How Positioning Wearable Haptic Interfaces on Limbs Influences Virtual Embodiment

Dwivedi, Anany; Yu, Shihan; Hao, Chenxu; Salvietti, Gionata; Prattichizzo, Domenico; Beckerle, Philipp

DOI
10.1109/TOH.2023.3347351

Publication date
2024

Document Version
Final published version

Published in
IEEE Transactions on Haptics

Citation (APA)
Dwivedi, A., Yu, S., Hao, C., Salvietti, G., Prattichizzo, D., & Beckerle, P. (2024). How Positioning Wearable Haptic Interfaces on Limbs Influences Virtual Embodiment. *IEEE Transactions on Haptics*, *17*(2), 292-301. https://doi.org/10.1109/TOH.2023.3347351

How Positioning Wearable Haptic Interfaces on Limbs Influences Virtual Embodiment

Anany Dwivedi, Shihan Yu, Chenxu Hao, Gionata Salvietti, *Senior Member, IEEE*, Domenico Prattichizzo, *Fellow, IEEE*, and Philipp Beckerle, *Senior Member, IEEE*

***Abstract*—With increasing use of computer applications and robotic devices in our everyday life, and with the advent of metaverse, there is an urgent need of developing new types of interfaces that facilitate a more intuitive interaction in physical and virtual space. In this work, we investigate the influence of the location of haptic feedback devices on embodiment of virtual hands and user load during an interactive pick-and-place task. To do this, we conducted a user study with a 3x2 repeated measure experiment design: feedback position is varied between the distal phalanx of the index finger and the thumb, the proximal phalanx of the index finger and the thumb, and the wrist. These conditions of feedback are tested with the stimuli applied synchronously to the participant in one case, and with an additional delay of 350 ms in the second case. The results show that the location of the haptic feedback device does not affect embodiment, whereas the delay, i.e., whether the feedback is applied synchronously or asynchronously, affects embodiment. This suggests that for pick-and-place tasks, haptic feedback devices can be placed on the user's wrist without compromising performance making the hands to remain free, allowing unobstructed hand visibility for precise motion tracking, thereby improving accuracy.**

***Index Terms*—Haptic feedback, wearable haptics, virtual hand illusion, virtual reality.**

I. Introduction

OVER the past decades, the technological advancements have led to an increased influence of robotic systems and computer applications, including virtual reality (VR) and augmented reality (AR), in our everyday life. Interfaces between humans and machines are a crucial component required for intuitive and safe interactions. Such interfaces can also be used in healthcare to augment a surgeon's capabilities by increasing the range of motion of the surgical tool, allowing them to exert forces with great precision. Teleoperated robots can aid in reducing travel related time delays by allowing the surgeon to apply their expertise without spending time and effort on transport [1]. Such intuitive remote telepresence interfaces may also lead environment friendly interactions by reducing the carbon emissions due to travel.

Now, with the talks for a new means of interaction with the digital world, called the "Metaverse" this influence is predicted to grow even more. Big tech companies like Meta, Microsoft, Nvidia etc, consider it as the future of internet, describing it as an "embodied internet" [2], [3], leading to a seamless integration of machines, robots, computer applications including those in VR and AR. Furthermore, with the advent of "Tactile Internet", the robots will be able to act as multimodal avatar of the humans [4]. This implies a need to develop new types of interfaces to improve the embodiment within the environment [5].

While interacting with real world environment through a robotic agent or in a virtual environment through computer applications, psychological concepts like "embodiment" must be considered for a more intuitive and comfortable interaction [6]. Embodiment deals with capturing the extent to which a virtual or artificial limb is perceived as one's own limb [6]. Having a feeling of embodiment with an external hand has been of interest to researchers for quite some time. This was first studied by Botvinick and Cohen in the year 1998 by showing embodiment of a rubber hand as ones own limb [7]. In this experiment, participants were asked to place one hand on the table that was hidden from them, but a visible rubber hand was placed in close proximity. The experimenter stroked the participants' hidden hand and the visible rubber hand simultaneously. Participants reported that they experienced that the visible rubber hand was their own hand. This occurs due to multisensory integration, which leads to a combination of vision, touch, and proprioception by the brain which tends to shift the perceived sensations to the position of the rubber hand, since only the rubber hand is visible to the participants [8].

Human beings are able to perceive the surrounding environment through different sensory feedback from their senses (vision, hearing, touch, smell, and taste). The sense of touch

Manuscript received 17 March 2023; revised 12 November 2023 and 21 December 2023; accepted 21 December 2023. Date of publication 29 December 2023; date of current version 20 June 2024. This paper was recommended for publication by Guest Editors Haptics in the Metaverse Special Issue and Editor-in-Chief S. Choi upon evaluation of the reviewers' comments. *(Corresponding author: Anany Dwivedi.)*

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Ethik-Kommission der FAU under Application No. 22-89-S, and performed in line with the Declaration of Helsinki.

Anany Dwivedi is with the Artificial Intelligence (AI) Institute, Division of Health, Engineering, Computing and Science, University of Waikato, Hamilton 3216, New Zealand (e-mail: anany.dwivedi@waikato.ac.nz).

Shihan Yu is with the Department of Electrical Engineering, Friedrich-Alexander-Universität Erlangen-Nürnberg, 91052 Erlangen, Germany (e-mail: shihan.yu@fau.de).

Chenxu Hao is with the Department of Intelligent Systems, Delft University of Technology, 2628 CD Delft, The Netherlands (e-mail: c.Hao-1@tudelft.nl).

Gionata Salvietti and Domenico Prattichizzo are with the Department of Information Engineering and Mathematics, University of Siena, 53100 Siena, Italy (e-mail: salviettigio@dii.unisi.it; prattichizzo@dii.unisi.it).

Philipp Beckerle is with the Chair of Autonomous Systems and Mechatronics, Department of Electrical Engineering, Friedrich-Alexander-Universität Erlangen-Nürnberg, 91052 Erlangen, Germany, also with the Department of Artificial Intelligence in Biomedical Engineering, Friedrich-Alexander-Universität Erlangen-Nürnberg, 91052 Erlangen, Germany (e-mail: philipp.beckerle@fau.de).

Digital Object Identifier 10.1109/TOH.2023.3347351

is responsible for proprioception of the body (ability to sense movement, action, and limb location) allowing the user to perceive their body location in the environment [9]. As a result, haptic feedback is one of the most preferred method to inform the user regarding the state of interactions with various devices and applications [10], ranging from mobile phones to robotic devices and computer applications including both VR and AR [11]. The reason for a ubiquitous use of haptics can be attributed to the fact that it can act directly on the user, and increasing the intensity of the feedback can inform the user regarding the dynamics of the interaction as compared to just the kinematic information obtained using visual feedback (e.g., increasing grasping forces with a prosthetic hand can be conveyed using increasing intensity of the vibration feedback).

Haptic feedback devices are gaining prominence in the gaming industry, utilized not only in computer-based games but also in VR gaming. Majority of these devices provide vibration feedback to users through handheld controllers [12]. More advanced implementations have also gained popularity as researchers aim to enhance users' sense of presence and bodily engagement. Sallnäs et al. [13] observed that the incorporation of a force feedback mechanism yielded positive outcomes, including enhanced physical presence and improved task performance. Furthermore, Cornelio et al. argue that increasing the sense of agency should always augment the user capabilities (e.g., improving speed, dexterity, productivity, etc.) [14]. Therefore, to facilitate a more intuitive interaction through such interfaces, the embodiment and ownership of the devices being controlled needs to be maximized [15], [16].

