EMBODIMENT AND CO-ADAPTATION THROUGH HUMAN-MACHINE INTERFACES: AT THE BORDER OF ROBOTICS, NEUROSCIENCE AND PSYCHOLOGY

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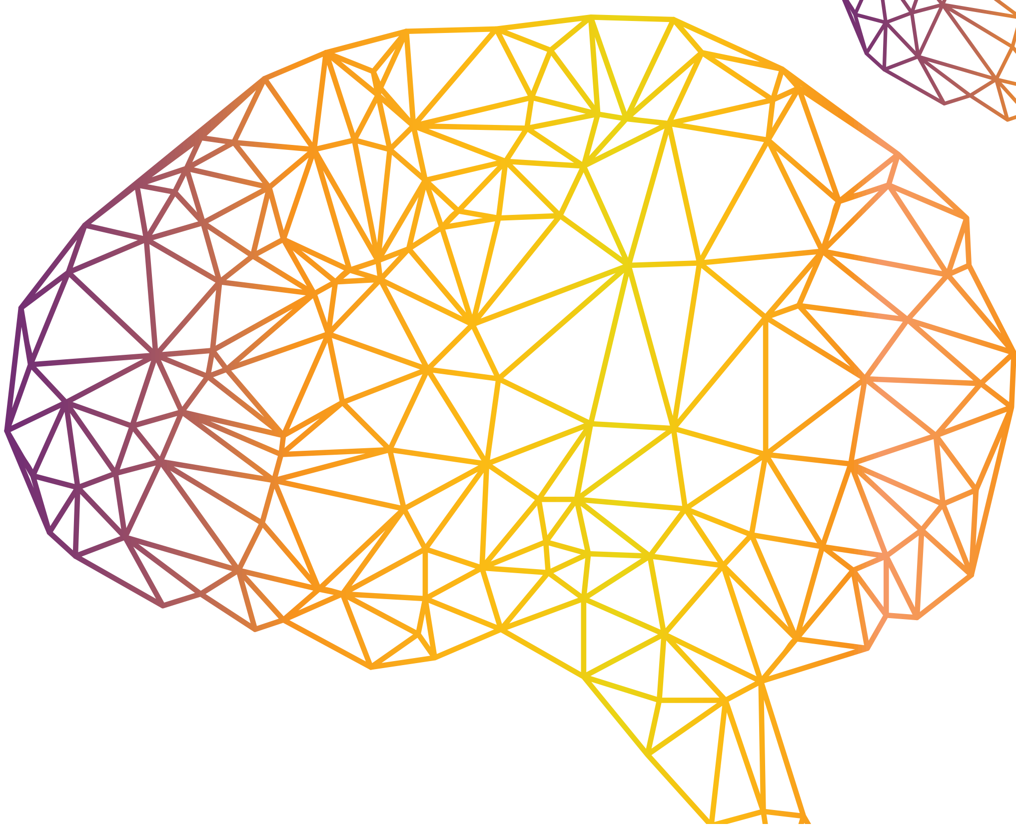

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EMBODIMENT AND CO-ADAPTATION THROUGH HUMAN-MACHINE INTERFACES: AT THE BORDER OF ROBOTICS, NEUROSCIENCE AND PSYCHOLOGY

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EDITORIAL
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Editorial: Embodiment and Co-adaptation Through Human-Machine Interfaces: At the Border of Robotics, Neuroscience and Psychology

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Keywords: human-machine interfaces, sensorimotor control and learning, brain plasticity, constructivist psychology, cognitive models, embodiment, agency

Editorial on the Research Topic

Embodiment and Co-adaptation Through Human-Machine Interfaces: At the Border of Robotics, Neuroscience and Psychology

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INTRODUCTION

Traditionally, robotics and psychology have little to share; at least, if we think of robotics as an endeavor to build machines able to *autonomously* perform tasks that are undesirable or impossible for human beings. Nevertheless, besides addressing safety requirements for close physical interaction, which are tackled by approaches like soft robotics and impedance/admittance control (Albu-Schäffer et al., 2008; Kim et al., 2013; Schumacher et al., 2019), the two fields gradually approached each other over the recent years. Together with the surge of virtual and extended reality technologies that can provide immersive environments, this opens up an exceptional opportunity to the scientific community: that of studying the human being via *human-robot interaction*, for which joint competencies from robotics, neuroscience, and psychology are critical (Rognini and Blanke, 2016; Beckerle et al., 2018a).

Driven by two specific concepts encircled by the aforementioned idea, namely embodiment and co-adaptation, we have launched this Research Topic (RT). In this context, we understand embodiment as something being "experienced as a part of the body schema due to multisensory integration" (Nostadt et al., 2020) and co-adaptation as the robot learning to align to "its human operator/user while the human adapts to it" (Beckerle et al., 2018a). Especially in the fields of rehabilitation and assistive robotics, where the robotic device is physically attached to the user's body, the tighter integration between user's needs and system design is particularly critical. To what extent a robot can, should or should not feel like a part of the user's bodily self through mutual adaptation has been increasingly investigated and discussed (Makin et al., 2017; Beckerle et al., 2018a). This human-centered approach appears crucial for assistive robotics and requires methodological instruments and knowledge from human psychology, e.g., theories of constructivist psychology, and insights into multisensory foundations of the bodily self and human motor control (Makin et al., 2017; Beckerle et al., 2018b; Niedernhuber et al., 2018).

We are happy to present and discuss the essence of the 14 contributions that we collected in this RT, which all concentrate on embodiment, co-adaptation, and bidirectional human-machine interfaces. Through joint contributions from engineers, neuroscientists, and psychologists, this RT shows a remarkable level of interdisciplinarity, which we deem necessary to tackle this research area. We hope that this RT will boost such research and provoke thoughts and ideas in young and established scientists alike, with the aim of building further bridges between different disciplines.

EMBODIMENT

A central question for assistive robotics is to what extent the robot is integrated into the user's body schema and body image. However, to answer this question, we first need to understand the integration processes and elucidate factors that can affect the feeling of embodiment as well as develop methods to modulate it. In a perspective article, Matamala-Gomez et al. present ideas for a new rehabilitation approach that employs full virtual body-ownership illusions, using 360° videos to assess and modulate the representation of the impaired limb, to improve motor rehabilitation of stroke patients. They put forward that such "positive technology" could precede more conventional motor rehabilitation methods and normalize a distorted body schema and image. Barresi et al. assess whether modulating the psychophysiological state through controlled breathing affects the feeling of embodiment induced by an experimental protocol akin to the virtual hand illusion. Their results indicate that slowing down breathing pace using online biofeedback of respiratory rate seems to induce stronger embodiment of the virtual hand compared to the condition with normal breathing rate. Their study emphasizes that embodiment is indeed a complex experience that depends on multiple factors, including interoceptive processes. Bekrater-Bodmann also investigates the multifaceted nature of this phenomenon by elucidating factors associated with the embodiment of a lower limb prosthesis. His findings point to the particular importance of subjective-evaluative variables related to how a person perceives the amputation and the device, also revealing a positive relationship between embodiment and user satisfaction. Similarly, Sturma et al., who investigate the body image pre and post elective amputation and prosthetic reconstruction in a longitudinal study in patients with brachial plexus injuries, stress the huge interindividual differences in the patient's sense of embodiment. Nevertheless, their data suggests a more positive body image 2.5 years after the surgical procedure. Middleton and Ortiz-Catalan use deep semi-structured interviews with three prosthesis users to elucidate personal and social implications of living with an upper limb prosthesis. From a medical anthropology perspective, the study shows that the relation between the users and their bionic limb is subject-dependent, complex, and constantly evolving. They find a tight coupling between the quality of prosthesis use in daily life and users' self-esteem, self-image, and incorporation of the device into the body.

CO-ADAPTATION

Embodiment is likely shaped by a process of adaptation and tight interaction between the user and the machine. If the system can also adapt to the user, e.g., as in prosthetics (Hahne et al., 2017), this process is called mutual adaptation or *co-adaptation*. Some of our authors have hereby tried to define and determine, measure, and quantify co-adaptation, in order to draw a path toward fostering and exploiting it. Studying co-adaptation in a team, van Zoelen et al. engage 18 participants in a cooperative human-robot task and define co-adaptation as a rather fast, changing attitude in human-robot interaction. This model enables them to recognize four categories of interaction (stable, sudden, gradual, and active), which are denoted as *interaction patterns*. De Santis takes a more quantitative approach and proposes a general framework for user-machine interaction. The problem is explicitly formulated as a closed-loop block diagram, monitoring the change in the parameters of both the user and a machine to define co-adaptation. Schofield et al.'s perspective argues that embodiment in myoelectrically-controlled prostheses is the key to achieve optimal control and user satisfaction. Tool incorporation, agency and ownership are the three pathways the authors identify to achieve, in the long run, an embodied bionic limb.

HUMAN-MACHINE INTERFACES

To facilitate embodiment and co-adaptation during human-robot interaction, the implementation of suitable interfaces between human and machine is a challenge of crucial relevance (Beckerle et al., 2018a). For efficient communication between the interacting partners, these interfaces must inevitably be *bidirectional*. They need to enable the user to send commands to the system but they also need to convey sensor data from the device back to the user, thereby closing the control loop. Accordingly, Moore et al. investigate the question of how to convert haptic feedback from prosthetic fingertips into vibrotactile feedback provided to another part of the participants' bodies. They conclude that embodiment was similar for natural feedback compared to providing proximal vibrotactile feedback. Cansev et al. review neurophysiological and psychological design criteria to create haptic interfaces that can mediate affective touch and derive recommendations for interface design. To enable this, future bidirectional human-machine interfaces need to transmit slow and low-force motion or force/torque patterns and consider their relation to the users' experiences. Mouchoux et al. investigate how different schemes for the integration of volitional and automatic control influence the performance and usability of a semi-autonomous prosthesis. The study finds that all semi-autonomous schemes increased the performance with respect to the purely manual control. However, the study also reveals that the specific approach to integrating automatic and manual control is an important factor for the design of a semi-autonomous prosthesis, as different schemes resulted in different performance, especially when automatic control was less reliable. Beyond this, Falandays et al. examine joint decision-making in human-machine interfaces and how choices are influenced by the characteristics of the provided response options. Their results imply that users will often begin acting before their cognitive choice has been finalized, and in addition, synergies between humans and machines are reported.

INTERDISCIPLINARY PERSPECTIVES

Wudarczyk et al. contributed an exquisitely meta-scientific paper relating to the lessons learned during an interdisciplinary project. We cannot but agree with most of their claims, such as, e.g., the necessity of finding common goals, agreeing on publication outlets and a common language, reciprocally transferring technology and discussing the differences in research practices belonging to different fields. Lastly, in a short but dense contribution, Bettoni et al. propose that radical constructivism might be used as a unifying framework to design the machine-learning core of a myocontrol system for prosthetics. Elements of this psychological discipline seem particularly suited to the authors to shape the interaction protocols, interface, and channels of myocontrol, with the aim of fostering co-adaptation.

In conclusion, we believe that an interdisciplinary perspective is crucially required to achieve human-machine interfaces that promote embodiment and co-adaptation. Despite such collaborations demand for continuous adjustment between project partners from different domains, the contributions to this RT underline that such interaction is well worth the efforts. Crossing the field boundaries is enriching for all the sides, yields promising results, and is therefore the approach that shall be welcomed and further developed in the next years.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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ORIGINAL RESEARCH
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Neuromusculoskeletal Arm Prostheses: Personal and Social Implications of Living With an Intimately Integrated Bionic Arm

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People with limb loss are for the first time living chronically and uninterruptedly with intimately integrated neuromusculoskeletal prostheses. This new generation of artificial limbs are fixated to the skeleton and operated by bidirectionally transferred neural information. This unprecedented level of human–machine integration is bound to have profound psychosocial effects on the individuals living with these prostheses. Here, we examined the psychosociological impact on people as they integrate neuromusculoskeletal prostheses into their bodies and lives. Three people with transhumeral amputations participated in this study, all of whom had been living with neuromusculoskeletal prostheses in their daily lives between 2 and 6 years at the time of the interview. Direct neural sensory feedback had been enabled for 6 months to 2 years. Participants were interviewed about their experiences living with the neuromusculoskeletal prostheses in their home and professional daily lives. We analyzed these interviews to elucidate themes using an interpretive phenomenological approach that regards participants' own experiences as forms of expertise and knowledge-making. Our participant-generated results indicate that people adapted and integrated the technology into functional and social arenas of daily living, with positive psychosocial effects on self-esteem, self-image, and social relations intimately linked to improved trust of the prostheses. Participants expressed enhanced prosthetic function, increased and more diverse prosthesis use in tasks of daily living, and improved relationships between their prosthesis and phantom limb. Our interviews with patients also generated critiques of the language commonly used to describe human-prosthetic relations, including terms such as "embodiment," and the need for specificity surrounding the term "natural" with regard to control versus sensory feedback. Experiences living with neuromusculoskeletal prostheses were complex and subject-dependent, and therefore future research should consider human–machine interaction as a relationship that is constantly enacted, negotiated, and deeply contextualized.

Keywords: prosthetics, implanted electrodes, qualitative research, social studies of science and technology, human–machine interface

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INTRODUCTION

Prosthetic research and development have long sought to replace a lost biological limb with a functionally equivalent artificial one. In the early 1970s, researchers realized that implanted electrodes could provide superior control (Hoffer and Loeb, 1980; Stein et al., 1980), as well as intuitive sensory feedback via direct nerve stimulation (Clippinger et al., 1974, 1981). Recent work has provided further evidence on functional improvements enabled by implanted neuromuscular interfaces (Wendelken et al., 2017; Schiefer et al., 2018; Valle et al., 2018; Mastinu et al., 2019, 2020; Zollo et al., 2019). However, clinical implementation of these efforts had been hindered by the lack of a safe and long-term stable bidirectional interface between implanted electrodes and external prosthetic limbs. Neuromusculoskeletal prostheses, a novel concept in artificial limb replacement, solves this longstanding problem by utilizing a percutaneous osseointegrated implant for direct skeletal attachment of the prosthesis to the body, while also providing bidirectional interfacing to the user's neuromuscular system via implanted electrodes in nerves and muscles (Ortiz-Catalan et al., 2014, 2020) (**Figure 1**).

