visual feedback delay in active and passive self-body movements. Experimental brain research 201:359–364.

Shokur S, Gallo S, Moioli RC, et al. (2016) Assimilation of virtual legs and perception of floor texture by complete paraplegic patients receiving artificial tactile feedback. Scientific reports 6:

Slachevsky A, Pillon B, Fourneret P, et al. (2001) Preserved adjustment but impaired awareness in a sensory-motor conflict following prefrontal lesions. Journal of cognitive neuroscience 13:332–340.

Slater M, Perez-Marcos D, Ehrsson HH, Sanchez-Vives MV (2008) Towards a digital body: the virtual arm illusion. Frontiers in human neuroscience 2:

Sofia KO, Jones L (2013) Mechanical and psychophysical studies of surface wave propagation during vibrotactile stimulation. IEEE transactions on haptics 6:320–329.

Spitzer RL, Williams JB (1980) Diagnostic and statistical manual of mental disorders. American Psychiatric Association

Stevens JC, Patterson MQ (1995) Dimensions of spatial acuity in the touch sense: changes over the life span. Somatosensory \& motor research 12:29–47.

Suzuki K, Lush P, Seth AK, Roseboom W (2019) Intentional binding without intentional action. Psychological Science 30:842–853.

Tajadura-Jiménez A, Basia M, Deroy O, et al. (2015) As light as your footsteps: altering walking sounds to change perceived body weight, emotional state and gait. Proceedings of the 33rd annual ACM conference on human factors in computing systems. pp 2943–2952

Taylor-Clarke M, Kennett S, Haggard P (2004) Persistence of visual-tactile enhancement in humans. Neurosci Lett 354:22–5.

Thomas D, Whitney R (1959) Postural movements during normal standing in man. Journal of anatomy 93:524.

Tipper SP, Phillips N, Dancer C, et al. (2001) Vision influences tactile perception at body sites that cannot be viewed directly. Experimental Brain Research 139:160–167.

Tong J, Mao O, Goldreich D (2013) Two-point orientation discrimination versus the traditional two-point test for tactile spatial acuity assessment. Front Hum Neurosci 7:579. doi: https://10.3389/fnhum.2013.00579

Tsakiris M (2010) My body in the brain: a neurocognitive model of body-ownership. Neuropsychologia 48:703–712.

Tsakiris M, Haggard P, Franck N, et al. (2005) A specific role for efferent information in self-recognition. Cognition 96:215–231.

Vallbo A, Olausson H, Wessberg J, Kakuda N (1995) Receptive field characteristics of tactile units with myelinated afferents in hairy skin of human subjects. The Journal of physiology 483:783–795.

Vallbo AB, Johansson RS, others (1984) Properties of cutaneous mechanoreceptors in the human hand related to touch sensation. Hum neurobiol 3:3–14.

Verrillo RT (1966) Vibrotactile thresholds for hairy skin. Journal of Experimental Psychology 72:47.

Verrillo RT (1963) Effect of contactor area on the vibrotactile threshold. The Journal of the Acoustical Society of America 35:1962–1966.

Viola C, Marco D, Lorenzo B, et al. (2018) Design of a Wearable Tactile Interface to Convey Gravitational Information.

Wacker P, Wacharamanotham C, Spelmezan D, et al. (2016) VibroVision: an on-body tactile image guide for the blind. Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems. pp 3788–3791

Wagenmakers E-J, Marsman M, Jamil T, et al. (2018) Bayesian inference for psychology. Part I: Theoretical advantages and practical ramifications. Psychonomic bulletin \& review 25:35–57.

Wall C, Weinberg MS (2003) Balance prostheses for postural control. IEEE Engineering in Medicine and Biology Magazine 22:84–90.

Wall C, Weinberg MS, Schmidt PB, Krebs DE (2001) Balance prosthesis based on micromechanical sensors using vibrotactile feedback of tilt. IEEE Trans Biomed Eng 48:1153–61.