In [17], Slater et al. employed computer-generated visuotactile sensory stimulations in VR to induce body ownership illusions. In [18], authors explored the case of virtual hand illusion. In their experiments, participants were asked to self-stimulate with their left hand and a feedback was provided through a haptic device in an active or passive manner. Through questionnaires, they showed that synchronous visuomotor or visuotactile stimulations lead to an illusion toward ownership of the virtual hand, and active movements of the real hand synchronously to the virtual hand may elicit stronger feelings of ownership than observing passive movements of the real hand. The research community has also explored which questions should be asked to evaluate the sensation of subjective embodiment in the most credible way. To do this, Longo et al. found three main subcomponents of the embodiment of rubber hand: ownership, location, and agency [19]. To assess those factors, Longo et al. suggest using 10 questions, which they extracted from their 27 suggested questionnaire items with a factorial analysis.

Inspired by existing questionnaires in the literature, Gonzalez-Franco and Peck [20] proposed a questionnaire consisting of 25 questions for studying the embodiment of virtual avatars, which includes subscales of body ownership, agency and motor control, tactile sensations, location of the body, external appearance, and response to external stimuli. In their follow-up study [21], they refined their questionnaire to 16 questions with subscales of appearance, response, ownership, multi-sensory, and embodiment. However, this study is strongly inspired by the classical rubber hand illusion paradigm, for which the Longo

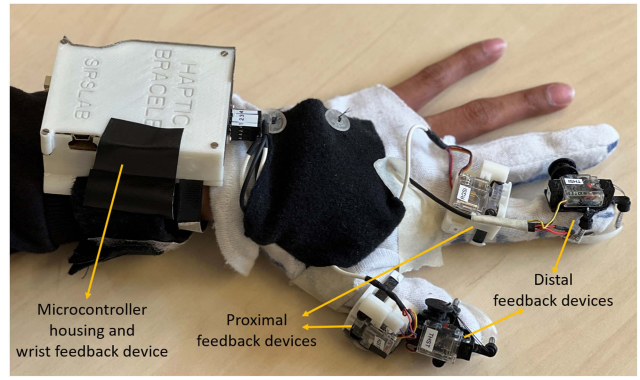


Fig. 1. Haptic glove used in this study. Haptic feedback devices are placed on the distal and proximal phalanx of index finger and the thumb and also on the wrist of the participant. The wrist bracelet also houses the microprocessor for the control of the glove.

et al. [19] questionnaire is a quasi-standard. Therefore, we use questionnaire based on their study.

Our previous work [22] showed that including haptic feedback in the interactions with virtual environments can improve the subjective embodiment of a virtual hand. Moreover, we found that force-based feedback leads to stronger responses to certain subscales of subjective embodiment as compared to vibrotactile feedback. In this study, we extend this analysis by exploring the effects of location of haptic feedback with respect to the visual feedback of the interactions with the environment. To evaluate these effects, we designed a 3x2 repeated measure experiment, where haptic feedback is applied to the participants in three different locations (distal phalanx, proximal phalanx, and the wrist) over two different (synchronous and asynchronous) conditions through a wearable haptic feedback glove (see Fig. 1).

We hypothesize that the closer haptic feedback is provided to the point of actual interaction, higher the proprioceptive drift (hypothesis 1a), the higher the subjective embodiment (hypothesis 1b), the lower the user load (hypothesis 1c). Furthermore, we expect that delaying the motion of the virtual hand leads to a lower proprioceptive drift (hypothesis 2a), a lower feeling of subjective embodiment (hypothesis 2b), a higher user load (hypothesis 2c). To explore these hypotheses, in our study, we asked the participants to interact with a virtual environment receiving haptic feedback on their fingertips (distal phalanx), proximal phalanx, or the wrist. To measure the feeling/experience of embodiment of the virtual hand when haptic feedback is provided to different locations, we employ several behavioral metrics and questionnaires.

The outcome of the study would help us understand better, besides visual feedback, how the haptic feedback's locations and its synchronicity with the visual feedback in the task affect task performance and subjective embodiment. These results will also enable the interface designers to develop interfaces which facilitate more intuitive interactions. To ensure comfortable interactions, interface designers strive to create devices that allow users to engage with the environment hands-free [23], [24], [25]. This emphasizes the need to understand the significance of haptic feedback device placement so that designers can make informed decisions regarding the best locations for these devices to close the interaction loop efficiently. For example, moving the haptic feedback device more proximal in case of VR/AR applications allow the hands to be free and also reduces the complexities of the device, making it cheaper. Furthermore, in the case of prosthetic applications (for transradial amputations), it may be ideal to place the haptic devices on the upper arm, away from the myography devices which are generally placed on the forearm [25], [26].

The rest of the paper is organized as follows: Section II describes the experimental setup, procedure, and the subjective measures, Section III discusses the results obtained, and finally, Section V concludes the work.

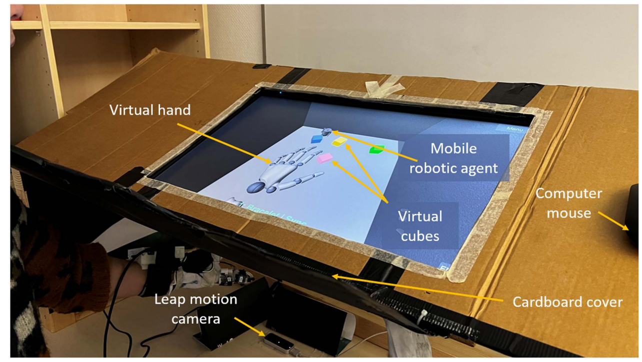


Fig. 2. Experimental setup for the virtual hand illusion experiments. Here, a participant can be seen interacting with the virtual environment, with their hand motion being tracked using a Leap Motion infrared camera. The participant's hand was hidden from their view using a cardboard cover and only the virtual hand was visible to them.

II. Methods

In the rubber hand illusion experiments, generally the rubber hand is kept within a reasonable distance (roughly 10 cm - 30 cm) from the actual hand [8], [27]. Previous studies on rubber hand illusion have found that the illusion is stronger with the left hand [28]. Therefore, in this study the left hand was used by all the participants to interact with the virtual environment and to receive feedback from the haptic feedback glove. Furthermore, in this experiment, the virtual hand was located with an offset of 18 cm to the right of the actual location of the participants' left hand.

To evoke the illusion of embodiment, literature suggests that the rubber hand should look like one's own hand [8], however, it should be made sure that the hand does not fall in the uncanny valley [29]. Therefore, in this study the virtual hand was selected to look like an artificial prosthetic hand instead of a human-like hand, to avoid the uncanny valley [29]. Regarding the asynchronous condition of the experiment protocol, a delay of 350 ms was selected, in addition to the intrinsic system delays to reduce the effect of the illusion. Literature shows that the asynchronous touch leads to a strong decline or even disappearance of the illusion [19], [30].

This study has a 3x2 repeated measures design and has six experimental conditions with varying location and synchronicity of the haptic feedback on the participant's hand. The six conditions are as follows:

1) Haptic feedback on the distal phalanx with no delay.
2) Haptic feedback on the distal phalanx with 350 ms delay.
3) Haptic feedback on the proximal phalanx with no delay.
4) Haptic feedback on the proximal phalanx with 350 ms delay.
5) Haptic feedback on the wrist with no delay.
6) Haptic feedback on the wrist with 350 ms delay.