FIGURE 1 | A neuromusculoskeletal arm prosthesis. An artist's rendering of the signal chain of bidirectional communication between the prosthesis and neuromuscular system via implanted electrodes and a percutaneous osseointegrated implant system.

Three participants (P1, P2, and P3) with unilateral transhumeral amputations were implanted with neuromusculoskeletal limb prostheses and have used them in daily life for over 7 (P1) and 3 (P2 and P3) years without interruption (Ortiz-Catalan et al., 2020). Two participants (P2 and P3) also received targeted muscle reinnervation for intuitive control of their prosthetic hand (Kuiken et al., 2009). Whereas the long-term home use of non-invasive sensorimotor prosthetic systems has been studied with surface electrodes (Schofield et al., 2020), this was the first time people with limb loss could use implanted electrodes to control and receive somatosensory feedback from their prostheses in their daily lives unsupervised and outside the constraints of research laboratories. This breakthrough, which at first glance appears purely technological, has important social consequences, as humans once deprived of an extremity are now living with an intimately integrated artificial limb connected to their skeleton, nerves, and muscles. Quantitative investigations, while indicative of the technology's stability and performance, tell only part of the story. They do not speak directly to the human side of the human–machine relationship. Here, we address for the first time the personal and social experiences of those living with such highly integrated bionic limbs used chronically and ecologically in their environments.

Whereas qualitative research has been limited and conducted in the context of less intimately integrated limb prostheses (Murray, 2004; Lundberg et al., 2011; Widehammar et al., 2018; Cuberovic et al., 2019; Franzke et al., 2019; Graczyk et al., 2019; Hansen et al., 2019), it has nevertheless shown that the perspectives and opinions of those impacted by such medical interventions form a particular kind of evidence and expertise (Murray, 2004). The embodied knowledge (Merleau-Ponty, 1962; Bourdieu, 1990) produced from firsthand experience is unique from data gathered from traditional quantitative methods, serving to complement and at times even challenge quantitative data. Science is a practice of both knowledge-making *and* meaning-making. In our particular case, this relates to how humans experience the world they inhabit and how they create meaning from said experiences. Tending to meaning-making as an integral part of knowledge-making is crucial when studying the human impact of embodied biomedical technologies and served as a motivation for this study. Incorporating qualitative perspectives of those directly impacted by biomedical interventions can offer a more holistic, nuanced understanding of these phenomena, with the capacity to influence both their development and practice (Long et al., 2006).

This study is motivated by patient-driven knowledge about the experience of living with neuromusculoskeletal limb prostheses in patients' own homes and social worlds, outside the laboratory and clinical confines (**Figure 2**). To better understand how and to what extent people incorporate these artificial limbs into their lives and senses of body and self, we conducted in-depth, semi-structured interviews (Bernard, 2006) with the three aforementioned participants. We chose interviews as opposed to questionnaires because we wanted to understand the stories

FIGURE 2 | Neuromusculoskeletal prostheses used in daily life. Participants used an arm prosthesis directly interfaced to their skeleton, nerves, and muscles (neuromusculoskeletal) in professional and personal activities of the daily living for over 7 years. The prostheses do not require additional computational or powering equipment that is not already contained within the prosthetic arm itself (self-contained).

and experiences of patients through open-ended questions and explore more deeply the themes offered by patients *in situ*, unearthing greater detail from their stories than possible in questionnaire form. We used an interpretive phenomenological approach (IPA) for thematic content analysis (Holloway and Todres, 2003; Sandelowski and Barroso, 2003; Smith et al., 2012), which places peoples' experiences and ways of knowing at the center, as lenses to understand lived phenomena. We chose IPA as our analytical tool because this method is best suited for approaching peoples' lived experiences not as objective realities passively perceived (Brocki and Wearden, 2006), but rather actively crafted through peoples' own processes of interpretation and sense-making. IPA was more appropriate to this end than discourse analysis (DA). DA largely bypasses subjects' cognition and perception, focusing instead more linearly on the relationship between respondents' verbal statements and pre-existing discourses (Smith et al., 2012), of which there are few in this emerging phenomenon of neuroprosthetics, particularly from first-person patient perspectives. IPA is also more suitable than grounded theory methodology (Creswell, 2007) because with a sample size of three patients, we did not seek to produce a model universalizing patient experience, but rather to attend to the particularities inherent in this very nascent and emerging human–machine interface. While these first accounts of living with a neuromusculoskeletal prosthesis can help illuminate how users relate to and make sense of intimately integrated biomedical technologies, a more robust sample size and longitudinal study would be needed to derive any grounded theory of significance.

In concert with IPA, we analyzed themes generated by the data itself as opposed to preordained categories. While we prioritized the themes common among all three participants, we also create space for nuances (i.e., noting when one patient raised a perspective not articulated by the other two). Although IPA encourages "dropping" themes not robustly provided in the data, the particularity or singularity of these findings do not necessarily indicate their insignificance. Rather, they indicate that people's values and experiences regarding a phenomenon are inherently nuanced and varied. As the first author is an anthropologist, paying attention to such differences remains important, spawning further research inquiry. What ensues is a depiction of said nuances as well as more generalizable themes as they relate to peoples' firsthand experiences living with neuromusculoskeletal prostheses.

MATERIALS AND METHODS

Experimental Design

An interpretive phenomenological approach (IPA) for thematic content analysis (Holloway and Todres, 2003; Sandelowski and Barroso, 2003; Smith et al., 2012) of semi-structured deep interviews was employed to understand the lived phenomena of uninterrupted, unmonitored home use of the neuromusculoskeletal limb prostheses. At the time of the interviews in February 2019, subjects had been using the system for a period of 6 (P1) or 2 (P2 and P3) years. Participants have continued to use the system up to the publication of this manuscript. In order to reduce biases due to patient compliance, the interviewer was independent from the healthcare and technology providers.

Neuromusculoskeletal Arm Prostheses

The neuromusculoskeletal prosthesis consists of a percutaneous osseointegrated implant (skeletal interface), implanted electrodes in nerves and muscles (neuromuscular interfaces), and signal transfer mechanisms embedded in the skeletal interface enabled by bidirectional communication between the external prosthesis and the internal neuromuscular interfaces. The osseointegrated implant was based on the OPRA implant system (Integrum AB, Sweden) originally used for transfemoral amputations (Brånemark et al., 2001, 2019) and later employed in upper limb amputations (Jönsson et al., 2011). This implant system was further developed to include signal feed through mechanisms and implanted neuromuscular electrodes (e-OPRA), effectively serving as a neuromusculoskeletal human-machine interface (Ortiz-Catalan et al., 2014, 2020). Epimysial electrodes were implanted on remnant muscles as a source for prosthetic control, and spiral cuff electrodes were wrapped around severed nerves to deliver electrical stimulation for sensory feedback. P2 and P3 received targeted muscle reinnervation (TMR) surgery (Kuiken et al., 2009), in which the ulnar nerve was transferred to the short head of the biceps muscle and the distal branch of the radial nerve was transferred to the lateral head of the triceps muscle (Ortiz-Catalan et al., 2020). Myoelectric signals from the reinnervated muscles were observed as soon as 4 weeks after surgery (Mastinu et al., 2018). A custom-designed embedded system within the prosthetic arm was used to control the prosthesis using signals from the epimysial electrodes and to deliver electrical stimulation via the cuff electrodes (Mastinu et al., 2017). The use of the percutaneous osseointegrated implant as a means of bidirectional communication between the prosthesis and the implanted electrodes, as opposed to mechanically unstable percutaneous leads, allowed for the long-term and uninterrupted use of the prosthetic system in daily life (Ortiz-Catalan et al., 2020).

Participants

Three people, all Swedish males with upper-limb transhumeral amputations, participated in this study. Since provided with the neuromusculoskeletal prostheses 4–6 weeks after implantation, all subjects have worn them all the time while awake, except while showering or swimming. No special training or rehabilitation was provided for the subjects to start utilizing their neuromusculoskeletal prostheses, as these subjects had used myoelectric prostheses in the past. Participants were not paid to participate in this study other than reimbursement of their travel costs. Their backgrounds are described subsequently.

Participant 1

Participant 1 (P1), a 46-year-old male, had his right arm amputated due to a malignant tumor in 2003. He used a conventional myoelectric prosthesis with two surface electrodes and socket suspension until 2009, when he was operated with a percutaneous osseointegrated implant for bone-anchoring of the prosthesis. He used a myoelectric prosthesis with surface electrodes and direct skeletal attachment until he became the first subject to be implanted with the neuromusculoskeletal prosthesis in 2013 (Ortiz-Catalan et al., 2014). Between 2013 and 2017 he only used the implanted electrodes for prosthetic control without sensory feedback. Since 2017, he has used the implanted electrodes for control and sensory feedback in daily life. He has commanded the prosthetic hand (SensorHand, Ottobock, Germany) using two electrodes via "direct control" (one myoelectric signal activates one action in the prosthesis) and locking/unlocking the elbow using co-contraction (ErgoArm, Ottobock, Germany). At the time of the interview, P1 had been living with the new neuromusculoskeletal prosthesis at home for the past 6 years (2 years with closed-loop control), sometimes even sleeping while wearing it. He works as a truck driver and deliverer, with a physical job that demands carrying heavy loads. He lives with his partner and three children, and enjoys skiing, ice fishing, and snow scootering in his free time.

Participant 2

Participant 2 (P2), a 45-year-old male, lost his left arm in a high-voltage electrocution accident while working as an electrician in 2011. He underwent osseointegration surgeries in 2014 (Jönsson et al., 2011). From 2014 to 2017 he lived with an osseointegrated prosthetic and two surface electrodes. In January 2017, P2 received implanted electrodes as part of the neuromusculoskeletal interface. He used the implanted electrodes without sensory feedback until 2018 when the sensory feedback was enabled to be used in daily life. He commanded the prosthetic hand (SensorHand, Ottobock, Germany) using "direct control" from two native muscles until 10 weeks after surgery, when the control was switched to the two TMR muscles (Mastinu et al., 2018). He locks/unlocks the elbow using co-contraction (ErgoArm, Ottobock, Germany). At the time of the interview, he had been using the neuromusculoskeletal prosthesis in daily life for 2 years (6 months with closed-loop control). He currently works as a project leader for an installation company, where he heads the electricity division. P2 lives with his wife and three children, and enjoys rally racing and working on cars in his spare time.

Participant 3

Participant 3 (P3), a 43-year-old male, lost his right arm in a work accident as a seaman at sea in 1997, at the age of 22. As he puts it, "I've lived half my life with two arms and half my life with one arm." P3 first received a socket prosthesis in 1997, the summer after his amputation. After 5 years of use, he abandoned the prosthesis due to its cumbersome nature, preferring to live without one for nearly 12 years. During this time, he developed concerns that his body was becoming "crooked" due to the compensation and overuse of one side. He also started developing back pain and spasms. In 2014 he was operated with osseointegration and began using a myoelectric prosthesis again with two surface electrodes. In January 2017, he was implanted with the neuromusculoskeletal interface. He used the implanted electrodes for control without sensory feedback until 2018, when sensory feedback was enabled for closed-loop control in daily life. He commanded the prosthetic hand (SensorHand, Ottobock, Germany) using "direct control" from two native muscles until 40 weeks after surgery, when the control was switched to the two TMR muscles (Mastinu et al., 2018). He locks/unlocks the elbow using co-contraction (ErgoArm, Ottobock, Germany). At the time of the interview, he had been using the neuromusculoskeletal prosthesis at home in daily life for 2 years (6 months with closed-loop control). P3 is an IT consultant, an athletic individual who enjoys orienteering, running, canoeing, and skiing. He lives with his wife and two children.

Data Collection

The first author, who is independent from the development team and a medical anthropologist conducting a larger ethnographic study about patient experiences living with neuromusculoskeletal prosthetics, conducted in-depth, semi-structured interviews (Bernard, 2006) with each of the participants, ranging from 40 to 75 min. An interview guide can be found in the **Supplementary Material** (S1) based loosely on the work by Hansen et al. (2019). A framework of questions was used for each interview, beginning with more general questions to establish rapport and learn about the participant's life, then focusing upon the themes of the participant's history with prosthetics, prosthetic function and control, use in various home and daily life settings and environments, experiences of sensory feedback, and experiences with the phantom limb (pain and sensation). These questions were used to structure the conversation, but the interviewee led the way, making free associations and asked by the interviewer to expand and comment upon them. These interviews were conducted in the participants' native language, Swedish, and audio recorded. Audio files of the interviews were then transcribed into Swedish by a professional transcription service and then translated into English by the first author.

Data Analysis

This study aimed to place the firsthand experiences and perspectives of participants living with neuromusculoskeletal prostheses at the center, focusing on how people make meaning from said experiences to incorporate a device into their lives and sense of body and identity. From these experiences and firsthand reports, we sought to elucidate themes that spoke to the unique knowledge and expertise generated by prosthesis users themselves. Interviews were recorded in the participants' native language (Swedish), transcribed, and then translated to English for thematic coding using the software NVivo (QSR International, Australia) in preparation for further analysis.

The first author read interview transcripts, identifying repeating patterns, categories, and themes present. The first author then cross-validated these themes with the second author. From the agreed-upon themes, the first and second authors iteratively derived a descriptive coding system, with several umbrella categories containing subthemes. To organize data according to these codes, the software NVivo 12 was used (NVivo qualitative data analysis Software; QSR International Pty Ltd. Version 12, 2018). NVivo is a tool for organizing sections of text according to codes (called "nodes") generated by the user. See **Table 1** for the code categories, themes, subthemes, and descriptions used.

From the NVivo coding, we interpreted themes and subthemes using interpretive phenomenological analysis (IPA) (Holloway and Todres, 2003; Sandelowski and Barroso, 2003; Smith et al., 2012). This entailed suspending our own expectations about the data and instead focusing on how participants articulated making a sense of meaning from their experiences. It is important to note that these themes and the coding system were generated from the data, as opposed to predetermined prior to the interview. IPA is derived from the philosophical and theoretical contributions of Martin Heidegger, whose phenomenology centers upon the embeddedness of the human subject in the world as "being in the world," and thus focuses on the emic perspective of subjects themselves (Heidegger, 1927; Horrigan-Kelly et al., 2016). The method espoused in this study acknowledges that the researchers are also subjects, making sense of participants' narratives (Smith and Osborn, 2015); thus, interpretation is an intersubjective process.