Weber EH (1834) De pulsu, resorptione, auditu et tactu: annotationes anatomicae et physiologicae, auctore. prostat apud CF Koehler

Weinstein S (1968) Intensive and extensive aspects of tactile sensitivity as a function of body part, sex and laterality. The skin senses

Williams DR, Warren JD, Lees AJ (2008) Using the presence of visual hallucinations to differentiate Parkinson’s disease from atypical parkinsonism. Journal of Neurology, Neurosurgery \& Psychiatry 79:652–655.

Winfree KN, Pretzer-Aboff I, Hilgart D, et al. (2013) The effect of step-synchronized vibration on patients with Parkinson’s disease: Case studies on subjects with freezing of gait or an implanted deep brain stimulator. IEEE Transactions on Neural Systems and Rehabilitation Engineering 21:806–811.

Wittwer JE, Webster KE, Hill K (2013) Music and metronome cues produce different effects on gait spatiotemporal measures but not gait variability in healthy older adults. Gait \& posture 37:219–222.

Wolpert DM, Ghahramani Z, Jordan MI (1995) An internal model for sensorimotor integration. Science 1880–1882.

Woollacott M, Shumway-Cook A (2002) Attention and the control of posture and gait: a review of an emerging area of research. Gait \& posture 16:1–14.

Yogev-Seligmann G, Hausdorff JM, Giladi N (2008) The role of executive function and attention in gait. Movement disorders: official journal of the Movement Disorder Society 23:329–342.

Yoo Y, Yoo T, Kong J, Choi S (2015) Emotional responses of tactile icons: Effects of amplitude, frequency, duration, and envelope. 2015 IEEE World Haptics Conference (WHC). pp 235–240

Yoshikawa T, Nagura A (1997) A touch and force display system for haptic interface. Proceedings of International Conference on Robotics and Automation. pp 3018–3024

Zhang H, Yin Y, Chen Z, et al. (2020) Wearable Biofeedback System to Induce Desired Walking Speed in Overground Gait Training. Sensors 20:4002.

Abbreviations

ActD	Activation delay
ASYNC	Asynchronous
BSC	Bodily self-consciousness
B_{Pre}	Pre-baseline without tactile feedback
B_{Post}	Post-baseline without tactile feedback
BF	Baysian factor
CV_{ST}	Stride time coefficient of variation
DD	Direction discrimination
DeactD	Deactivation delay
DEV_{ST}	Stride time deviations
DoS	Duration of stimulation
ERM	Eccenteric rotating mass
F_{PP}	Peak poking Force
FBI	Full body illusion
FD	Full delay
GUI	Graphical user interface
HD	Half delay
LRA	Linear resonant actuator
MA	Motor awareness
M_{ST}	Mean stride time
ND	No delay
OBE	Out of body experience
PH	Presence hallucination
PLT	Point localization task
PL	Point localization
RHI	Rber hand illusion
SD	Standard deviation
SYNC	synchronous
SE	Standard error

SoA	Sense of agency
SOA	Stimulus onset asynchrony
T_{PD}	Poking duration
T_{PI}	Poking interval
VAM	Vibration apparent movement
VET	Visual enhancement of touch

Curriculum Vitae

✉ Atena.fadaeijouybari@gmail.com
Birth date: 21/01/1991
in http://www.linkedin.com/in/atena-fadaei-jouybari

Education

2017- Present

PhD. in Robotics, Laboratory of Cognitive Neuroscience and Laboratoire de Systèmes Robotiques, **EPFL.** Thesis title: "*Portable, torso-worn haptic displays to investigate bodily self-consciousness*"

- Engineering and multi-disciplinary system design: experience in the field of portable, torso-worn haptic displays
- Trained in designing and running psychophysical and cognitive neuroscience experiments with the aim of evaluating haptic robotic systems on a healthy population
- Strengthened analytical and statistical skills through analyzing behavioral study data
- Developed professional presentation and documentation skills
- Proven supervision skills through supervising more than ten students (master/bachelor/intern)