A. Experimental Setup

The experiment design is based on our previous work [22] that focused on evaluating the importance of feedback during interactions with virtual environment. Our previous work [22] showed that including haptic feedback in the interactions with virtual environments greatly improves the subjective embodiment of a virtual hand and that force-based feedback leads to stronger responses to certain subscales of subjective embodiment as compared to vibrotactile feedback. These findings align with those of Richard et al. [31], who demonstrated the significant superiority of force feedback over no haptic feedback in terms of embodiment. Additionally, their study revealed that force feedback outperformed both no feedback and vibrotactile feedback in subjective performance. Therefore, in this study, we extend our previous work [22] by assessing the optimal location of the feedback devices using the force-based haptic feedback modality. In the experiments, the participants were asked to stand in front of a display. They wore the haptic feedback glove on their left hand and a passive noise cancellation headphone to cancel the noise from the haptic device as well as the environment. The glove has haptic devices on each distal and proximal phalances of both, index finger and thumb, as well as on the wrist (see Fig. 1). Their left hand was hidden from their view, and was placed under the screen and then covered with a cardboard cover that lay on the participant's chest to further hide the hand from view (see Fig. 2).

A computer mouse was placed next to the setup, on the right side, which was reachable by the right hand of the participants (right hand was free and has no haptic device on it). The computer mouse was used in-between the different conditions of the experiment to get the user input for the different questions related to the proprioceptive drift, subjective embodiment, and the user load (see Section II-D).

To track the left hand motion of the participant and to display it in the Unity-based virtual environment, a Leap Motion camera, *Leap Motion, Inc.* was used. This camera employs an infrared rays-based motion tracking method. Using the tracked motion, a virtual hand was displayed on the screen which can mimic actual hand motions and gestures made by the participants. The hardware interface with the haptic devices was created using an Arduino Nano microcontroller, *arduino.cc*. This board was selected due to its light weight and compact design, allowing the whole electronics to be worn as a bracelet on the wrist. A haptic feedback was provided to the user as soon as a contact between the user's virtual hand and the objects in the Unity environment was detected.

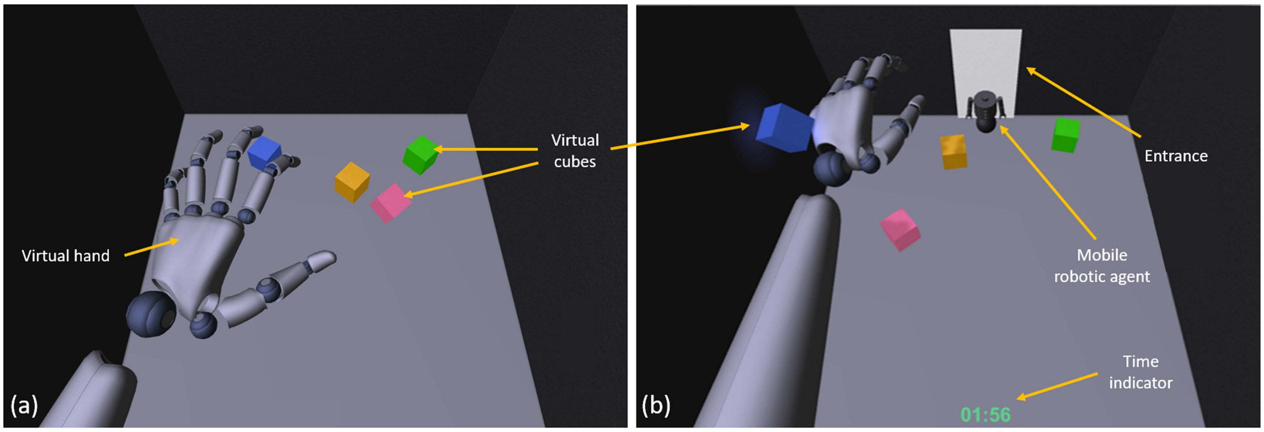


Fig. 3. Scene from the experiments. Subfigure (a) shows the scene before the start of the experiment with the virtual hand and the cubes. Subfigure (b) shows the beginning of the experiments with the mobile robotic agent entering the scene, the cubes falling from above to the ground, and an indicator of the remaining time in the experiment condition.

The distal haptic device (Fig. 1) consists of two platforms interconnected by three cables and three springs. The upper platform houses a servo motor with a pulley able to contemporary adjust the length of all the three cables. Controlling this length it is possible to move the lower platform toward the finger pulp to generate finger skin indentation similarly to the principle proposed in [32]. Conversely, the proximal and wrist feedback device provide skin indentation through a servomotor that controls the length of a belt loop, similarly to the devices introduced in [33] and [34] respectively. These wearable haptic devices with a single degree of freedom (1-DoF), can be controlled so to apply contact forces proportional to those computed in the virtual environment using different techniques [35]. However, in this study a constant predetermined force value was applied by the haptic interfaces during the contact between the virtual fingers and the objects. These values were set for each participant during the calibration phase before the beginning of the experiments and mostly depended on the size of the participants' limbs.

B. Participants

Twenty five people participated in the study (9 female and 16 male, 1 left hand dominant and 24 right hand dominant). The mean age of the participants was 28.0 years and the standard deviation (SD) was 4.0 years. The participants of the study were healthy and able-bodied, and reported no weakness related to their vision and haptic perception. All the participants participated on self volunteer basis and signed an informed consent before the start of the experiments. In the demographics questionnaire, one question surveyed if participants had prior knowledge of the rubber hand illusion and it was found that 10 participants were aware of the concept. This study was conducted with a positive vote by the ethics board of Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany and is in accordance with the Declaration of Helsinki in its current version.

C. Task

The pick-and-place task is one of the most important tasks due to its fundamental nature in human interaction with the environment. Therefore, in the experiments, the main task was to put a virtual cube on a virtual moving target. To ensure participants' engagement and to make sure their attention was solely on the task itself, rather than the "real environment" around them, this pick-and-place activity was transformed into an engaging game featuring moving targets. As shown in Fig. 3(a), there were four different colored cubes in the environment. The environment also has robots, which enter the environment without heads, and the participants were asked to put each virtual cube on the randomly moving virtual robots. Once the cube was successfully placed on the robotic agents as the head, the robots start dancing.

The initial experimental scene starts with the four cubes and the first robotic agent enters the scene through the white entrance (see Fig. 3(b)) after four seconds of the beginning. The participant is required to pick up the cubes and attach it as the head of the robotic agent. When the object is grasped, a predefined force is applied through the haptic device on the location of feedback to indicate that the object has been grasped. Once a cube was attached to the robotic agent as its head, a new robot enters the scene. This repeats to a maximum of four robotic agents in the scene. Once all four colored cubes were attached to the robotic agents, a disco light appears to show the participants that the task has been completed. At this point, the participants can use a computer mouse to click the "next" button which takes them to the questionnaire form (see Section II-D) to be completed related to the experiment run. To make the task challenging, the participants were required to complete the task in 120 sec. A timer was shown at the bottom of the screen to inform the participants regarding the remaining time. This protocol was repeated for all the six experimental conditions.

D. Measures

For each of the experimental condition, four different dependent variables were measured, which were: task performance, proprioceptive drift, subjective embodiment, and user load. These data were collected during and after each condition to determine differences between each tested condition. These measures are selected based on our previous work [22].

1) Task Completion: The completion of the task was measured using two metrics, the first was the rate of completion of the task, which is the inverse of the time taken to complete the task of placing the four cubes on the robotic agents. The second was the percentage of the participants that were able to put all four cubes on the moving robotic agents. In this study, the inverse of the time duration was used, which can also serve as a measure of the capability of task finishing within a specific time unit. In other words, the shorter the time required to place the cube, the higher is the task completion. A scaling to have higher weights for faster task completion was used to weigh the difficulty of the tasks accordingly. An easy condition implies that the particular feedback location with the delay condition makes the task more intuitive for the users.