RESULTS

Our thematic content analysis of the interviews yielded themes largely grouped into seven categories. Three categories were exogenous elements introduced by the intervention: (1) mechanical attachment of the prosthesis to the body, (2) intuitive control of the prosthesis, and (3) the experience of sensory feedback. Four categories were endogenous elements resulting from patients' experiences with said intervention: (4) practices and use of the prosthesis in daily life, (5) relationship of the prosthesis with the phantom limb, (6) self-image and self-esteem, and (7) social relations (**Figure 3**).

Category 1: Mechanical Attachment

Participants Preferred Direct Skeletal Attachment via Osseointegration Over Socket Suspension of Prosthesis

All participants, unsolicited, invoked comparison between their past experiences with socket suspension as the means of attaching their prosthesis to their own body, and their current osseointegrated prosthesis with direct skeletal fixation. Participants used the words "uncomfortable," "sweaty," and "impractical" to describe their prior socket prostheses, in contrast to the words "comfortable," "easy," and "pleasant" to characterize their osseointegrated prostheses. P2 described deleterious effects in other parts of his body as a result of compensating to adapt to the socket fitting and overusing his intact arm: "I started getting crooked in the back and I lost sensation in the (remaining) hand's fingers, and I thought 'this won't work long-term." Furthermore, P2 described feeling the stump moving around independently and asynchronously inside the socket when attempting to perform movements. P1 and P3 also reported greater degrees of mobility and decreased associated bodily discomfort and pain when they switched from a socket to direct skeletal attachment.

All patients reported using their neuromusculoskeletal prostheses for longer periods than they did their socket prostheses. "It's pleasant. I don't get tired of having it on me," P1 reflected. P3 was the most minimal user of his prior socket prosthesis ("It just hung there. . .As soon as I got home, I took off my prosthesis"), eventually abandoning his socket prosthesis for 12 years prior to osseointegration. Today, all patients use their prostheses for all waking hours of the day.

TABLE 1 | NVivo coding structure of categories and themes derived from participant interviews.

Category/node	Sub-themes	Participants' descriptions of:
Mechanical attachment of prosthesis to body	Past experiences with socket prosthesis	Past experiences and practices using and wearing a socket prosthesis.
	Comparisons between socket and osseointegration	Comparison between participants' past experiences with socket and current with osseointegration.
	Bodily adjustments and accommodations to prosthesis	Posture, pain in other parts of the body, compensation, numbness and tingling in other body parts (not missing body part), or lack thereof, for both socket and osseointegrated prostheses.
	Removing and putting on the prosthesis	Experiences with removal and attachment of the device, for both socket and osseointegration.
Control of prosthesis by user	Surface electrode experiences	Past experiences wearing and using surface electrodes, putting them on, challenges faced.
	Implanted electrode experiences	Current experiences with implanted electrodes.
	Electrical interference	Experiences with electrical interference from environment with prosthesis's electrical system.
	Trust in the prosthesis	Participants' degree of trust in prosthesis to not malfunction.
	"Naturalness" of control of prosthesis	The degree to which intuitive control of the prosthesis feels "natural."
	Scenarios of use facilitated by control	New scenarios and occasions in which use is facilitated by improved control.
	Habituation and training	The training required to habituate body and prosthesis.
	Breakdown and malfunction	Challenges with control, breakdown and malfunction of the device.
	Description of feedback's sensory qualities	Language about the quality or type of sensation users experience with regard to touch, location, size/area, frequency, and duration.
Experience of sensory feedback via neurostimulation [-10pt]	Sensory discrimination	Location of sensor contact with object and prosthetic hand in relation to felt sensation in the phantom hand.
	Appraisal of sensory feedback's utility	Opinions regarding the utility, purpose, relevance, or quality of sensory feedback.
	Reliance on other forms of feedback	Other non-sensory (i.e., visual and auditory) feedback used to locate prosthesis in space or exercise control.
	The term "natural" with regards to sensory feedback	Invocation and use of the word "natural" to describe (or purposely not describe) different elements of sensory feedback.
	Stump sensation	Presence or absence of sensation or pain on the stump or residual limb.
Prosthesis use in daily life	Extent of usage	Amount of time prosthesis is used, including periodic removal and reattachment throughout the day, charging requirements.
	Diversity of tasks and activities of use	The tasks and activities participants use prosthesis for, comparison with past socket prosthesis and/or surface electrode activities of use.
Relationship between prosthesis and phantom limb	Phantom limb pain	The presence or absence or degree of phantom limb pain with and without prosthesis on, before and after use, and general patient history of phantom limb pain.
	Phantom limb position	The position of the phantom limb with and without the prosthesis.
	Phantom limb mobility	The mobility of the phantom limb with and without the prosthesis.
	Phantom limb sensation	Phantom limb sensation, particularly with respect to its relationship with neurostimulation for sensory feedback.
Self-esteem, self-image, and incorporation of prosthesis into body	Self-efficacy and independence	Participants' sense of being independent and self-efficacious with regards to performing tasks and activities themselves.
	Self-esteem	Participants' self-esteem before and after neuromusculoskeletal prosthesis, including comments on self-image, body-image, and identity.
	Feeling "handicapped"	The term "handicapped" and explanations of its meaning, its relevance to prosthesis use and function, as well as overall self-image in a societal context.
	Mood	Mood state and overall affective wellbeing before and after receiving a neuromusculoskeletal prosthesis.
	Ownership and prosthesis as "part of me"	The degree to which participants consider prosthesis part of their body, self, and/or identity.
	Prosthesis as tool	The degree to which participants experience prosthesis as an external tool.
Social and emotional wellbeing	Relationships with family members	Family members' perceptions of neuromusculoskeletal prosthesis, interactions with family members in relation to neuromusculoskeletal prosthesis.
	Relationships with friends and coworkers	Friends' and coworkers' perceptions of neuromusculoskeletal prosthesis, interactions with friends and coworkers in relation to neuromusculoskeletal prosthesis.
	Interactions in public with strangers	Interactions with strangers in public with regard to the neuromusculoskeletal prosthesis.

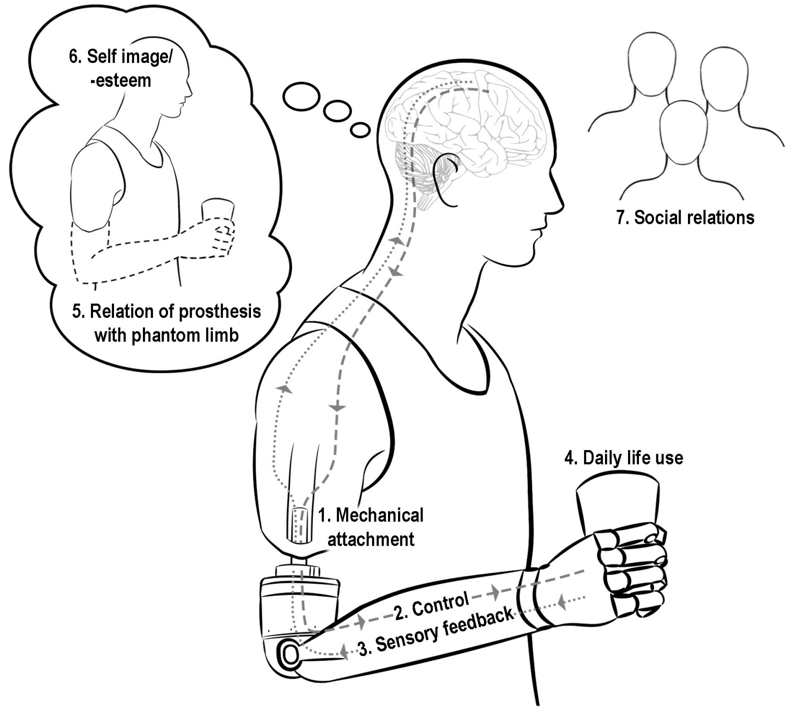

FIGURE 3 | Diagram of the seven key themes derived from participant interviews. The seven themes include three exogenous elements (introduced by the intervention): (1) mechanical attachment of the prosthesis to the body, (2) intuitive control of prosthesis, and (3) the experience of sensory feedback; and four endogenous elements (resulting from patients' experiences with said intervention): (4) practices and use of the prosthesis in daily life, (5) relationship of the prosthesis with the phantom limb, (6) self-image and self-esteem, and (7) social relations.

Patients also reported feeling more incentivized to remove and put on the neuromusculoskeletal prosthesis in occasions where they previously would not. P2 described this shift in use:

> "Say (before bed) I've . . . showered . . . and taken off the prosthesis . . . Had it been a socket prosthesis, I would have never put it back on again, because it's such a mess to get it to sit right. Then to set the electrodes (on the skin), find and get them to work, it's not worth it. But (with osseointegration) one can just click (the prosthetic arm) into place and then it works again. One might think that's a small thing, but that is quality of life."

Category 2: Control of the Prosthesis

Participants Experienced Improved Prosthetic Control With Implanted Electrodes

All three participants, unsolicited, drew comparison between surface electrodes and implanted electrodes, specifically emphasizing the increased sense of control gained from implanted electrodes. Recalling his time using surface electrodes, P2 recounted, "There were many disturbances. If I walked by an electromagnetic field or something (like a stove), I dropped things, or the elbow would activate. . ." Similarly, P3 remarked, "There are so many outer factors that can disturb (a myoelectric prosthesis with surface electrodes). It can open and close itself."

All participants recalled instances of erratic hand movements with surface electrodes, prompted by electromagnetic interference in the environment. With implanted electrodes, all participants reported a greater degree of agency over the prostheses' movements. As P2 described:

> "All such disturbances are gone now with the implanted electrodes. It's a lot smoother. I'm in better control. With implanted electrodes, it's *me who decides* when I will open and close the hand."

P2 recalled functional limitations in daily life activities with surface electrodes. "Eating with a knife and a fork using a socket prosthesis, that was . . . worthless." These functional challenges were surmounted, P2 reported, once he changed from surface to implanted electrodes: "now I can hold a knife in my left hand and cut with it and make very small movements, and the prosthesis stays in place."

Improved Control and Decreased Interference Strengthened Participants' Trust of the Prosthesis, Engendering Prosthetic Use in More Diverse Scenarios

All participants said that interferences and disturbances with surface electrodes gave the sense that it was not them who was controlling the prosthesis, but rather other environmental factors. Consequently, participants expressed mistrust of the prosthesis with surface electrodes: "I couldn't trust that I could carry something," P2 explained. P3 also described the surface electrodes as "not really trustworthy."

Participants drew a causal relationship between improved control and trust. As P3 described:

> "It's me who has control. I trust the prosthesis. I can carry a wineglass (now). A wineglass with wine in it. I would have never done that with a (surface electrode) prosthesis."

In adapting to the increased functionality and control afforded by the implanted electrodes, participants described adjusting their tolerance levels of prosthetic function and malfunction, with higher expectations for their new neuromusculoskeletal system. For example, with the neuromusculoskeletal system, if P3's hand did happen to open or close when he did not intend, this signaled to him "a malfunction in the hand or software." P3 then sought to correct this malfunction with the engineering team, whereas with surface electrodes he would have "just accepted (that) as part of the limitations of the electrodes."

Participants Described Functional Control of the Neuromusculoskeletal Prosthesis as Intuitive and "Natural"

All participants used the word "natural" to describe the "thought-steered" (as referred to by P2) control and responsiveness of their prostheses. P2 said that the benefits of the prosthesis are most apparent when he *isn't* wearing it:

> "When I don't have the prosthesis on, I do so many small things that I don't think about, because it's become so natural (for me) to wear the prosthesis. I very rarely go without the prosthesis, but say I've taken it off if it's run out of power or something, then I do things in the air because the prosthesis is gone. It has become so natural."

Category 3: The Experience of Sensory Feedback

At the time of the interviews, participants had been using neural sensory feedback in daily life for 2 years (P1) or 6 months (P2 and P3). Participants were provided with a conservative but biologically inspired neuromodulation strategy that consisted of modulating the frequency of stimulation proportional to grip force (5–30 Hz roughly corresponding to 5N to 25N) (Ortiz-Catalan et al., 2020). The maximum frequency of stimulation (30 Hz) was orders of magnitudes lower than the natural frequencies at which peripheral nerves can communicate information, but it had to be constrained owing to safety considerations (Günter et al., 2019). As expected, frequency discrimination was initially poor due to the limited bandwidth and required a stimulation frequency change of approximately 50% to be noticeable. Over time, a smaller difference of frequency of about 30% was required for the participants to perceive a change of intensity (Ortiz-Catalan et al., 2020). From the time of contact with an object, participants received sensory stimulation for 5 seconds, at which point stimulation was stopped for safety purposes (Günter et al., 2019).

Participants Did Not Describe Sensory Feedback as "Natural" and Expressed Doubt as to Whether It Needed to Be

All three participants used the words "electric" and "numb" to explain how the sensory feedback felt. P1 described the area of sensation as small, "like the point of a pen," which then "grows outward" as the sensation increases. P3 recalls the first time he received sensory feedback:

> "In the beginning it was very strange, to just, feel. . .I feel all of a sudden something I haven't felt for so many years. I have not had any sensation in that way."

When asked whether they considered the sensory feedback "natural-feeling," all participants hesitated to describe it as such. P2 and P3 clarified that a "natural" sensation depends not only upon its sensory quality, but also its perceived location with respect to the sensor in the prosthetic hand. All participants used the same prosthetic hand (SensorHand, Ottobock, Germany) with the sensors located in the prosthetic thumb (center of the distal phalanx), and thus participants must press the thumb against an object to generate sensory feedback. However, owing to the placement of the neural electrodes and consequent lack of selectivity, the participants experienced the elicited sensation in various locations on their phantom hand other than the thumb (Ortiz-Catalan et al., 2020). P2 described himself as "lucky" because "the sensation (I feel) exists in the thumb. . .and the sensor (on the prosthetic hand) is located there, too, so it is quite natural. . .that (both) get to be in almost the same spot." Yet P3 experienced the sensation elsewhere. "When I touch this," he demonstrated during the interview, touching a water bottle with his thumb, "I have sensation there," he pointed to the lateral side of his middle finger. According to P3, the discrepancy between the location of the sensor in the prosthetic hand (thumb) and location of the perceived sensations (middle finger) made the sensation feel "not natural." When asked what a natural sensation would feel like, P3 said "we would feel where we touch." P1, who experienced the sensory feedback in the palm, did not comment on the perceptual difference with regard to the sensor location on the hand.