2013-2015

M.Sc., Aerospace Engineering, Flight Mechanics, *Sharif University of Technology*, Iran. Thesis title: "*Robust Control of Spacecraft Rendezvous in Halo Orbits in Three Body Problem*"

- GPA: 19.03/20 [5.7/6] (Ranked 1st)

Key Work Experience

Aug 2016-
Feb 2017

Robotic Software Developer: Joint project between Laboratoire de Systèmes Robotiques, **EPFL** and **Robo Medical Co.**, LTD, China

- Experience as the only software developer, contributing to a team of four engineers to prototype a surgery teleoperation system
- Strengthened programming skills (C^{++}) by design and implementation of master control software, including control system architecture and GUI
- Hands-on experience in the testing and validation of the customized surgery system

2014-2016

Control and Mechatronic Engineer, SADRA Co., Iran

- Enhanced skills in dynamic modelling and control of quadrotors (Matlab, Simulink)
- Acquired practical knowledge of the design and implementation of flight controller algorithms for a specific quadrotor (C^{++}), and experience of in-field drone testing
- Improved programming skills through enhancement of the quadrotor ground station software features (*C#*)
- Hands-on experience in the testing and evaluation of AHRS systems and their real-time performance

2014-Fall

Research and Development Engineer, Sharif-Sat (Technology satellite of Sharif University of Technology), Iran

- Modeling, simulation, and analysis of different environmental disturbances on the CubeSat's translation dynamics and orbital life cycle in Low Earth Orbit

March 2014-
Sep. 2014

Dynamic Modeling and Control Engineer, RealSim, Iran-Internship

- Gained practical knowledge in the modeling and simulation of Ducted Fan UAV (*Matlab/Simulink*)
- Experience in the design and implementation of different control schemes, e.g. PID, LQR, State feedback, to control an inverted pendulum (*Matlab/Simulink*)

Selected Publications

Torso-mounted Vibrotactile Interface to Experimentally Induce Illusory Own-body Perceptions, **Fadaei J.**, G. Rognini, M. Hara, H. Bleuler, and Olaf Blanke, "
2019 *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*

Cogno-vest: A Torso-Worn, Force Display to Experimentally Induce Presence Hallucinations and Related Bodily Sensations, Fadaei J., K. Jeanmonod, O. A. Kannape, J. Potheegadoo, H. Bleuler, M. Hara, and Olaf Blanke,
Published in *IEEE Transaction Human Machine System (THMS).*

Tactile spatial discrimination on the torso using vibrotactile and force stimulation, Fadaei J., M. Framza, O. A. Kanappe, M. Hara, and Olaf Blanke,
Under revision in *Experimental Brain Research*.

"FeetBack" touch remapping of action consequences produces accurate awareness but limited (loco)motor adap-tation, Fadaei J., N. Ferraroli, Mohammad Bouri, O. A. Kannape, and Olaf Blanke,
In preparation.

Key Skills

- **Hard working**, capable of handling pressure
- Self-organized, responsible and **multi-tasking**
- Strong social communication & **team playing**
- Super-**fast learner** & **self-motivated**
- Team leading and **supervision** experience
- Strong in **coding** and **computational** works

Computer Skill

Python, PyTorch, R, C++ (Qt), C#, Matlab/Simulink, Arduino, Tableau, SQL

Honors & Awards

- Selected as the recipient of 1-year ***National Elite Foundation*** **fellowship**, Iran, 2014 - 2015.
- **Unconditional admission** to the **PhD.** program in Aerospace Engineering at Sharif University of Technology (2015); 1st out of 20+ M.Sc. students
- **Unconditional admission** to the **MSc** program in Aerospace Engineering at Sharif University of Technology (2013); 2nd out of 100+ B.Sc. students
- Selected as author of the **best national undergraduate thesis** by the *Iranian Aerospace Society*

Language skills

- English: Fluent (C1)
- French: Intermediate (A2)
- Persian: Native speaker