2) Proprioceptive Drift: Proprioceptive drift (PPD) is a common method for the illusion strength evaluation by measuring the imagery of hand position [36]. It indicates the tendency to assign the location of one's own body part to that of the virtual/external object after a successfully evoked illusion [37]. To evaluate PPD, the participants were requested to point the index fingertip of the illusion hand with the non-illusion hand while their eyes were closed [36]. The PPD test is an objective method for measuring the sensation of embodiment with an external limb.

In this study, the PPD was measured at the end of each condition. To do this, after each condition was completed, the screen was turned black and the participant was asked to point at the tip of the index finger of their left hand using a computer mouse with their right hand. During this time, their left hand was still not in view of the participant, as it was under the screen and hidden by the cardboard cover. PPD is measured as the difference between the location of the virtual hand and the indicated location by the participant.

3) Subjective Embodiment: To evaluate the subjective embodiment, a questionnaire developed by Longo et al. was employed [19], which estimates the embodiment based on ten items as discussed in Section I.

In this study, the participants were asked to complete this questionnaire at the end of each of the tested condition using a computer mouse with their right hand (which did not have the haptic device). The input from the participant was taken in the form of a 7 point Likert scale [38], ranging from "strongly disagree" to "strongly agree" using a slider. The slider started at the center of the scale and had to be moved at least once for the answer to be accepted for the particular question. Once the slider was moved, moving it back to its original position was also allowed.

To avoid development of any biases to the order of the questions, all the questions after the PPD measurement were presented in a randomized order. Furthermore, the questionnaire by Longo et al. [19] was adapted from rubber hand to virtual hand, e.g., the question in the subscale location, "It felt like the touch I felt was caused by the paintbrush touching the rubber hand" to "It seemed like the touch I felt was caused by touching the virtual cube". Finally, all the modified questions were also translated in to German, since the experiments were conducted in Germany. All the modified English and translated German questions are listed in Table I.

TABLE I
EMBODIMENT QUESTIONNAIRE USED IN THIS STUDY BASED ON THE WORK BY LONGO ET AL. [19] IN ITS ENGLISH VERSION (LEFT) AND ITS TRANSLATED VERSION IN GERMAN (RIGHT)

English statement	Translated statement (German)
During the experiment it seemed like...	Während des letzten Blocks...
Subscale ownership	
... I was looking directly at my own hand, rather than at a virtual hand.	... hatte ich den Eindruck, direkt meine eigene Hand anzuschauen, nicht eine virtuelle Hand.
... the virtual hand began to resemble my real hand.	... schien es, als ob die virtuelle Hand meiner realen Hand ähnlicher wurde.
... the virtual hand belonged to me.	... schien es, als ob die virtuelle Hand zu mir gehören würde.
... the virtual hand was my hand.	... schien es, als ob die virtuelle Hand meine eigene Hand war.
... the virtual hand was part of my body.	... schien es, als ob die virtuelle Hand ein Teil meines Körpers war.
Subscale Location	
... my hand was in the location where the virtual hand was.	... schien es, als ob meine eigene Hand in der Position der virtuellen Hand war.
... the virtual hand was in the location where my hand was.	... schien es, als ob die künstliche Hand in der Position meiner eigenen Hand war.
... the touch I felt was caused by touching the virtual cube.	... hatte ich den Eindruck, dass die Berührung, die ich fühlte, durch das Berühren des virtuellen Würfels verursacht wurde.
Subscale Agency	
... I could have moved the virtual hand if I had wanted.	... hatte ich den Eindruck, dass ich die virtuelle Hand bewegen könnte, wenn ich gewollt hätte.
... I was in control of the virtual hand.	... hatte ich den Eindruck, die Kontrolle über die virtuelle Hand zu haben.

4) User Load: NASA-TLX is a subjective user load evaluation tool that allows users to measure the user load of operators using a variety of human-machine interface systems [39]. A standard NASA-TLX calculates an overall user load score based on a weighted average of ratings on six subscales using a multi-dimensional assessment technique. In this study, the user load was measured with a modified form of the original NASA-TLX questionnaire, where the weighting is omitted [40] to reduce the user load as a result of NASA-TLX questionnaires. The user load questionnaire was asked after the embodiment questionnaire at the end of each condition.

E. Procedure

Before the start of the experimental sessions, the participants were provided with the information sheet informing about the experiments. They were asked to read the information and sign the informed consent form. After the informed consent was provided, the participants were briefed about the experimental protocol and were asked to wear the haptic feedback glove (see Fig. 1. The haptic feedback of the glove was then calibrated to participant's level of comfort. The calibration process comprises of a process of manually fine-tuning the forces exerted by each haptic device to be comfortable for the user to not hurt them. A procedure of calibration is required for adjusting to variations in the hand sizes thickness of the fingers. After the calibration, the participants were provided with some information on the working of the Leap Motion camera tracking for allowing better tracking of the hand. The experiments were designed to naturally have execution of a pinch grasp for the completion of the task. This allows to complete the task with minimal occlusion, as the Leap Motion cameras work the best with the palm flat and parallel to the camera. After this, the participants were given a demo run, to get acquainted to the device before the experiments.

Once the participants were ready, the actual experiments began. During this time, the experimenter went behind a partition in the room, to not interfere with the experiments but still be available if the participant needed assistance. After the start of the experiments, no further input from the experimenter was needed and the whole experiment was completed autonomously. All the participants performed experiments with six different conditions, with a duration of 120 sec each. The order of the conditions was randomized using Latin square design. The conditions were run as described in the Section II-C and were run for 120 sec or until the completion of the tasks, at which point the participant may choose to proceed to the next step. The next step was to take the measure for PPD, which was followed by the questionnaires about the subjective embodiment and the user loads. The only difference between the conditions was the point at which the feedback was applied and if the hand was displayed synchronously or asynchronously to the actual motion.

III. Results

We investigate how the independent variables, *delay* (synchronous vs. Asynchronoushronous) and locations of *feedback* (Distal, Proximal, Wrist), influence four dependent variables: *task completion*, *proprioceptive drift*, *subjective embodiment*, and *user load*. *Task completion* includes the inverse of task duration, i.e., the time each participant used to complete the task and the percentage of the participants that were able to complete the task. *Proprioceptive drift* is the difference between the location of the virtual hand and the indicated location by the participant. Each participant's *subjective embodiment* is the mean rating of the provided ratings for all questions. Each participant's *user load* is the mean rating of all questions from the NASA-TLX questionnaire. All four variables are centered for the following analyses.

Among all dependent variables, we found that there is a positive correlation between *subjective embodiment* and *task completion*, $r(148) = 0.32$, $p < 0.001$, a negative correlation between *task completion* and *user load*, $r(148) = -0.31$, $p < 0.001$, and a negative correlation between *subjective embodiment* and *user load*, $r(148) = -0.59$, $p < 0.001$. Therefore, we analyze the data with a multivariate multiple regression:

$$\begin{aligned} &\textit{task completion}, \textit{proprioceptive drift}, \textit{subjective}\\ &\textit{embodiment}, \textit{user load} \sim \textit{delay}\\ &\quad + \textit{feedback} + \textit{delay} \times \textit{feedback} \end{aligned} \tag{1}$$

TABLE II
Results From the Type II MANOVA Test (Pillai's Trace Test)

Variable	Df	test stat	approx F	num DF	den DF	p-Value
delay	1	0.22	9.69	4	141	<0.001***
feedback	2	0.03	0.54	8	284	0.82
delay:feedback	2	0.01	0.28	8	284	0.97

TABLE III
Results for the Comparison Between the Full Model and the Simple Model, the Large p-Value Suggests That Both Models Fit the Data Equally Well

Res.Df	Df	Gen.var.	Pillai	approx F	num Df	den Df	p-Value
144		2.09					
148	4	2.06	0.05	0.42	16	576	0.98

We first tested the model assumptions: we tested the normality assumption with Shapiro-Wilk test on each dependent variable in each condition. The normality assumption holds in most subgroups (except for subgroups *Asynchronous-Distal-Task Completion*, $p < 0.01$, *Asynchronous-Wrist-Task Completion*, $p < 0.01$, *Asynchronous-Proximal-Proprioceptive drift*, $p < 0.01$, and *Synchronous-Proximal-Proprioceptive drift*, $p < 0.01$).