When probed further, all participants expressed doubt whether "natural-feeling" was necessarily the most important goal of sensory feedback. Instead, they highlighted its functional benefits. P1 found it most important that the sensation merely exists, because it allows him to take grip of objects more confidently, often without relying on sight. P2 expressed skepticism that the sensation could ever feel "natural," but made an important distinction that it need not feel natural in order to be helpful: "to find a sensation that feels natural, I think that's very difficult, but to get a signal that is helpful, that can probably happen."

Participants Attributed Limited Benefits to Current Sensory Feedback

Participants' reports were not unanimous regarding the quality of their experiences of the sensory feedback. P1 described, "I feel two levels (of intensity). A lighter level when I grip lightly, and then when I grip a little harder, then it's stronger." In contrast to P1's reported experience, P2 and P3 reported difficulty differentiating between intensity levels. Rigorous psychometric evaluations showed that an approximately 30% change in stimulation frequency was required for the participants to perceive a difference in intensity (Ortiz-Catalan et al., 2020); however, the available bandwidth for stimulation was limited (5–30 Hz), thus directly impacting the resolution of perception. Of all subjects, P1 voiced the most utility in knowing how hard he is gripping an object, reporting improved ability to handle delicate objects like his smartphone or a glass without breaking them. P2 described the sensation as "so weak that when I do something active, I don't think it's there." As he explained:

> "It works. It's there. But I have not yet seen its benefit. I don't really know what it's going to be good for. When you do something with precision slowly and properly concentrate, then you feel the feeling, but the benefit. . .it's difficult for me to see. The (sensory feedback) is there, but it doesn't add anything for me."

P3 expressed a similar reaction when asked about the utility of the sensory feedback:

> "It's exciting, interesting to see but I don't know if it does so much more. There is of course big potential with sensory feedback, and everything must begin with something. But the way it is now, it's mostly just exciting and cool."

When prodded further to explore what he considered the biggest barrier or limitation of the current sensory feedback, P2 explained:

> "To have a sensation that you're grabbing something, that's not so meaningful for me, because I see that I'm doing that. I would rather have a sensation where I feel like I'm *losing* the grip of something."

Visual Feedback Remained Relied Upon to Supplement or Confirm Grip

Two participants (P2 and P3) reported needing to rely on visual feedback to supplement sensory feedback, while P1 reported that he can gauge a grip by feeling without having to look at the object. P2 explained using sight because "the sensation is not good enough" to rely on solely to grab an object out of sight. P2 referred to using sight as a supplemental sensation confirming his grasp. P3 compared the sensory feedback of his biological hand with his prosthetic:

> "When I pick something up (with my biological hand) I feel it and I don't need to look at it. But with the sensory feedback, to know 'oh, I have taken that up,' I must still have visual contact."

Participants Reported Either No Change or Improvement in Stump Sensation

P1 and P3 reported no change in sensation in or around the residual limb and amputation site. P2 reported improvements with pain and sensation on the surface of residual limb. "Earlier it was quite sensitive," he explained, "it could be tight and tingle. . .for a year after the operation (amputation) I was very sensitive with small shock (sensations)." This sensitivity, P2 reports, has gotten "much, much better." None of the three participants could feel the electrodes inside their arm.

Category 4: Practices and Use of Prosthesis in Daily Life

Participants Increased Amount of Time and Diversity of Daily Life Tasks Using the Neuromusculoskeletal Prosthesis

All participants reported an increase in the amount of time they wear the neuromusculoskeletal prosthesis during the day, compared to prior experiences with socket prostheses and/or surface electrodes. All reported wearing the neuromusculoskeletal prosthesis from waking up until going to sleep ("It's among the first things I do: I put on my prosthesis, to the last thing I do: take it off" – P2) for periods ranging from 12 to 20 h. While P2 and P3 removed their prostheses overnight to charge its battery, P1 often slept with the prosthesis on, especially when traveling for work.

All participants also described performing an expanded diversity of tasks with the neuromusculoskeletal prosthesis, compared to a myoelectric socket prosthesis or osseointegration with surface electrodes. All participants emphasized increased involvement and participation in family chores and activities, including: cooking, washing the dishes, shoveling the snow, mowing the lawn, skiing, gardening, and hanging laundry. The only activities participants reported *not* using the prosthesis for were swimming, bathing, and running.

Each participant highlighted increased involvement in family life as the most beneficial element of increased prosthetic use, with P2 and P3 reporting feeling "more helpful" to their families. "I can do things faster than I could before," P3 explained. P2 articulated that his needs for a prosthesis in everyday life are modest and simple, but that these very simple things matter most: "You don't necessarily have to have a super advanced hand. . .it's all about these small things."

Participants also reported using their neuromusculoskeletal prostheses for work to varying degrees, depending on their professional demands. As a truck driver and deliverer, P1 explained that his work can be quite physical; he used the prosthesis not only for holding the wheel and steering while driving, but also tying anchoring chains for cargo and lifting heavy items off his truck. While P2 used his prosthesis for everyday office tasks, like collecting paper from the printer and stapling, he expressed more benefit at home than at work:

"Say the prosthesis breaks and I must go without it for a week (while it's being repaired). I would suffer more at home than I do at work. . .I would miss it more."

P2 attributed this difference to his work's non-physical nature, compensated for by using his sound arm. Likewise, P3 works primarily on the computer, and he expressed minimal work-related functional benefits from his prosthesis. He described the prosthesis as "clumsy" when trying to type on a keyboard. Rather, P3 explained that the benefits he perceived at work with regard to his neuromusculoskeletal prosthesis were due to increased self-esteem, which in turn improved the quality of his work and relations with colleagues.

Category 5: Relationship of the Prosthesis With the Phantom Limb

Participants Experienced Significant Decrease of Phantom Limb Pain

Two out of three participants (P1 and P3) reported having experienced phantom limb pain (PLP) prior to being implanted with the neuromusculoskeletal interface. P1 experienced PLP after his amputation and during the years he used a socket prosthesis. The pain diminished but still lingered after he received osseointegration, but "after they implanted the electrodes, it . . . disappeared." Prior to osseointegration, P3 also experienced significant phantom limb pain, which presented as electrical shocks, or the feeling of something cutting into his hand. This pain made sleep difficult, waking him in the middle of the night and impacting his energy and quality of life. After receiving the neuromusculoskeletal interface, P1 and P3 reported that phantom limb pain ceased completely.

Participants Experienced Locational Synchrony Between Phantom Limb and Prosthesis Positions, as Well as Improved Mobility of Phantom Hand

All participants reported changes in the position and mobility of their phantom hand as a result of using the neuromusculoskeletal prosthesis. These changes were described as spatial affinity and confluence in location between the phantom hand and the prosthetic hand when worn.

While not wearing the prosthesis, all participants described the phenomenon of their phantom hand "telescoping" (resting closer to the residual limb as opposed to its correct anatomical position) and remaining immobile. P2 described his phantom hand as clenched, paralyzed in a tight claw, as if "floating" near his shoulder. Yet when putting on the neuromusculoskeletal prosthesis, all participants reported experiencing the phantom hand lengthening to closely meet the position of the prosthetic hand. P2 described this experience as "getting an arm"; his phantom hand relaxed and became animated once again. The topographical synchrony between phantom hand and prosthesis did not only occur in a static position, but also in motion, participants reported. As P1 articulated, "when I open my (phantom) hand, the prosthesis opens." P2 and P3 also described greater ease moving their phantom limbs while wearing the neuromusculoskeletal prosthesis. P3 emphasized that this mobility occurred only when wearing the prosthesis:

"When I didn't have a prosthesis, I couldn't move anything in the phantom, so it has come back now that I've gotten this prosthesis, that I can move the phantom. And when I take off the prosthesis, I can't move the phantom so easily."

P2 explained that this synchrony occurs in only a matter of seconds after putting on the prosthesis. P2 described the differences before and after using the neuromusculoskeletal prosthesis as follows:

"With these implanted electrodes, I steer the hand with the right thought. . .it has become more active. It follows much faster. Earlier (with socket prosthesis and surface electrodes), the hand was almost where the prosthetic hand was, but it didn't follow. . . I opened (the prosthesis) so (the phantom hand) opened, but it went very slowly. (With the neuromusculoskeletal prosthesis) it follows almost exactly."

P2 added that his phantom hand tracked the movement of his prosthetic hand even without not looking at it:

> "Even if I sit and hold it out like this, away from the eyes. . . (the phantom hand) follows."

The animation of his phantom limb and positional synchrony between phantom and prosthesis contributed to the sense that the prosthetic was part of his body, in P2's words:

> "Now with these implanted electrodes that you control with . . . thought, I think this also made it feel more like a part of the body, because my phantom hand has become more alive. It follows along in the movements much more similarly to the prosthesis."

Participants Describe Difficulty Distinguishing Between Artificially Elicited Sensory Feedback and Naturally Occurring Phantom Limb Sensation at Times

All participants reported experiencing naturally occurring phantom limb sensations, which they did not categorize as painful, and which sometimes proved challenging to differentiate from the somatosensory percepts elicited via neural stimulation. P2 emphasized that in addition to the artificially elicited sensations, "the phantom hand is there the whole time, and it sends signals too." P2 and P3 described difficulty distinguishing between the artificial and biological phantom sensations. As P2 described:

"(the phantom hand) vibrates and pulsates, and then to distinguish the sensory feedback (by neurostimulation) from the noise that is in the phantom hand, that's sometimes difficult."

In the lab, during neurostimulation tests, P2 experienced challenges distinguishing between the two:

> "when one . . . does the tests, sometimes it's like 'okay, do I feel the sensory feedback or was that my phantom hand that just did something?'"

P2 described his phantom limb sensation as "(like) it has slept. . .like when you've sat on your hand and made it go numb."

P3 described a sensory convergence between the sensation prompted by neurostimulation and the sensation he naturally had in his phantom hand:

> "I have had phantom sensation but now all of a sudden, (with the sensorized prosthesis) I pick up something. . .so. . .the body, or the brain, understands the connection that when I touch something or hold it, then I feel it in the phantom hand. Now it's a little harder to know, is it a phantom sensation or an artificial sensation? Is the sensation made by the machine, or is it my brain?"

P3 emphasized the increasing challenge of describing the artificial sensation with language, as well as discerning it from the phantom sensation.

Category 6: Self-Esteem, Self-Image, and Incorporation of the Prosthesis Into Body

Participants Experienced Improvements in Self-Esteem and Self-Image

All participants credited increased time of use, diversity of tasks performed, and improved functionality to the neuromusculoskeletal prosthesis. Along with these improvements, they cited peripheral social and emotional benefits, which in turn yielded shifts in their relationship with their prosthesis. They described these shifts with regards to their body and their identity, in the areas of self-esteem and self-image.

Twelve years of living without a prosthesis, P3 described, led to varying struggles with self-esteem:

> "I had some days that were good and other days that were not so good, with my self-image. I almost never wore just a t-shirt, instead it was just something to hide. I had a hard time at the beach. Sometimes it went well, other days you feel like 'no, let me be.' And . . . I was treated differently by people when they saw 'he only has one arm.'"

Since living with the neuromusculoskeletal prosthesis, P3 remarked, "My self-image has gotten better." In turn, so has his mood, which he described as at a higher, more sustained level.

P2 noticed a similar improvement in his self-esteem, despite his commitment to accepting his body and "not caring" about "look(ing) different" post-amputation. When probed deeper about what "self-esteem" and "caring" meant to him, he replied:

> "(the neuromusculoskeletal prosthesis) means something for self-esteem. If I . . . investigate myself a bit more, it means a lot more than I want to admit. I want to appear like a person who doesn't really care about it, but I do probably (care), because it's tough if (the prosthesis) doesn't work. It means more than I admit."

P2 commented upon a shift in how he relates to having two- versus one- arms:

> "It's really strange. . .but now (the prosthesis) feels like it's more a natural part of my body, and so it feels stranger to be without it. . .I am not longer even comfortable without it. I wouldn't say that I am ashamed to go without an arm, but it is a little harder now than it was then, strangely enough."

Similarly, P1 grew so habituated to wearing the neuromusculoskeletal prosthesis over the last 6 years that he most noticed its significance to his self-esteem and identity when he removed it:

> "I always have (the neuromusculoskeletal prosthesis) on me and when I wear it then I feel like. . . I have two arms and then it's more like 'here I am.' But take the arm away, then it's like. . .as if. . .this isn't (participant says his own name)."

P3, reflecting on his experience with limb loss in light of receiving the neuromusculoskeletal prosthesis, described:

> "I wouldn't want to change (what happened). I want to be what I am. There are many who are amputated or have been with other things who want them undone, want to have back how it was earlier, but I don't want that. And it's clear, a part of all this is of course also that I have gotten such a functioning. . . a good prosthesis. I think that does a great deal for self-esteem."

Participants Described Feeling Less "Handicapped"

All participants invoked the word "handicapped" (an unprompted word not used by the interviewer) when asked about any changes in self-identity and self-perception since using the neuromusculoskeletal prosthesis. P1 described the experience as "so good, I don't feel handicapped." P1 recalled that, for example, when traveling with a socket prosthesis, he would often remove it because it was cumbersome, sweaty, and uncomfortable. When probed as to what the term "handicapped" meant to him, P1 explained:

> "If I have a prosthesis. . .that works, that is easy to wear, easy to use, then I use it and then I don't feel so handicapped. Handicapped means that you have a functional reduction that prevents you from doing all the chores, work. I have lost a part of my body. So in that way I am handicapped, but I don't feel like I am handicapped when I wear this (neuromusculoskeletal) arm. Because I can do many things."

P2 and P3 echoed P1's commentary on feeling "handicapped" by the socket prostheses, contrasted by a sense of greater functionality, self-sufficiency, and integration with the neuromusculoskeletal prosthesis. As P2 explained, "The earlier socket prosthesis, it was an aid that I carried. This prosthesis, I don't carry it; it *is* me. I *have* it."

Participants Considered the Neuromusculoskeletal Prosthesis as Part of Their Body, but Not Always as Part of Their *Self*, and Sometimes as a Tool — Depending on Context

During the interviews, participants were asked to describe their neuromusculoskeletal prostheses in relation to their body and self, using a metaphor or analogy. The question was left purposefully vague as to not lead participants or feed them language.

P2 first described the socket prosthesis as a tool, and then explained the difference with the neuromusculoskeletal prosthesis:

> "The earlier socket prosthesis, it was an aid that I carried. This prosthesis (neuromusculoskeletal), I don't carry it; it *is* me. I *have* it. For me it's as natural as having glasses. The socket prosthesis, that was more of a tool."

When asked to clarify whether he considered the neuromusculoskeletal prosthesis a part of his body, P2 responded:

> "A little bit. The neuromusculoskeletal prosthesis is not biological, no, but you don't have to think about it. Socket prosthesis, I had to go and think 'now I must arrange this so that it fits. Change the strap. . .' This (neuromusculoskeletal prosthesis) you put it on, and you don't do anything more."

When asked whether he identified the neuromusculoskeletal prosthesis as part of his *self* (identity), P2 was more hesitant:

> "Maybe not that far, but along those lines. And now with these implanted electrodes that you control with the right thought, I think this also made it feel more like a part of the body, because my phantom hand has become more alive. It follows along in the movements much more similarly to the movements of the prosthesis."

P3 described a sense of *ownership* over his prosthetic arm, akin to his own arm:

> "My prosthesis is a part of my body. . .It's my arm now. The (surface electrode) prosthesis. . .was like a foreign object. I was almost surprised every time I saw it. But this one is, it's *my* hand, it is *my* arm."

The interviewer probed this concept of ownership, asking if the fact that the arm is *his* means that it's a part of *him*, larger than just his body, but extending to a larger sense of self. P3 responded:

> "Sometimes when I pick (the prosthesis) up then it becomes another (separate) arm. But the brain has more to do with these electrodes. . .it becomes more active thinking and using the prosthesis. I (control) the prosthesis with my brain, but then it becomes more like. . .I want to use this hand as I use the hand. It becomes more of the same (thing). So it (the arm) becomes more of a body part."

When the interviewer asked the participants whether they considered their neuromusculoskeletal prosthesis as an external tool, the participants pointed out the importance of context. P1 explained that he felt his prosthesis was more of a tool (as opposed to his hand) when, "I'm about to do something quickly, then I realize that this (prosthesis) is not as fast as a (human) hand," gesturing to the prosthesis's delayed responsiveness for quick tasks. P3 responded, "Yes, (the neuromusculoskeletal prosthesis) is a tool, but in the way that this is also a tool," gesturing to his biological hand, waving the fingers. He said the neuromusculoskeletal prosthesis is no more a tool than his biological hand.

Challenges With Durability, Mostly From the Terminal Device, Make Participants Feel Less Integrated With Their Prostheses

The neuromusculoskeletal interface increased the use of the commercially available prosthetic hardware (elbow and terminal device), and thus challenged its durability. For all participants, the degree to which they considered the neuromusculoskeletal prosthesis a part of their body depended upon its functionality. All participants reported experiencing occasions of breakdown or malfunction of the prosthetic elbow and terminal device. "I use this (prosthesis) so much that it breaks down regularly," P1 explained. P1 attributed this breakdown largely to the prosthesis's material – plastic – and said that he'd rather have a more durable material, such as metal. All participants expressed most problems with the elbow, which P2 said could not withstand heavy loads. P3 reiterated this weakness: "I am stronger than the prosthesis itself. The elbow can break if I take something too heavy, or it gets worn out."

When breakdowns happened, participants mailed their terminal device for repairs and often used a spare myoelectric hand in the interim. On one occasion, P3 did not have a spare prosthesis and expressed the challenge of sending away the terminal device to an orthopedic engineer for repairs:

> "It's gone for 2–3 weeks. It is really tough to be without the arm, because it has become such a part of me now. I don't like the prosthesis when it's broken, or it doesn't work as it should. . .then I can get angry at the prosthesis."

Battery life of the prosthesis is another limitation. P1 voiced a desire for a more durable battery; his current one only lasts about 8–10 h. He always carried a spare battery with him, in his pocket, to change over in order to last him through the day. Overnight, he charged both.

Category 7: Social Relations

Participants Attributed Peripheral Social and Emotional Benefits to Increased Use and Functional Improvements of the Neuromusculoskeletal Prosthesis

In addition to functional changes in daily life, participants articulated improvements in their social and emotional wellbeing since using the neuromusculoskeletal prosthesis. As P3 explained, "there's a functional side of it all, and . . . there's also an emotional side of it all." Since using the neuromusculoskeletal prosthesis, P3 has noticed he has far fewer "bad days" spent ruminating about his condition and can therefore be more present and engaged with his family.

All participants reported that family members and friends have positively adapted to their neuromusculoskeletal prostheses. P2 noted that his friends responded to his increased capacity to perform movements and partake in shared activities: "they do not offer to help do things for (me. . .any more). It's become so natural (for them too)." P1 likewise described feeling more self-sufficient among friends and coworkers: "I don't need to always ask for help, I can do (things) myself." He also noted that, with the neuromusculoskeletal prosthesis, acquaintances or strangers didn't as readily notice his prosthesis or that he was amputated. P3 reported a similar shift among acquaintances and strangers, and furthermore noticed that, with his neuromusculoskeletal prosthesis, he's grown more comfortable with telling his story and explaining his situation. Whereas living without the prosthesis he sometimes felt beleaguered and bothered by others' questions of "what happened," he found it "fun" to explain his new implanted electrodes and "brain-controlled" prosthesis to those interested. "They think everything is very exciting," he said with a grin.

DISCUSSION

A thread running through all observed categories and themes is the degree to which participants incorporated the prosthesis into their daily lives, and by extension what effect this incorporation had on how they consider the prosthesis as a part of their body, self, and identity.

Mechanical Attachment (Osseointegration) and Control (via Implanted Electrodes) Yield Separate, Distinct Benefits for Participants

In the interviews, participants drew two types of comparisons between their experiences with the neuromusculoskeletal prosthesis and prior prostheses: (1) socket-versus-osseointegration mechanical attachment and (2) surface-versus-implanted electrodes. It was thus critical to maintain the integrity of these two categories by disentangling them in our analysis. All participants received osseointegration prior to the surgical implantation of electrodes, ranging from months to years. It should also be noted that participants received the neural sensory feedback for home use (i.e., not confined to the laboratory) relatively recently. These temporal considerations introduce an element of chronology which may or may not have influenced and produced difference among participants' experiences (i.e., varying degrees of adaptation and familiarity with the neuromusculoskeletal prosthesis' use and function).

With regard to the mechanical attachment of the prosthesis to body, the benefits of osseointegration have been reported at length, particularly regarding improvements in functionality with resultant increased engagement in life activities (Lundberg et al., 2011; Hansen et al., 2019) as well as the challenges of training and adapting (Hansen et al., 2019). Our participants' reports of enhanced mobility and improved connection between stump and prosthesis post-osseointegration also indicated a greater sense of comfort and overall bodily balance. Furthermore, in emphasizing the ease with which they were able to remove and put on the osseointegrated prosthesis, participants drew connections between improved mechanical attachment and increased use throughout the day. Consistent with the findings of the only two other known qualitative studies focusing on osseointegrated prostheses and patient experiences (Lundberg et al., 2011; Hansen et al., 2019), our findings suggest an enhanced sense of energy, engagement, and positive affect.

Yet unlike the aforementioned qualitative studies on osseointegration for skeletal attachment (Lundberg et al., 2011; Hansen et al., 2019), neuromusculoskeletal prostheses introduced the additional elements of implanted electrodes for reliable control and intuitive sensory feedback (Ortiz-Catalan et al., 2020). Beyond mechanical attachment, participants commented upon improvements in motor control with implanted electrodes, emphasizing the reduction of electromagnetic interference they experienced with surface electrodes. Most notable was participants' use of agentive language (i.e., "it's *me who decides*") linked to the movement and control of the prosthesis. This sense of agency furthermore engendered a greater degree of trust that the prosthesis would behave according to users' intentions. Increased trust influenced participants to use their prosthesis in situations where they would not have otherwise with surface electrodes, leading them to take greater risks with their neuromusculoskeletal prosthesis (i.e., carrying fragile objects, like glasses and smart phones). As such, the implanted electrodes seem to have raised both patients' confidence in and expectations for the degree of control they can expect of their prostheses. Previous studies have suggested that distrust or degrees of caution and risk aversion toward limb prostheses could be due to early adoption or ongoing device development (Graczyk et al., 2019). This was not observed in our participants owing potentially to the reliability and long-term stability of the neuromusculoskeletal prosthetic system when used unsupervised in daily life.

The Descriptor "Natural" Carries Different Meanings for Participants Depending on Different Contexts

It is important to note that participants used the word "natural" with differing connotations and degrees of enthusiasm, depending on the context, with regard to: (I) reliable and intuitive control, (II) somatosensory feedback via neurostimulation, and (III) the incorporation of the neuromusculoskeletal prosthesis as a body part as opposed to a separate entity.

(I) Participants described the prosthesis as "natural" with regard to reliably and intuitively controlling its function. To them, a "natural" control was experienced when the prosthesis behaved according to their will consistently and in a timely manner.

(II) Participants hesitated to call the quality of sensory feedback "natural," choosing instead the words "electric" and "numb" as descriptors. In addition, one of the three participants (P3) emphasized that the discrepancy between the *location* of the sensor on the prosthetic thumb and the felt sensation elsewhere on the phantom hand (third finger) created a less-natural feeling, perhaps due to a cognitive or visual dissonance. Location and quality are two different aspects of what could be considered a natural experience. Technological limitations to selectively stimulate different afferent fiber types make it difficult to produce a natural quality (Ortiz-Catalan et al., 2019), although biomimetic approaches have reported to improve it (Valle et al., 2018; George et al., 2019).

(III) Participants also used the word "natural" to describe their incorporation of the neuromusculoskeletal prosthesis into their body ("now [the prosthesis] feels like it's more a natural part of my body, and so it feels stranger to be without it. . .I am no longer even comfortable without it." – P2).

The ambiguity surrounding the use of the word "natural" underscores the importance of identifying what such generalized descriptors *mean* to participants in different contexts. Previous qualitative studies invoking the term "natural" with regard to describing sensory feedback have not differentiated between these multiple contexts and possible nuances in meaning (Graczyk et al., 2019). This suggests the need for ongoing research on the various possible meanings of the term "natural" and the importance of precision when using it in qualitative and quantitative research on artificially elicited sensation. It also demands a degree of epistemological reflexivity, remembering that terms and words themselves carry a weight and history that condition their use and meaning.

Regarding sensory feedback, participants identified limited benefits and expressed a degree of skepticism as to its utility. Participants spoke about the neuromusculoskeletal prosthesis' intuitive control and function much more positively (evoking words like "trust" and "natural") than they did the sensory feedback (which they called "not natural"). Participants prioritized the functional benefits of sensory feedback (i.e., improvements in ease of use to perform tasks) as more important than whether or not the sensation itself felt "natural" in its quality. Still, residual reliance on visual feedback to supplement tactile feedback remained for two participants (P2 and P3), perhaps due to perceived weakness of signal strength. Recent work has shown that the selected neuromodulation strategy (frequency modulation proportional to grip force) was far from optimal, and more biologically inspired approaches yield better results (Okorokova et al., 2018; Valle et al., 2018; George et al., 2019; Mastinu et al., 2020). This is because at the point of contact, a critical instant for object manipulation, the elicited sensation was at its weakest, thus requiring certain cognitive effort to be perceived during dynamic tasks in daily life. This issue has now been addressed by neuromodulation strategies that deliver an easily noticeable sensation at contact and release (Mastinu et al., 2020), as provided by fast adaptive afferent fibers in biological touch (Johansson and Flanagan, 2009). Another ongoing improvement is to allow for participants to detect slippage of an object by employing said noticeable discharges in such events.

Participants drew our attention to the challenge of using language to describe a felt sensation. They also used the same words ("asleep, numb") to describe the sensory feedback as to describe their naturally occurring phantom limb sensation. This underscores an additional challenge that participants faced in discriminating between these two types of sensation. These observations highlight the challenges and limitations of using language to describe, much less measure, interpret, or assess, sensory experience—speaking directly to a larger epistemological debate on the measurement of sensation, particularly pain (Scarry, 1985).

The observed disconnect between participants' experiences with control and sensory feedback raises the question of whether higher quality control lessens the need or perceived importance of sensory feedback, a question warranting further research. It should be noted that the stimulation paradigm used to provide sensory feedback, to which these results correspond, was in a rather nascent and imperfect form at the time of the interviews; further work on neuromodulation strategies is currently ongoing to improve the utility of somatosensory feedback in subjects with neuromusculoskeletal prostheses (Mastinu et al., 2020). As such, follow-up research with participants is necessary to determine the relevance and utility of sensory feedback when combined with reliable and intuitive control.

Increased Use of Neuromusculoskeletal Prostheses in Daily Life Yields Improvements in Both Internal (Body Image, Self-Esteem) and External (Social, Relational) Domains

We observed a tight coupling between participants' use of the neuromusculoskeletal prosthesis in daily life (category 4) and their self-esteem, self-image, and incorporation of the prosthesis into the body (category 5), both yielding peripheral social and emotional benefits (category 7). Our findings resonate with those of Lundberg and colleagues' study in that participants reported not only functional improvements, but also existential benefits in perceived quality of life (Lundberg et al., 2011). Performing more diverse tasks for longer durations and more holistically incorporating the prosthesis into daily life seems to have trickle-down effects with regard to patients' emotional wellbeing and the quality of their social lives. These include a greater sense of involvement in family life and an improved sense of self-sufficiency in tasks where they previously required help. Participants attributed these effects largely to improved control over prosthetic function as opposed to socio-affective elements such as touch. Furthermore, positive perception of the technology appeared to increase participants' positive self-identification with it. We observed a shift among participants from shame or frustration about their prosthesis or being amputated, toward a sense of "fun" and even pride regarding their neuromusculoskeletal prosthesis, particularly when explaining its capabilities to others.