We used the Box's test of equality of covariance matrices to test the homogeneity of covariance ($p < 0.01$). Although these results suggest that normality assumption is violated in a few subgroups and that the homogeneity of covariance assumption is violated, our analyses follow a balanced design of groups with $n = 25$ in each group, thus addressing the potential issue in the violation of this assumption [41].

Levene's test of equality of error variances suggests that the error variances of the dependent variable are equal across groups.

Below we show the results from the Pillai's Trace test (Table II), which suggest a statistically significant difference in the dependent variables between receiving synchronous feedback and asynchronous feedback.

In addition, such results suggest that we can apply a simpler multivariate regression model, which fits the data as well as the full model ((1); see Table III for model comparison results):

$$\begin{aligned} &\textit{task completion}, \textit{proprioceptive drift},\\ &\textit{subjective embodiment}, \textit{user load} \sim \textit{delay}, \end{aligned} \tag{2}$$

The results of the simple model investigating how delay influences each of the four dependent variables (Table IV) suggest that delay has a statistically significant effect on *subjective embodiment*, *task completion*, and *user load*. We will discuss the results with regard to each dependent variables in the corresponding sections below.

A. Task Completion

As discussed in Section II-D, the task completion is assessed based on the inverse of the time taken for the completion of the task and also on the percentage of participants that completed the tasks. Our results indicate that delay has a statistically

TABLE IV
FULL RESULTS FROM THE SIMPLE MULTIVARIATE REGRESSION ANALYSIS. WE SEE THAT DELAY HAS A STATISTICALLY SIGNIFICANT EFFECT ON *SUBJECTIVE EMBODIMENT*, *TASK COMPLETION*, AND *USER LOAD*

	Estimate	Std. Error	t-Value	p-Value
embodiment ~ delay				
(Intercept)	-0.34	0.12	-2.87	<0.01**
delaysync	0.68	0.17	4.06	<0.001***
task completion ~ delay				
(Intercept)	-0.00	0.00	-3.95	<0.001***
delaysync	0.01	0.0016	5.59	<0.001***
proprioceptive drift ~ delay				
(Intercept)	1.66	3.28	0.51	0.61
delaysync	-3.31	4.64	-0.72	0.48
user load ~ delay				
(Intercept)	5.13	2.18	2.35	0.02
delaysync	-10.26	3.09	-3.33	<0.01*

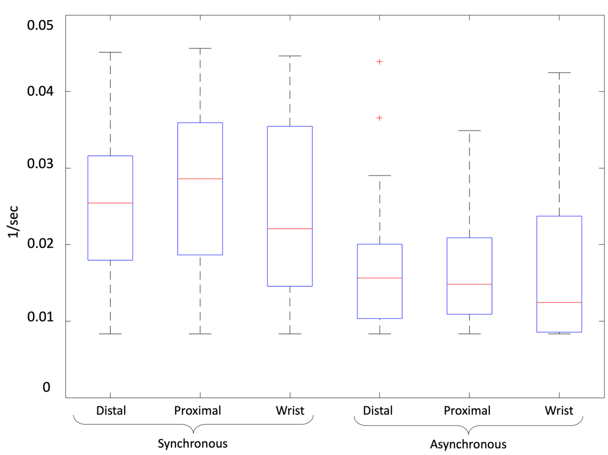


Fig. 4. Boxplots of task completion in the three feedback conditions with the feedback applied synchronously. The completion is based on the reciprocal of the completion time of the task.

significant effect on task completion. Specifically, task completion in the synchronous condition is slightly higher than that in the asynchronous condition (Table IV).

In the synchronous condition, the mean rate of task completion when the feedback is applied on the distal phalanx of the index finger and the thumb is slightly higher than the rate of completion for the other two cases, with the means for the three cases being: $Distal = 0.025\ 1/sec$, $Proximal = 0.025\ 1/sec$, and $Wrist = 0.024\ 1/sec$ (Fig. 4). Even though, the effect of the placement of the haptic feedback device is not significant, it should be mentioned that the percentage of task completion for the different conditions when the feedback was applied synchronously to the participant were slightly different: $Distal = 96.0\%$, $Proximal = 96.0\%$, and $Wrist = 88.0\%$.

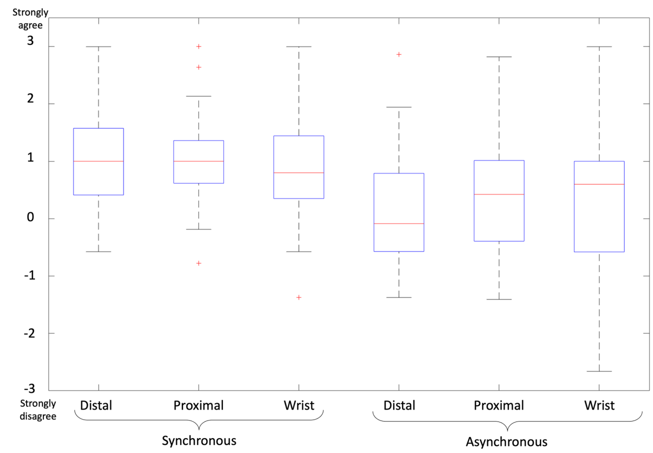


Fig. 5. Boxplots of the embodiment questionnaire based on the the work by Longo et al. [19]. The values -3 implied strongly disagree, while the values 3 implies strongly agree.

B. Proprioceptive Drift

The mean drift distance was 7.33 cm towards the virtual hand. Our results indicate that proprioceptive drift was neither affected by the placement of the feedback device nor by the delay. These results are inconsistent with our hypotheses 1a and 2a.

C. Subjective Embodiment

As mentioned above, the embodiment rating represents the mean of all the 10 questionnaire items listed in Table I. Fig. 5 presents the boxplots of the embodiment ratings obtained in the user study for all the feedback conditions tested with a synchronous feedback and asynchronous feedback to the participant. From Fig. 5, we can see that the there is no major impact on the embodiment across the different feedback locations. This suggests that moving the haptic device further away from the point of actual contact (the fingertips) will not decrease the feeling of embodiment of the user.

Our main results suggest that delay has a statistically significant effect on subjective embodiment (Table IV). Specifically, subjective embodiment ratings in the synchronous condition are higher than those in the asynchronous condition. Such results are inconsistent with our hypothesis 1b, whereas consistent with our hypothesis 2b.

In addition, we also analyzed the effects of delay and feedback location on each subscale of subjective embodiment ratings (ownership, location, agency; centered). We followed the same procedure as previously stated. A type II MANOVA (Pillai's Trace test) suggests that embodiment ratings for different subscales *only* differ statistically significantly based on delay ($F(3, 142) = 7.19, p < 0.001$), not on feedback location ($F(6, 286) = 0.50, p = 0.81$) or the interaction ($F(6, 268) = 0.37, p = 0.90$).