The field of critical disability studies has contributed significantly to interrogating the categories of "handicapped," "disabled," and "impaired" while pointing out their profound social, environmental, and linguistic contingency (Ginsburg and Rapp, 2013). With respect to these concerns, it should be noted that these terms were not used by the interviewer, but rather elicited by participants via free association. Still, participants emphasized feeling "not handicapped" while using the neuromusculoskeletal prosthesis. P1's self-initiated comments about his relationship to and identification with the term "handicapped" also indicate a shift in self-identification: ("Handicapped means that you have a functional reduction. . . I don't feel like I am handicapped when I wear this (neuromusculoskeletal) arm"). His words underscored that the feeling of being "handicapped" can be a subjective state related to degree of bodily function, rather than merely to the state of having lost a limb. P3's words further enforce this notion, gesturing to a broader shift in relation to the experience of having lost his arm: ["There are many who are amputated . . . who . . . want to have back how it was earlier, but I don't . . .a part of (that) is . . . I have gotten such a functioning. . . a good prosthesis. I think that does a great deal for self-esteem"]. Here P3 articulates a link between his functioning prosthesis and this acceptance of, and even a degree of pride in, his post-amputation, prosthetized body.

"Embodiment" Is Not Static, but Rather Context-Dependent

Participants' language choices ("part of my body," "here I am") raise important questions about proximity of the prosthetic device to their sense of body and self, particularly with regard to embodiment. "Embodiment" is a term used widely in the prosthetics literature, yet often without consensus or precision as to its meaning or definition. We take embodiment to mean not only a sense of ownership over the prosthesis (self-identification with the device as one's own body), but also a degree of agency over its use (reliable and intuitive control). While participants expressed feeling that their neuromusculoskeletal prosthesis was (at times) part of their body (embodied), they did not necessarily consider it a part of their "self" (a more amorphous category whose distinction from the body remains a long-debated philosophical quandary outside the scope of this article).

Studies in neurostimulation for sensory feedback have reported that participants can experience a sense of ownership of the prosthesis (Schiefer et al., 2016; Page et al., 2018; Rognini et al., 2019). However, it is important to keep in mind that these studies are often acute experiments conducted in controlled laboratory settings, and therefore the effects of ownership (not necessarily embodiment) claimed must also be interpreted as themselves acute and controlled, contained to a specific set of experimental conditions. We must be careful not to extrapolate a sense of ownership and agency (or both) that occur in a cultivated moment or instant to an irreversible, sustained phenomenon. It is for this reason that whereas de Vignemont has defined embodiment as a concomitant sense of ownership and agency, albeit to varying degrees (De Vignemont, 2011), our study suggests an additional element—temporality—must be given greater attention in analyses of embodiment. As people are now, for the first time, living with their neuromusculoskeletal prostheses outside of laboratory contexts and using them freely in their daily lives, embodiment takes on new meaning incorporating context and chronology. The chronic, lived nature of this reality introduces a range of uncontrolled variables, disruptions, and synergies that demand a more nuanced precision of what we mean when we speak about "prosthetic embodiment."

In our interviews with people living with neuromusculoskeletal prostheses, we found that a sense of embodiment with the prosthesis is conditional and deeply context-dependent, rather than constant or unwavering. For instance, P1, who otherwise refers to his neuromusculoskeletal prosthesis as "my arm," explained that he realized his neuromusculoskeletal prosthesis was unlike a human hand when he attempted to execute fast movements and found his prosthesis responded more slowly than he intended. Participants' experiences with mechanical breakdown of their prosthetic hand also underline that breakdown interrupts the sense of incorporating the prosthesis into the body. Frustration and angst ("I don't like the prosthesis" — P3) can interrupt an otherwise harmonious relationship ("My prosthesis is a part of my body. . .It's my arm now"). P3's language evinces how one's relationship to a prosthesis is not just a pragmatic one, but also an emotional, affective one. It is in these instances that a disruption occurs in the extent to which an individual identifies with the ownership of, and agency executed over, the device.

Furthermore, our participants did not necessarily seem to distinguish between "tool" and "body" in the dichotomous or mutually exclusive way that has been suggested in other studies of prosthetic embodiment (Murray, 2004; Miller et al., 2014; Gouzien et al., 2017). In using "glasses" as a metaphor for the neuromusculoskeletal prosthesis as an externalized but naturalized essential object, while also saying "it *is* me," P2 indicates that an object can also be considered part of the body. P3's somewhat humorous reminder that one's biological hand can also be considered a tool invites us to more closely examine the assumptions and dichotomies built into the language used to assess embodiment.

Limitations

Our study is limited by a small (N = 3) and homogenous pool of participants with regards to amputation level (transhumeral), gender (male), race (white), nationality (Swedish), and age (mid-40s). In regards to sensory feedback, the participants were provided with a conservative and simplistic neurostimulation strategy (frequency modulation), which has recently been found suboptimal (Mastinu et al., 2020). Taken together, these limitations constrain the generalizability of these findings to other patient populations, genders, amputation level, neural sensory feedback systems, and prosthetic devices.

The three participants, in being the first people implanted with the neuromusculoskeletal system, have received close interaction with experimenters that may differ from the later downstream population of general users. However, this scenario is not unique to our study and is often the case of those who volunteer to participate in early clinical trials and use of highly experimental biotechnologies. Sociologist Everett Rogers's "diffusion of innovations theory," first written in 1962, provides a framework to understand the way an innovation is adopted in a social system over time (Rogers, 2003). In this framework, we can understand the three participants as part of the first category of "innovators," who are often willing to take risks, interested in the technology, and sometimes more positively inclined toward the intervention. While this must be kept in mind in interpretation of the results, we still hold the experiences of these patients as valuable indicators of how people will live with and experience the neuromusculoskeletal prosthesis. Ours is an upstream study in the evolution of this innovation; our findings can be used to guide future design as well as therapeutic and rehabilitative interventions as the technology continues to be adapted for a wider population of users. Furthermore, despite participants' relative homogeneity and access to clinical service, even among these three users we found differences and nuances in users' opinions and values based on their lived experiences and contexts. These differences and nuances are noted and, along with shared experiences, form the substance of this study's analysis.

This is the first account of a long-term implementation of such an integrated neuroprosthetic limb system. These three participants were the first people to permanently utilize implanted electrodes to control and sense with a prosthesis in daily life. Therefore, the importance of this study is in its representation of the firsthand experiences of the first to use such an intimately integrated prosthesis independently. Despite these limitations, this study can still give insight into possible ways humans will integrate and interact with sophisticated prostheses as they proliferate in the future.

The interviews were conducted by one interviewer, holding the style, tone, and focus of the interview consistent. The interviewer was not part of the development team and the interviews were conducted in isolation from other participants or the development team. The participants were at no time dependent on the interviewer for treatment or services. This same interviewer and the co-author were the only two analyzers of the data. Coming from two different disciplines—medical anthropology and biomedical engineering—this provides a complementary view on the experiences of humans as social *and* biological beings, as well as on the technical counterparts that make such an integration of human and machine possible.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Regional Ethical Committee in Gothenburg, Sweden (Dnr # 1098-17). The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

AM and MO-C contributed to the conception and design of the study. AM conducted the interviews and translated the interview transcripts from Swedish to English. AM performed initial analysis and identified themes, which MO-C then cross-validated. AM and MO-C derived descriptive coding system. AM coded and analyzed the interview data. AM wrote the first draft of the manuscript. MO-C wrote sections of the manuscript. AM and MO-C contributed to manuscript revision, read and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnbot.2020.00039/full#supplementary-material

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Changing Body Representation Through Full Body Ownership Illusions Might Foster Motor Rehabilitation Outcome in Patients With Stroke

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How our brain represents our body through the integration of internal and external sensory information so that we can interact with our surrounding environment has become a matter of interest especially in the field of neurorehabilitation. In this regard, there is an increasing interest in the use of multisensory integration techniques—such as the use of body ownership illusions—to modulate distorted body representations after brain damage. In particular, cross-modal illusions such as mirror visual feedback therapy (MVFT) have been widely used for motor rehabilitation. Despite the effectiveness of the MVFT for motor rehabilitation, there are some limitations to fully modify the distorted internal representation of the paretic limb in patients with stroke. A possible explanation for this relies on the physical limitations of the mirror in reproducing upper-limb distortions, which can result in a reduced sense of ownership of the mirrored limb. New digital technologies such as virtual reality (VR) and 360° videos allow researchers to create body ownership illusions by adapting virtual bodies so that they represent specific morphological characteristics including upper-limb distortions. In this manuscript, we present a new rehabilitation approach that employs full virtual body ownership illusions, using a 360° video system, for the assessment and modulation of the internal representation of the affected upper limb in stroke patients. We suggest modifying the internal representation of the upper limb to a normal position before starting motor rehabilitation training.

Keywords: body representation, body ownership illusions, 360° videos, virtual reality, body schema, neurorehabilitation

INTRODUCTION

How our brain represents our body has been a matter of interest in the field of neuropsychology and neuroscience for many years (Lhermitte, 1942). In this regard, the sense of embodiment (or bodily self), that is, the sense of having a body (Gallagher, 2000), emerges from a complex interaction between bottom-up sensory signals and top-down cognitive processes occurring within a body frame (Longo et al., 2008; Tsakiris, 2017). More specifically, the sense of embodiment has been described as composed of several different structurally organized subjective components: (1) ownership, (2) agency, and (3) self-location (Longo et al., 2008; Kilteni et al., 2012a). In fact, one fundamental component of embodiment is the sense of body ownership (Tsakiris, 2017). The sense of body ownership is described as the percept of a body part or entire body belonging to oneself (Ehrsson, 2020). The sense of agency, meaning the sense of being the initiator or the source of the body's actions, is another fundamental component of embodiment (Gallagher, 2000). In addition, the sense of embodiment is constructed around the first-person pronoun from a conceptual point of view (Gallagher, 2012), where the subject feels self-located inside a physical body (Lenggenhager et al., 2006). The perceptual distinction between what is part of one's body and what is not is a crucial factor for human perception, action, and cognition (Ehrsson, 2020). Then, the sense of embodiment is multisensory in nature and relies on how all different sensory modalities come together into a coherent percept of an owned body or body part (Ehrsson, 2020).

The representation of embodiment (or bodily self) is typically explained according to two distinct concepts: body image and body schema (Gallagher, 1986). The conscious body image, as Gallagher described it, consists of three different components: first, the perception of the body in the immediate consciousness; second, the cognitive conceptualization of the body that is influenced by the immediate consciousness and the knowledge about the body; and third, the emotions and feelings toward the body that may be generated by conscious or unconscious experiences. Therefore, body image is constructed based on perceptual, cognitive, and emotional components. Body schema, on the other hand, was described by Gallagher as a more organized representation of the body in relation to the environment. More specifically, Gallagher refers to body schema as an active component of body representation, which integrates different body positions and movements in relation to the environment (Gallagher, 1986). Body schema is additionally defined by different authors as a dynamic sensorimotor representation of the body that leads to body perception and body action (Dohle et al., 2004; Haggard and Wolpert, 2005; de Vignemont, 2010; Longo et al., 2010).

Body representation can change due to an injury to the nervous system, resulting in the modification of the body's internal multisensory interactions (Berlucchi and Aglioti, 2010). It is known that nervous system injuries, as well as mental illnesses, can change the internal representation of the body (Berlucchi and Aglioti, 2010; Leemhuis et al., 2019). Internal representations of the body refer to relatively stable representations of the body and define the body as it usually is (Berlucchi and Aglioti, 2010). Damage in the right hemisphere of the brain, specifically in the temporoparietal and insular areas, can disrupt spatial and body representations, as in spatial neglect (Heilman et al., 2000). Moreover, in amputee or hemiparetic patients, a sensorimotor interruption after the injury, arm amputation, or paresis of a body part can distort the internal body representation, leading to consequences such as phantom limb phenomena or motor anosognosia (denial of the motor deficits commonly observed in patients with right-hemisphere brain damage; Berlucchi and Aglioti, 2010). Brain damage can also lead to distorted body representations that bring about alterations in proprioceptive and kinesthetic signals and in the perception of the peripersonal space (the space around the body; Wallwork et al., 2016). Such sensory alterations after brain damage affect movement planning, preparation, and execution, since motor performance is continuously fostered by sensorimotor loops that constantly update internal predictions about the outcome of a motor command (Wolpert and Ghahramani, 2000). In addition, it has been argued that all these neural interactions occur within a cortical body matrix frame, which can be thought of as a neural network that is implicated in the regulation, control, and protection of the body and the surrounding space, at both physiological and perceptual levels (Moseley et al., 2012). Some studies have attempted to modulate body distortions in patients suffering from brain damage using cross-modal illusions based on multisensory integration techniques and the "free-energy principle" (FEP; Friston et al., 2010; Limanowski and Blankenburg, 2013), through mirror visual feedback therapy (MVFT) and the rubber hand illusion (RHI; Bolognini et al., 2015; Tosi et al., 2018), or by manipulating visuo-tactile stimulation feedback in amputee patients presenting a telescoped effect (which occurs when the distal part of the phantom limb is perceived as shrinking within the stump; Schmalzl, 2011).

In this perspective article, we propose a new rehabilitation approach based on the use of full-body ownership illusions induced using a 360° video system designed to assess and later modulate the distorted internal body representation of the paretic upper limb in patients with stroke. The main aim of the proposed intervention is to provide kinesthetic and proprioceptive stimuli to patients with a paretic upper limb so that the internal representation of the affected limb changes from the distorted position to a normal one before starting conventional motor rehabilitation training. This intervention may help physicians to improve the outcome of motor rehabilitation. We additionally explore the current understanding of body perception and consequent distortions of internal upper-limb representations following a stroke injury. We then describe some cross-modal illusions used for upper-limb motor rehabilitation in patients with stroke such as the MVFT or the RHI. Finally, we discuss recent developments in virtual body ownership illusions using 360° video systems for the modulation of body representations.

BODY PERCEPTION DISTORTION AND MOTOR DISRUPTION IN PATIENTS WITH STROKE

It is known that negative plastic changes can occur in the brain after a stroke injury (Takeuchi and Izumi, 2012), affecting the patients' functional mobility (Morone et al., 2018). Moreover, the disuse of the affected part of the body, such as the arm in patients with stroke presenting hemiparesis or hemiplegia of the body, can enhance negative plastic changes in the brain

(Takeuchi and Izumi, 2012; Bassolino et al., 2014b). In particular, disuse of the upper limb following a brain injury can lead to a reduction of the cortical representation in motor and sensorimotor areas (Flor et al., 2006; Dohle et al., 2009; Bassolino et al., 2014a), further affecting the functionality of the affected limb. This process is commonly known as "learned paralysis" and has been investigated in humans in a study in which the author suggested that the no-movement visual feedback of the affected limb following a motor intention reinforces the acquired knowledge that the limb cannot move (Ramachandran, 1993). Then, the lack of movement of the affected limb results in a progressive shrinking of the representation of the affected limb in the somatosensory cortex (Ramachandran, 1993).

Besides the shrunken representation of the affected limb in the somatosensory cortex, other studies have reported that the lack of movement of the affected limb can lead to other types of body distortions in patients with stroke, such as the supernumerary phantom limb sensation (Bakheit and Roundhill, 2005)—the feeling of having an extra limb—which involves bilateral frontal, right parietotemporal cortices and the basal ganglia (Srivastava et al., 2008), or anosognosia—the denial of sensory, motor, or perceptual deficits in the paretic limb after brain injury—which occurs in patients with left brain damage (Berlucchi and Aglioti, 2010). In addition, patients with right-hemisphere brain damage presenting hemispatial neglect have a complex distortion of the body schema (e.g., ipsilesional deviation of the representation of the median sagittal axis of the body, or a bilateral narrowing in estimated body width; Rousseaux et al., 2014). Other studies have shown that brain damage affecting the motor system can lead to a disrupted awareness of motor actions, as well as of the control of such motor actions (Frith et al., 2000), as occurs in the alien hand syndrome (Biran and Chatterjee, 2004). Such disruptions can be associated with a distorted representation of the body or body parts in the brain (Frith et al., 2000). As a consequence of these sensorimotor alterations after brain damage, some studies have reported an impaired sense of ownership of the paretic limb in patients with stroke (Burin et al., 2015). Hence, based on the studies commented above, one may postulate that there is a link between alterations in internal models of body representation and motor awareness and motor control after suffering brain damage such as stroke. Such alterations of the internal models of the body might interfere with motor rehabilitation, for example, when using the MVFT due to mismatch between sensory signals and internal models of body representation.

CROSS-MODAL ILLUSIONS IN NEUROREHABILITATION: MIRROR THERAPY VS. VIRTUAL REALITY AND 360° VIDEO

In the last years, some researchers have proposed the use of cross-modal illusions for neurorehabilitation purposes (Bolognini et al., 2015), with the intention to regulate possible alterations of body representation in the brain and to restore motor ability after suffering brain damage. Cross-modal illusions occur when one sensory modality (e.g., touch) affects the experience of another sensory modality (e.g., vision). These illusions are not only mediated by inferential or higher-level cognitive processes, but also mediated by automatic multisensory interactions occurring at brain level (Bolognini et al., 2015). One example is the RHI, in which healthy participants experience the illusion of owning a rubber hand by receiving synchronous visuo-tactile stimulation to the real hidden hand and to the visible rubber hand (Botvinick and Cohen, 1998). One of the most well-known types of cross-modal illusions in the field of neurorehabilitation is MVFT, whereby the healthy limb of the patient is reflected in the mirror and, seeming visually superimposed on the location of the affected limb, it creates the illusion that the affected limb has recovered (Ramachandran et al., 2009 for a review). Then, when patients move their healthy limb, they have the illusion of moving their affected limb. Such movement illusions resulted in pain relief in patients with phantom limb pain, and in re-learning motor patterns in patients with stroke (Altschuler et al., 1999; Sathian et al., 2000; Garry et al., 2005; Chan et al., 2007; Sütbeyaz et al., 2007; Altschuler and Hu, 2008; Darnall, 2009; Ramachandran et al., 2009). Moreover, recent meta-analysis studies showed that motor visual feedback using MVFT may enhance motor rehabilitation outcome (Yang et al., 2018; Zeng et al., 2018). Even though cross-modal illusions are considered an attempt by the multisensory system to reconnect the affected sensory neural networks and bypass injured areas, these can be maladaptive when atypical or even when they are generated as a consequence of rearranged multisensory networks (Bolognini et al., 2013). One example of this is illustrated in a study conducted by Foell and colleagues, in which amputee patients with telescoped phantom limbs had an atypical illusory multisensory experience after completing MVFT, which did not cause any pain relief (Foell et al., 2014). Nevertheless, others have shown that it is possible to modify the distorted internal representation of the affected limb using MVFT in patients with stroke (Tosi et al., 2018). For instance, in the study conducted by Tosi et al. (2018), a forearm bisection task was specifically designed to measure the metric representation of the arm (i.e., its size). The results showed that after performing an MVFT session, bisection scores shifted distally from baseline, showing a partial correction of the distorted metric representation of that arm.

One explanation of the results obtained in the study by Foell et al. (2014) could be that the perceived internal distortion of the phantom limb influenced the vividness of the ownership illusion of the healthy limb reflected in the mirror. The mismatch between the internal distorted representation of the arm and the observed reflection of the arm in a normal position could reduce the feeling of ownership of the reflected arm, thus reducing the effectiveness of the therapy for pain relief. In this regard, the development of new augmented or VR systems, as well as the use of new 360° videos, through which it is possible to induce embodiment of a full virtual body observed from a first-person perspective (Maselli and Slater, 2013; Aitamurto et al., 2018), and the manipulation of morphological characteristics of the represented virtual body (Kilteni et al., 2012b; Serino et al., 2019), offers a potential alternative to the traditional MVFT (Rothgangel and Bekrater-Bodmann, 2019). In this line, a large number of studies have demonstrated that by changing the morphological characteristics of the represented body in VR, it is possible to modulate pain perception in healthy and clinical populations (Matamala-Gomez et al., 2019, 2020) and to improve motor performance in patients with stroke (Ambron et al., 2018). Hence, new VR or 360° video systems offer the possibility to fully reproduce the distorted internal representation of the affected body part while feeling embodied in a full virtual body before starting the rehabilitation process. One example of this was discussed by Turton and colleagues, where the authors presented a new digital media tool for communicating body perception disturbances through a virtual avatar in patients suffering from complex regional pain syndrome (Turton et al., 2013). The tool allowed the modification of a virtual avatar in terms of size, shape, and color, including the ability to lengthen or shorten limb segments, make them thicker or thinner, and even change the limb position to anatomically impossible positions, thus adapting the avatar's limb position to the patient's verbal description. Even though the effectiveness of MVFT to modulate body representation and to improve motor recovery after stroke has been largely demonstrated (Altschuler et al., 1999; Yavuzer et al., 2008; Michielsen et al., 2011; Rothgangel et al., 2011), there are still some physical limitations when representing the distorted internal representation of the body, which lead to a reduced sense of ownership of the observed limb and ultimately weaken the rehabilitation outcome. Here, a solution to tackle the mismatch between the sensory information provided and the internal models of body representation when using cross-modal illusions for motor rehabilitation is proposed.

INCREASING MIND-BODY COMMUNICATION THROUGH 360° VIDEOS TO ENHANCE MOTOR REHABILITATION OUTCOME

Body ownership may rely on some degree of matching between internal models of the body and the experienced sensory feedback when using cross-modal illusions to induce BOIs. The use of cross-modal illusions for rehabilitation is made more difficult when people feel like the body they see (e.g., reflected in a mirror) is not in keeping with their internal representation. In this regard, the incorporation of new technologies such as VR to update the distorted body representation in clinical populations has been proposed before (Riva, 2008; Riva et al., 2017, 2019). These studies have shown a possible theoretical way to correct a dysfunctional representation of the body using virtual body ownership illusions and explain how a distorted self-perception within the FEP framework is the result of an inference process that minimizes prediction errors associated with self-perception (Friston et al., 2010; Limanowski and Blankenburg, 2013) More specifically, the FEP is based on the assumption that the brain implements hierarchical dynamical models to predict the causes of the processed sensory information (Friston and Kiebel, 2009; Bubic et al., 2010). Then, the FEP proposes that subjects can model their self-representation as a consequence of hierarchical predictive modeling, mediated by the sensory information arriving to the body (Friston, 2011, 2013). Conceptually, the FEP assesses the improbability (surprise) of the sensory information under a hierarchical generative model (Friston et al., 2006, 2010, 2011). In the case of body ownership illusions, altered body perception results from a self-representation that is updated dynamically by the brain to minimize sensory conflicts (i.e., the differences between the predictions about sensory data and the real sensory data at any level of the hierarchical model). Then, when using body ownership illusions our brain tries to minimize the "surprise" through the predictive coding scheme, when encountering a signal that was not predicted, it will generate prediction errors and will update the model in order to minimize the differences between the predictions about sensory data and the real sensory data at any level of the hierarchical model (e.g., synchronous visuo-tactile feedback in the RHI study; Friston and Kiebel, 2009; Bubic et al., 2010; Friston et al., 2010). Therefore, the subjects will update their internal body representation.

Here, we propose a new rehabilitation approach by means of full-body ownership illusions recorded from a first-person perspective by a 360° video system and delivered through a head-mounted display (HMD) also from a first-person perspective. The use of 360° video to provide body ownership illusions from a first-person perspective has been previously shown (Aitamurto et al., 2018). Moreover, 360° videos have also been used in clinical populations with neurological disorders (Serino et al., 2017; Realdon et al., 2019). The intervention aims to reproduce internal upper-limb distortions in patients with stroke while they embody a virtual body by means of colocation of the real body with the virtual one. In this regard, colocation has been identified as a key component to provide body ownership illusions by itself without the need to induce synchronous visuo-tactile or visuo-motor correlations (Slater et al., 2010). The proposed intervention is composed of four different phases: (1) The "*baseline phase or distortion assessment phase*": in this phase, patients will provide a verbal description of their distorted internal representation of the upper limb, and a picture of the body of the patients from a first-person perspective will be taken. (2) "*Phase 1 or the virtual embodiment phase*": in this phase, patients will embody a virtual representation of their own body, which will be colocated with the real one and which will show the described upper-limb distortion from a first-person perspective through the HMD. Patients will be seated on a chair and in front of a table (same pose as the observed virtual body) and will be asked to place their real body in the same position in which the virtual body is so that they are colocated. Patients will observe their virtual body for at least 45–60 s to induce the ownership illusion of the virtual body. (3) "*Phase 2 or the normalization of the distorted upper-limb representation phase*": once the embodiment phase is done by means of colocation, and the ownership illusion of the distorted virtual arm and the body is induced, patients will progressively observe how the position of the

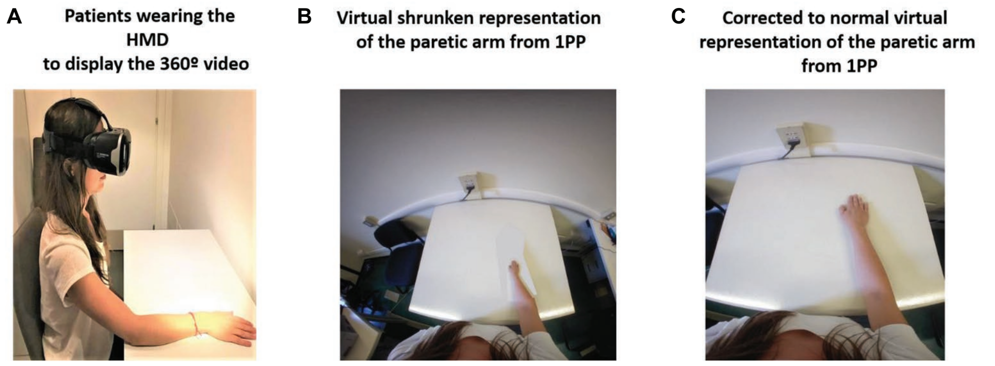

FIGURE 1 | 360° video protocol for managing body distortions in patients with stroke. Phase 1: **(A)** Patients wearing the head-mounted display (HMD) displaying the 360° video. **(B)** Virtual shrunken representation of the affected arm: Patients will observe the virtual body that will be colocated with their real body and will represent the patient's described distorted representation of the upper limb from a first person-perspective (1PP; e.g., a shrunken upper limb). Phase 2: **(C)** First-person perspective observation of the progressive transformation of the affected upper limb from the distorted representation to a normal one through an edited 360° video viewed through the HMD.

upper limb whose representation is distorted changes until it arrives at a normal position. Phases 1 and 2 are represented in **Figure 1**, where the upper-limb distortion is shown as a shrunken representation of the affected limb. (4) "*Phase 3 or the motor training phase*": once the normalization of the distorted upper-limb representation is achieved, patients will perform their conventional motor rehabilitation training using either visual feedback techniques, such as MVFT or VR training, or conventional physical rehabilitation training. The rehabilitation approach proposed here allows the therapist to correct the internal body representation of the affected upper limb before starting motor rehabilitation, bringing them the opportunity to provide proper kinesthetic and proprioceptive feedback. Hence, we hypothesize that visual exposure to a corrected representation of the paretic limb through a virtual body ownership illusion generated in a 360° video should provide enough predictive errors, based on the FEP explained above, to update the distorted internal representation of the body to a normal one (Riva et al., 2017; Riva, 2018).

CONCLUDING REMARKS

In conclusion, we suggest that full virtual body ownership illusions provided by 360° videos may bring new opportunities for the assessment and modulation of distorted upper-limb representations in patients with stroke. Moreover, if this intervention is applied before starting conventional motor rehabilitation training, this could provide proper kinesthetic and proprioceptive feedback to the affected upper limb. Whether or not the introduced approach is capable of enhancing treatment effects of MVFT for motor recovery after stroke, however, has to be explored in the future. The rehabilitation approach proposed here uses a "Positive Technology" approach (Wiederhold and Riva, 2012; Inghilleri et al., 2015; Riva et al., 2016), to build a potential bridge between basic research and clinical applications in the field of neurorehabilitation.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

ETHICS STATEMENT

Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

MM-G contributed to the conceptualization of the manuscript, bibliographic review, and writing. CM contributed to the bibliographic review and writing of the manuscript. PC contributed to the conceptualization and revision of the manuscript. EP and OR contributed to the bibliographic suggestions, conceptualization, and revision of the manuscript. FM and GR contributed to the supervision of the manuscript. All the authors approved the final version of the manuscript for submission.