The simple multivariate regression suggests that delay has a statistically significant effect on each of the subscale of embodiment rating. Consistent with the results above, subjective embodiment ratings are higher in the synchronous condition for subscale ownership ($F(1, 148) = 7.25, p <$

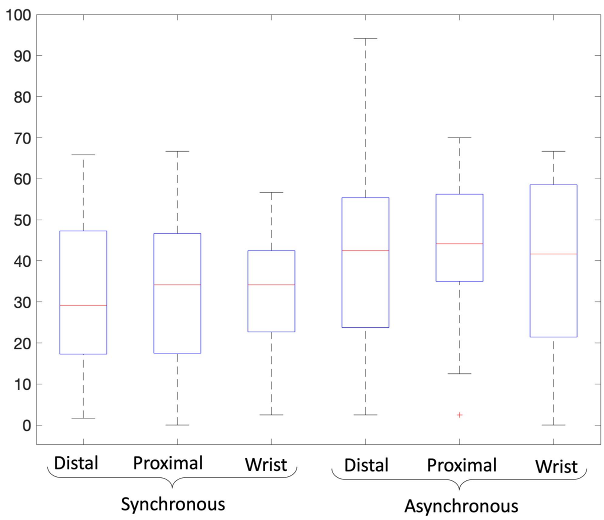


Fig. 6. Means and deviation of the user load based on the NASA-TLX questionnaire [40].

0.01), location ($F(1, 148) = 15.74, p < 0.001$), and agency ($F(1, 148) = 19.2, p < 0.001$).

D. User Load

As mentioned earlier, user load is measured with the NASA-TLX questionnaire, and lower values in user load indicate a lower load on the participant during the interactions with the device. Therefore, lower values in user load are considered better for the interactions done using the device. Our main results suggest that delay also has a statistically significant effect on user load, where user load in the synchronous condition are lower than that in the asynchronous condition (Table IV). These results are inconsistent with our hypothesis 1c, whereas consistent with our hypothesis 2c. In Fig. 6, we show the descriptive results of user load for different feedback conditions in the synchronous condition. From the descriptive results, we observe a slightly higher user load in the condition when the haptic feedback was applied to the wrist of the participant than the other two cases when the feedback was applied synchronously to the participants.

We also analyzed the effects of delay and feedback location on each individual item in the NASA-TLX questionnaire (mental demands, physical demands, temporal demands, own performance, effort, and frustration). We followed the same procedure as previously stated. A type II MANOVA (Pillai's Trace test) suggests that ratings for different items *only* differ statistically significantly based on delay ($F(6, 139) = 3.70, p < 0.01$), not on feedback location ($F(12, 280) = 0.45, p = 0.94$) or the interaction ($F(12, 280) = 0.19, p = 1.00$).

The simple multivariate regression suggests that ratings are statistically significantly higher in the asynchronous condition for temporal demands ($F(1, 148) = 6.751, p < 0.022$), own performance ($F(1, 148) = 13.34, p < 0.001$), effort ($F(1, 148) = 13.48, p < 0.001$), and frustration ($F(1, 148) = 10.33, p < 0.01$). The effect of delay is not statistically significant on mental demands ($F(1, 148) = 1.59, p = 0.21$) and physical demands ($F(1, 148) = 2.49, p = 0.12$).

IV. Discussion

The results reported in this manuscript confirm some aspects of wearable haptics and embodiment theory that were already known in the literature and introduce some novel possibilities that can be importantly exploited in the design of new devices. In particular, the results of our study emphasize the critical role of minimizing the delay between actual contact and the application of feedback [42]. Additional delays reduce the user's sense of embodiment within the virtual environment. Therefore, it is important to design interfaces with minimal delays to enhance user performance and increase the feeling of embodiment. Notably, the results reveal that the proprioceptive drift (PPD) remains unaffected by the positioning of the haptic device and the delay. In the existing literature, the influence of different factors on PPD has been a subject of debate [37], with some studies suggesting an effect of delay [30], [43], while others did not observe such an effect [44], [45]. Our prior work (Fröhner et al., 2018 [22]), employing a similar experimental design and protocols, aligns with our current findings, demonstrating no effect of delay on PPD.

From a design perspective, our results suggest that for tasks that can be paradigmatically represented by our pick-and-place scenario, haptic feedback devices can be placed proximally without compromising performance and experience, e.g., on the user's wrist. This implies that novel wearable wrist-worn devices can be developed that allow the fingers of the hands to remain free, facilitating the grasping of other real objects while receiving feedback from the VR environment. This aspect may be of particular interest in all the applications of mixed reality where users may need to interact both with a virtual and the real environment. Moreover, wrist-worn devices provide unobstructed hand visibility for precise motion tracking, thereby improving accuracy and making the interactions intuitive.

However, this work presents also some limitations. In light of our unconfirmed hypotheses, we recognize that the effect of feedback positioning on embodiment may be influenced by the considered task. Although pick-and-place tasks can represent a broader set of manipulation scenarios, other actions should be studied to understand if similar effects can be obtained, e.g. surface exploration. This evaluation will be considered in our future works. In addition, while our analyses suggested no effect of feedback location or interaction between feedback location and delay on perceived level of embodiment, it is worth exploring whether participants may intuitively associate the propagation of feedback with the delay of feedback. Therefore, we suggest future work that empirically investigate whether perceived embodiment is affected as the delay of the feedback changes proportionally to the distance between the haptic interface and the contact point. Furthermore, an inherent limitation of vision-based hand tracking is the potential degradation of hand tracking performance when devices are present on the fingertips or hand. This might have reduced the PPD values and embodiment ratings in our distal (and proximal) conditions. As discussed in Section I, interface designers aim to create hands-free devices to ensure comfortable interactions [23], [24], [25].

In future research, we intend to design tasks that engage users more deeply during execution and apply feedback proportional to the forces exerted in the virtual environment. We also plan to explore the use of motion capture systems that do not depend on vision-based tracking of the hands.

V. Conclusion

This study investigates the influence of the location of haptic feedback on the embodiment of virtual hands and user load. We proposed two hypotheses. First, the closer the haptic feedback to the point of actual interaction, higher the proprioceptive drift (hypothesis 1a), the higher the subjective embodiment (hypothesis 1b), the lower the user load (hypothesis 1c). Second, delaying the motion of the virtual hand leads to a lower proprioceptive drift (hypothesis 2a), a lower feeling of subjective embodiment (hypothesis 2b), and to a higher user load (hypothesis 2c). To investigate this, we conducted a 3x2 repeated measures study: feedback was varied between the distal phalanx of the index finger and the thumb, the proximal phalanx of the index finger and the thumb, and the wrist. All those cases were tested with the application of the feedback being applied synchronously to the participant in one case, and with an additional delay of 350 ms in the second case. Our results are not consistent with hypotheses 1a, 1b, 1c and 2a, but are consistent with hypotheses 2b and 2c. In addition, we found a positive correlation between subjective embodiment and task completion, and a negative correlation between subjective correlation and user load. The main implication of this result is that the delay between the actual contact and the application of the feedback is important, and the interfaces need to be designed to minimize these delays in order to increase the users' feeling of embodiment. Furthermore, since the results suggest that there is no significant loss in task completion with the location of the haptic feedback devices, they can be moved away from the fingertips to a proximal location (e.g., wrist or the forearm) without compromising the users' task completion or embodiment, at least for pick-and-place tasks. These results are specially interesting for designing interfaces for prosthetic applications where the feedback is far from the point of actual interaction.

References

[1] A. Dwivedi, G. Gorjup, Y. Kwon, and M. Liarokapis, "Combining electromyography and fiducial marker based tracking for intuitive telemanipulation with a robot arm hand system," in *Proc. IEEE 28th Int. Conf. Robot Hum. Interactive Commun.*, 2019, pp. 1–6.

[2] J. B. Iannuzzi and Z. Faulds, "Top companies chasing the metaverse," 2021, Accessed: Jan. 22, 2023. [Online]. Available: https://www.thestreet.com/technology/companies-making-money-metaverse

[3] C. Newton, "Mark in the metaverse," 2021, Accessed: Jan. 22, 2023. [Online]. Available: https://www.thestreet.com/technology/companies-making-money-metaverse

[4] S. Haddadin, L. Johannsmeier, and F. D. Ledezma, "Tactile robots as a central embodiment of the tactile internet," *Proc. IEEE*, vol. 107, no. 2, pp. 471–487, Feb. 2019.

[5] C. Hao, A. Dwivedi, and P. Beckerle, "A literature-based perspective on human-centered design and evaluation of interfaces for virtual reality in robotics," in *Proc. Hum.-Friendly Robot. 2022: HFR: 15th Int. Workshop Human-Friendly Robot.*, 2023, pp. 1–13.

[6] N. Nostadt, D. A. Abbink, O. Christ, and P. Beckerle, "Embodiment, presence, and their intersections: Teleoperation and beyond," *ACM Trans. Hum.-Robot Interact.*, vol. 9, no. 4, pp. 1–19, 2020.

[7] M. Botvinick and J. Cohen, "Rubber hands 'feel'touch that eyes see," *Nature*, vol. 391, no. 6669, pp. 756–756, 1998.

[8] M. Tsakiris and P. Haggard, "The rubber hand illusion revisited: Visuotactile integration and self-attribution," *J. Exp. psychol.: Hum. Percep. Perform.*, vol. 31, no. 1, 2005, Art. no. 80.

[9] I. S. MacKenzie, *Human-Computer Interaction: An Empirical Research Perspective*. Amsterdam, The Netherlands: Elsevier, 2012.

[10] J. K. Koehn and K. J. Kuchenbecker, "Surgeons and non-surgeons prefer haptic feedback of instrument vibrations during robotic surgery," *Surg. Endoscopy*, vol. 29, pp. 2970–2983, 2015.

[11] M. Maisto, C. Pacchierotti, F. Chinello, G. Salvietti, A. De Luca, and D. Prattichizzo, "Evaluation of wearable haptic systems for the fingers in augmented reality applications," *IEEE Trans. Haptics*, vol. 10, no. 4, pp. 511–522, Oct.–Dec. 2017.

[12] A. Adilkhanov, M. Rubagotti, and Z. Kappassov, "Haptic devices: Wearability-based taxonomy and literature review," *IEEE Access*, vol. 10, pp. 91923–91947, 2022.

[13] E.-L. Sallnäs, K. Rassmus-Gröhn, and C. Sjöström, "Supporting presence in collaborative environments by haptic force feedback," *ACM Trans. Comput.- Hum. Interact.*, vol. 7, no. 4, pp. 461–476, 2000.

[14] P. Cornelio et al., "The sense of agency in emerging technologies for human–computer integration: A review," *Front. Neurosci.*, vol. 16, 2022, Art. no. 949138.

[15] J. M. Juliano et al., "Embodiment is related to better performance on a brain–computer interface in immersive virtual reality: A pilot study," *Sensors*, vol. 20, no. 4, 2020, Art. no. 1204.

[16] S. Y. S. Kim, N. Prestopnik, and F. A. Biocca, "Body in the interactive game: How interface embodiment affects physical activity and health behavior change," *Comput. Hum. Behav.*, vol. 36, pp. 376–384, 2014.

[17] M. Slater, D. Pérez Marcos, H. Ehrsson, and M. V. Sanchez-Vives, "Towards a digital body: The virtual arm illusion," *Front. Hum. Neurosci.*, vol. 2, 2008, Art. no. 181.

[18] L. Raz, P. L. Weiss, and M. Reiner, "The virtual hand illusion and body ownership," in *Proc. Int. Conf. Hum. Haptic Sens. Touch Enabled Comput. Appl.*, 2008, pp. 367–372.

[19] M. R. Longo, F. Schüür, M. P. Kammers, M. Tsakiris, and P. Haggard, "What is embodiment? A psychometric approach," *Cogn.*., vol. 107, no. 3, pp. 978–998, 2008.

[20] M. Gonzalez-Franco and T. C. Peck, "Avatar embodiment. Towards a standardized questionnaire," *Front. Robot. AI*, vol. 5, 2018, Art. no. 74.

[21] T. C. Peck and M. Gonzalez-Franco, "Avatar embodiment. a standardized questionnaire," *Front. Virtual Reality*, vol. 1, 2021, Art. no. 575943.

[22] J. Fröhner, G. Salvietti, P. Beckerle, and D. Prattichizzo, "Can wearable haptic devices foster the embodiment of virtual limbs?," *IEEE Trans. Haptics*, vol. 12, no. 3, pp. 339–349, Jul.–Sep. 2018.

[23] T. S. Saponas, D. S. Tan, D. Morris, R. Balakrishnan, J. Turner, and J. A. Landay, "Enabling always-available input with muscle-computer interfaces," in *Proc. 22nd Annu. ACM Symp. User Interface Softw. Technol.*, 2009, pp. 167–176.

[24] M. Shahmohammadi, A. Dwivedi, P. Nielsen, A. Taberner, and M. Liarokapis, "On lightmyography: A new muscle machine interfacing method for decoding human intention and motion," in *Proc. IEEE 43rd Annu. Int. Conf. Eng. Med. Biol. Soc.*, 2021, pp. 4744–4748.

[25] J. Chapman, A. Dwivedi, and M. Liarokapis, "A wearable, open-source, lightweight forcemyography armband: On intuitive, robust muscle-machine interfaces," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2021, pp. 4138–4143.

[26] M. Shahmohammadi, B. Guan, R. V. Godoy, A. Dwivedi, P. Nielsen, and M. Liarokapis, "On lightmyography based muscle-machine interfaces for the efficient decoding of human gestures and forces," *Sci. Rep.*, vol. 13, no. 1, 2023, Art. no. 327.

[27] D. M. Lloyd, "Spatial limits on referred touch to an alien limb may reflect boundaries of visuo-tactile peripersonal space surrounding the hand," *Brain Cogn.*, vol. 64, no. 1, pp. 104–109, 2007.

[28] S. Ocklenburg, N. Rüther, J. Peterburs, M. Pinnow, and O. Güntürkün, "Laterality in the rubber hand illusion," *Laterality*, vol. 16, no. 2, pp. 174–187, 2011.

[29] M. Mori, K. F. MacDorman, and N. Kageki, "The uncanny valley [from the field]," *IEEE Robot. Automat. Mag.*, vol. 19, no. 2, pp. 98–100, Jun. 2012.

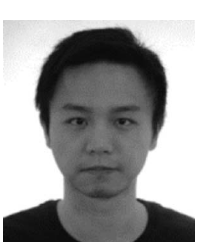
[30] S. Shimada, K. Fukuda, and K. Hiraki, "Rubber hand illusion under delayed visual feedback," *PLoS One*, vol. 4, no. 7, 2009, Art. no. e6185.

[31] G. Richard, T. Pietrzak, F. Argelaguet, A. Lécuyer, and G. Casiez, "Studying the role of haptic feedback on virtual embodiment in a drawing task," *Front. Virtual Reality*, vol. 1, 2021, Art. no. 573167.

[32] D. Prattichizzo, F. Chinello, C. Pacchierotti, and M. Malvezzi, "Towards wearability in fingertip haptics: A 3-DoF wearable device for cutaneous force feedback," *IEEE Trans. Haptics*, vol. 6, no. 4, pp. 506–516, Oct.–Dec. 2013.

[33] C. Pacchierotti, G. Salvietti, I. Hussain, L. Meli, and D. Prattichizzo, "The hring: A wearable haptic device to avoid occlusions in hand tracking," in *Proc. IEEE Haptics Symp.*, 2016, pp. 134–139.
[34] S. Casini, M. Morvidoni, M. Bianchi, M. Catalano, G. Grioli, and A. Bicchi, "Design and realization of the cuff-clenching upper-limb force feedback wearable device for distributed mechano-tactile stimulation of normal and tangential skin forces," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2015, pp. 1186–1193.
[35] A. G. Perez et al., "Optimization-based wearable tactile rendering," *IEEE Trans. Haptics*, vol. 10, no. 2, pp. 254–264, Apr.–Jun. 2017.
[36] M. Rohde, M. Luca, and M. O. Ernst, "The rubber hand illusion: Feeling of ownership and proprioceptive drift do not go hand in hand," *PLoS One*, vol. 6, 2011, Art. no. e21659, doi: 10.1371/journal.pone.0021659.
[37] O. Christ and M. Reiner, "Perspectives and possible applications of the rubber hand and virtual hand illusion in non-invasive rehabilitation: Technological improvements and their consequences," *Neurosci. Biobehavioral Rev.*, vol. 44, pp. 33–44, 2014.
[38] A. Joshi, S. Kale, S. Chandel, and D. K. Pal, "Likert scale: Explored and explained," *Brit. J. Appl. Sci. Technol.*, vol. 7, no. 4, 2015, Art. no. 396.
[39] S. G. Hart, "Nasa task load index (TLX)," Ames Res. Center, Mountain View, CA, USA, Tech. Rep. 20000021488, 1986.
[40] S. G. Hart, "Nasa-task load index (NASA-TLX); 20 years later," in *Proc. Hum. Factors Ergonom. Soc. Annu. Meeting*, 2006, pp. 904–908.
[41] C. Ateş, Ö. Kaymaz, H. E. Kale, and M. A. Tekindal, "Comparison of test statistics of nonnormal and unbalanced samples for multivariate analysis of variance in terms of type-I error rates," *Comput. Math. Methods Med.*, vol. 2019, 2019, Art. no. 2173638.
[42] W. Fu, M. M. van Paassen, D. A. Abbink, and M. Mulder, "Framework for human haptic perception with delayed force feedback," *IEEE Trans. Human-Mach. Syst.*, vol. 49, no. 2, pp. 171–182, Apr. 2019.
[43] D. Tajima, T. Mizuno, Y. Kume, and T. Yoshida, "The mirror illusion: Does proprioceptive drift go hand in hand with sense of agency?," *Front. Psychol.*, vol. 6, 2015, Art. no. 200.
[44] A. Marotta, M. Tinazzi, C. Cavedini, M. Zampini, and M. Fiorio, "Individual differences in the rubber hand illusion are related to sensory suggestibility," *PLoS One*, vol. 11, no. 12, 2016, Art. no. e0168489.
[45] H. H. Ehrsson, A. Fotopoulou, D. Radziun, M. R. Longo, and M. Tsakiris, "No specific relationship between hypnotic suggestibility and the rubber hand illusion," *Nature Commun.*, vol. 13, no. 1, 2022, Art. no. 564.

Anany Dwivedi received the Ph.D. degree with New Dexterity Research Group, the University of Auckland, Auckland, New Zealand. His work focused on deciphering the myoelectric activity of the muscles of the human forearm and hand to decode dexterous manipulation motions in both real and virtual environments. He is currently a Postdoctoral Researcher with the Artificial Intelligence Institute, University of Waikato, Hamilton, New Zealand, focusing in the field of eXplainable Artificial Intelligence (XAI). He was a Postdoctoral Researcher with the Chair of Autonomous Systems and Mechatronics, Friedrich-Alexander-Universität-Erlangen-Nürnberg, Erlangen, Germany, where his work focused on exploring bi-directional Human-Machine Interfaces to increase presence and embodiment of the user during interaction with various environments while considering human-centered design principles.



Shihan Yu received the B.E. degree in electrical engineering and automation from Tongji University, Shanghai, China, in 2016 and the M.S. degree in automation from the University of Erlangen-Nuremberg, Erlangen, Germany in 2023. His major focusis on control theory, sensor, and power engineering. His research interests include human-computer interaction design, wearable device development, robot navigation, signal processing, and the application of VR/AR.

Chenxu Hao received the Ph.D. degree in cognition and cognitive neuroscience from the Department of Psychology, University of Michigan, Ann Arbor, MI, USA. She is currently a Postdoctoral Researcher with the Department of Intelligent Systems, Delft University of Technology, Delft, the Netherlands.

Gionata Salvietti (Senior Member, IEEE) received the M.S. degree in robotics and automation and Ph.D. degree in information engineering from the University of Siena, Siena, Italy, in 2009 and 2012, respectively. He is currently an Associate Professor with the Department of Information Engineering and Mathematics, University of Siena. From 2012 to 2015, he was a Post-doc Researcher with the Istituto Italiano di Tecnologia, Genoa, Italy. He was a Visiting Researcher with the DLR Institute for Robotic and Mechatronics, in 2012 and a Visiting Student with TAMS Group, University of Hamburg, Hamburg, Germany, in 2008. He is an Associate Editor for the IEEE Robotics and Automation Letters, IEEE TRANSACTION ON ROBOTICS, and IEEE Transaction on Haptics. His research interests include robotic and human grasping, haptics, human centered robotics, and design of assistive devices.

Domenico Prattichizzo (Fellow, IEEE) received the M.S. degree in electronics engineering and the Ph.D. degree in robotics and automation from the University of Pisa, Pisa, Italy, in 1991 and 1995, respectively. He is currently a Full Professor of robotics with the University of Siena, Siena, Italy, the Senior Scientist with the Italian Institute of Technology, Genoa, Italy, Co-founder of WEART, Milan, Italy, a start-up on wearable haptic, Editor-in-chief of IEEE TRANSACTIONS ON HAPTICS, President of Eurohaptics society, and Co-founder of the Italian Institute of Robotics and Intelligent Machines. Human and robotic hands, along with haptic perception and the art of manipulating objects, have polarized his research, which is increasingly oriented towards highly wearable robotics and wearable haptics. Scientific Coordinator of several research projects funded by the European Union, within the Horizon 2020 and FP7 programs. From 2013 to 2017, he was General Co-ordinator of the FP7 IP collaborative project WEARHAP: WEARable HAPtics for Humans and Robots. His RemoTouch project, on tactile communication, was selected for presentation at Expo Shanghai 2010 as part of the Italia degli Innovatori initiative, promoted by the Minister for Public Administration and Innovation. He was the Co-Editor-in-chief of IEEE TRANSACTIONS ON HAPTICS from 2007 to 2013, Member of the editorial board of Springer Series on Touch and Haptic Systems (advisory board from 2018), Biomedical Robotics (Frontiers in Robotics and AI) (since 2014), IEEE Robotics and Automation Letters from 2015 top 2016, and IEEE TRANSACTIONS ON ROBOTICS and IEEE TRANSACTIONS ON CONTROL SYSTEMS TECHNOLOGIES from 2003 to 2007. He is the Author of more than 500 publications in scientific journals, books, and conference proceedings.

Philipp Beckerle (Senior Member, IEEE) received the Dr.-Ing. degree in mechatronics from TU Darmstadt, Darmstadt, Germany, in 2014 and the habilitation degree from TU Dortmund, Dortmund, Germany, in 2021. He is currently a Full Professor and the chair of Autonomous Systems and Mechatronics with FAU Erlangen-Nürnberg, Erlangen, Germany, and was a Visiting Researcher with Vrije Universiteit Brussel, Arizona State University, Tempe, AZ, USA and the University of Siena, Siena, Italy. His research interests include human-centered mechatronics and robotics and his work was honored with various awards.