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frontiers in Neurorobotics

ORIGINAL RESEARCH
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Factors Associated With Prosthesis Embodiment and Its Importance for Prosthetic Satisfaction in Lower Limb Amputees

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Perceptual integration of a prosthesis into an amputee's body representation, that is, prosthesis embodiment, has been proposed to be a major goal of prosthetic treatment, potentially contributing to the user's satisfaction with the device. However, insufficient knowledge about individual or prosthetic factors associated with prosthesis embodiment challenges basic as well as rehabilitation research. In the present study, hierarchical multiple regression analyses on prosthesis embodiment—as assessed with the recently introduced *Prosthesis Embodiment Scale*—were applied to the survey data of a large sample of prosthesis-using lower limb amputees, entering relevant objective-descriptive (i.e., unbiased characteristics of the amputation or the prosthesis) and subjective-evaluative variables (i.e., the amputee's perceptions related to the amputation or the prosthesis) as first- or second-level regressors, respectively. Significant regressors identified in these analyses together explained $R^2 = 36.3\%$ of prosthesis embodiment variance in the present sample, with a lower level of amputation, less intense residual limb pain, more realistic visual appearance of the device, higher prosthetic mobility, and more positive valence of prosthesis-induced residual limb stimulations representing significantly associated factors. Using the identical set of regressors hierarchically complemented by prosthesis embodiment on measures of prosthetic satisfaction—as assessed with the *Trinity Amputation and Prosthesis Experience Scales*—revealed that prosthesis embodiment was significantly and positively associated with aesthetic as well as functional prosthesis satisfaction. These findings emphasize the importance of psychological factors for the integration of a prosthesis into the amputee's body representation, which itself represents a crucial factor associated with prosthesis satisfaction. The results might have important implications for future prosthetic treatment; however, replication of the findings in an independent sample is required, as well as sophisticated experimental designs in order to elucidate the causality of effects.

Keywords: amputation—rehabilitation, human-machine interaction, prosthesis embodiment, prosthesis satisfaction, regression analysis

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INTRODUCTION

The amputation of a limb represents a severe impact on a person's physical integrity. The need to restore the body after amputation has been met with ever new prosthetic developments, seeking to equip the amputee with a virtually full replacement of the lost body part. To this end, prosthetic treatment is primarily guided by aspects of cosmetics and functionality.

Previous studies sought to reveal factors associated with the amputee's satisfaction related to the prosthetic device. Thus, better comfort of fit, better functionality, and more positive evaluation of weight (Glynn et al., 1986; Postema et al., 1999; Gallagher and MacLachlan, 2000; Biddiss and Chau, 2008; Sinha et al., 2014; Baars et al., 2018), higher frequency of prosthesis use (Dillingham et al., 2001), and more preferable appearance of the device (Postema et al., 1999; Harness and Pinzur, 2001) have been reported to be associated with higher prosthesis satisfaction or reduced prosthesis rejection in both upper and lower amputees. Individual characteristics of the amputation have also been identified as co-varying with prosthesis satisfaction, with a lower (compared to higher) amputation level, better residual limb health, and less post-amputation pain being often reported factors (Harness and Pinzur, 2001; Biddiss and Chau, 2007; Desmond et al., 2008; Berke et al., 2010; Webster et al., 2012; Sinha et al., 2014; Resnik et al., 2020).

A recent systematic review on factors associated with prosthesis satisfaction specifically in lower limb amputees (Baars et al., 2018) identified the device's appearance, functional and physical properties, and fit, as well as prosthesis use and medical issues of the residual limb as important variables. Sex, etiology and the level of amputation, as well as properties of the prosthesis socket might represent crucial modulating variables.

As clinically relevant as these results might be, they neglect the importance of psychological factors, such as the amputees' perceptions of their body in relation to their prosthesis. Recently, particular interest has been taken in the mechanisms underlying the so-called *prosthesis embodiment*, which describes the integration of the prosthetic device into the amputee's body representation (Murray, 2004, 2008; Makin et al., 2017; Niedernhuber et al., 2018). Prosthesis embodiment could be associated with several positive rehabilitative outcomes. Thus, embodied upper limb prostheses have recently been related to a stabilized body posture (Imaizumi et al., 2016) and improved motor planning (Gouzien et al., 2017). Furthermore, prosthesis embodiment has been epidemiologically related to reduced levels of post-amputation pain in both upper and lower limb amputees (Kern et al., 2009; Bekrater-Bodmann et al., 2020). Other results revealed prosthesis use-dependent brain plasticity, suggesting neural embodiment of the device (Lotze et al., 1999; Maimon-Mor and Makin, 2020). Psychometrically, prosthesis embodiment experiences in lower limb amputees have recently been characterized by (a) the sensation that the device is an actual body part, (b) the feeling of an intact physical integrity, (c) the experience of the prosthesis' posture and location as anatomically plausible, and (d) having control over the device's movements (Bekrater-Bodmann, 2020). In other words, prosthesis embodiment is the cognitive and perceptual incorporation of the prosthesis, which can then be better described as representing an actual body part, rather than as a mere tool loosely attached to the body (Murray, 2004; Makin et al., 2017). Recent results suggest a wide range in the intra-individual degree of prosthesis embodiment experiences in lower limb amputees, which have been shown to represent a temporally stable, but contextually dynamic perceptual feature co-varying with a given prosthetic device (Bekrater-Bodmann, 2020).

Research on factors associated with the embodiment of a prosthesis is scarce. Epidemiological studies on samples of both upper and lower limb amputees reported associations between certain manifestations of prosthesis embodiment and the presence of non-painful phantom phenomena (Giummarra et al., 2010), the absence of phantom limb pain (Kern et al., 2009), as well as a younger age, a leg (vs. arm) amputation, a longer residual limb, a longer time since amputation, and the frequency of prosthesis use (Bekrater-Bodmann et al., 2020). However, the interpretation of these results is complicated by heterogeneous operationalizations of prosthesis embodiment experiences with unknown validity. With the recently introduced *Prosthesis Embodiment Scale* (PEmbS; Bekrater-Bodmann, 2020), however, a psychometrically evaluated instrument for the assessment of prosthesis embodiment experiences is available, which might help to reliably identify factors associated with the perceptual integration of the prosthesis into an amputee's body representation. Moreover, since there is evidence for complex inter-relationships between individual and prosthesis variables (Bekrater-Bodmann et al., 2020), the often-used univariate statistical approaches (such as correlations for continuous data or tests for comparing the central tendency in subgroups) might be inappropriate to validly identify factors associated with prosthesis embodiment. Thus, multivariate statistical approaches are needed, which along with homogenous samples of sufficient sizes might help to identify factors associated with perceptual prosthesis embodiment. Knowledge about these factors might have important implications for theoretical concepts on body perception as well as future prosthetic design and treatment.

In the present study, a regression analytical approach was used, including a large sample of unilateral lower limb amputees using a prosthesis. Amputation and prosthesis factors were selected based on empirical results on prosthesis embodiment and prosthesis satisfaction. For both amputation and prosthesis factors, hierarchical models were applied, including objective-descriptive (i.e., unbiased characteristics of the amputation or the prosthesis) and subjective-evaluative variables (i.e., the amputee's perceptions related to the amputation or the prosthesis) as first- or second-level regressors, respectively. Regressors identified to be significantly associated with prosthesis embodiment were combined in order to better explain the variance in the criterion. Finally, the importance of prosthesis embodiment for prosthesis satisfaction was explored.

MATERIALS AND METHODS

Sample and Procedure

Between May 2019 and March 2020, 166 unilateral lower limb amputees using a prosthesis were recruited (71.69% male; mean age of 56.63 years with a standard deviation of 10.95). Various sources were used for recruitment, such as a previously

TABLE 1 | Amputation details of the present sample ($N = 166$).

Characteristics	%
Amputation	
Amputation of dominant limb[a]	37.25
Amputation of left limb	61.45
Level of amputation	
Foot amputation	3.01
Transtibial amputation	46.99
Knee exarticulation[b]	4.82
Transfemoral amputation	44.58
Hip exarticulation or hemipelvectomy	0.60
Reason for amputation (multiple responses allowed)	
Accident	63.86
Cancer	18.07
Injury	15.66
Infection	12.65
Peripheral vascular disease	8.43
Congenital limb deficiency	0.60
Other reasons	9.04

[a]valid data for the question Which leg did you use to kick an object, for example a ball, prior to amputation? (13 missing data due to not-remembering); [b]one participant with rotationplasty was assigned to this category.

established data base (initial description by Bekrater-Bodmann et al., 2015), flyers distributed to professionals working in prosthetic rehabilitation centers, and calls via print and social media. Inclusion criteria for the present study were an age between 18 and 80 years, unilateral lower limb loss, owning and using a prosthesis, and sufficient comprehension of the German language. The sample consisted of 118 participants, which were already described in a recent study on prosthesis embodiment (Bekrater-Bodmann, 2020), augmented by 48 newly recruited lower limb amputees. Clinical details of the present sample are provided in **Table 1**.

Recruited amputees were screened via telephone interviews for eligibility to participate before the consent form was sent postally or via email. After returning the consent form, an individualized link to an online questionnaire battery (implemented in Gorilla™; https://gorilla.sc/) was sent to most of the participants. Due to not having access to the internet, a printed version of the questionnaire battery was sent to ten participants postally. The battery (online or print version) included questionnaires on demographics, amputation, and prosthesis information, phantom phenomena, as well as instruments on mobility, prosthesis acceptance, psychosocial functioning, and body image. The study was approved by the ethics review board of the Medical Faculty Mannheim, Heidelberg University, and adhered to the Declaration of Helsinki in its current form.

Selection of Factors

Since it has previously been argued that prosthesis embodiment could contribute to prosthesis satisfaction (MacLachlan, 2004; Murray, 2008), the selection of regressors was guided by empirical results on both phenomena as identified in lower limb amputees. A recent systematic review on factors associated with prosthesis satisfaction in lower limb amputees (Baars et al., 2018) identified appearance, fit, and use of the prosthesis, medical issues of the residual limb, as well as properties of the device as important influencing factors, with sex, etiology of amputation, properties of the prosthesis socket, and the level of amputation representing crucial modulating variables. Further, Bekrater-Bodmann et al. (2020) found that a younger age, a longer residual limb, an increased amount of time since amputation, a higher frequency of prosthesis use, and the type of prosthesis (modular vs. exoskeletal) were associated with higher prosthesis ownership—representing a sub component of embodiment (Longo et al., 2008)—in a sample of more than 1,300 lower limb amputees. Phantom and residual limb sensations have further been related to prosthesis embodiment (Kern et al., 2009; Giummarra et al., 2010; Bekrater-Bodmann et al., 2020). Most of these variables can be categorized as being related to the amputation or the prosthesis, and can further be described as being objective-descriptive (i.e., unbiased characteristics of the amputation or the prosthesis) or subjective-evaluative features (i.e., the amputee's perceptions related to the amputation or the prosthesis). The grouping as well as operationalization of the variables is described below. Since there is evidence that surveyed amputees are rather unable to reliably indicate technical specifications of their prosthetic device (Bekrater-Bodmann, 2020), purely technical properties of the prosthesis were not included as regressors in the present study.

Operationalization and Grouping of Factors

The operationalization of included factors, grouped by content, is described below. Additional information, including the wording (translated to English) and the scaling of used items as well as the variables derived from them, is provided in **Supplementary Table 1**.

Amputation-Related Factors

Objective-Descriptive Amputation-Related Factors (First-Level Regressors)

As reviewed above, the level and etiology of and the time since amputation might influence prosthesis embodiment and/or prosthesis satisfaction in lower limb amputees. *Time since amputation* was measured in years, by using the difference between the date of amputation and the date of participation in the present study.

Since the majority of the included amputees in the present study suffered from transtibial or transfemoral amputation, both with a percentage of about 45% (see **Table 1**), the *level of amputation* was dichotomized and dummy-coded with 0 (foot and transtibial amputation) for *low amputation level* and 1 (knee exarticulation, transfemoral amputation, and hip exarticulation or hemipelvectomy) for *high amputation level*).

Most participants reported traumatic events such as accidents or injuries as the reason for their amputation; a minority reported other reasons such as cancer or peripheral vascular disease, and about 20% of the participants indicated more than one reason. *Etiology of amputation* was thus dichotomized into one group that indicated traumatic events (i.e., accidents or injuries) as reason for amputation (dummy-coded as 0), and another group that reported other or multiple reasons for the amputation (dummy-coded as 1; cf., **Table 1**).

Subjective-Evaluative Amputation-Related Factors (Second-Level Regressors)

Painful or non-painful sensations in the residual and phantom limb are the most common perceptual consequences following a limb amputation (e.g., Ehde et al., 2000), and there is evidence for different etiologies of these sensations (e.g., Foell et al., 2011). In the present study, three different phenomena were considered: phantom limb awareness (PLA), that is, the perceived presence of the amputated limb; phantom limb pain (PLP), that is, painful experiences located in the missing limb; and residual limb pain (RLP), that is, painful experiences located in the remaining part of the amputated limb.

Participants were separately asked whether they had experienced PLA, PLP, and RLP in the past three months (i.e., current presence of the phenomenon). Participants who responded affirmatively were then asked to indicate the average intensity of the phenomena in the past 4 weeks, using a numerical rating scale ranging from 0 (no pain/no sensations) to 10 (unbearable pain/very strong sensations). This measure was used as *PLA intensity*, *PLP intensity*, and *RLP intensity*, respectively.

Prosthesis-Related Factors

Objective-Descriptive Prosthesis-Related Factors (First-Level Regressors)

Participants were instructed to answer all prosthesis-related questions for their main prosthesis, which—in the case of owning more than one prosthesis—is the prosthesis they use most of the time.

It has been proposed that the perceptual system of amputees can change over time (Ehrsson et al., 2008) which would not only be true for time since amputation, but also for the time the amputee is faced with a given prosthetic device. Thus, participants were asked to indicate since when they had been using their current prosthesis, and *time with current prosthesis* was calculated in years.

Further, participants were asked how often they use the prosthesis (a) per week (1—less than twice; 2—every 2nd day; 3—almost daily; 4—daily) and (b) per day (1—1–2 h; 2—several hours, but not throughout; 3—half a day; 4—from morning to evening). By multiplying both ratings, an ordinally scaled *frequency of prosthesis use* index with nine ranks was obtained, ranging from rare to frequent use (cf., Bekrater-Bodmann et al., 2020).

Subjective-Evaluative Prosthesis-Related Factors (Second-Level Regressors)

Selection of subjective-evaluative prosthesis-related factors based on cosmetics, functionality, and fitting of the device, and thus included perceptions and evaluations of these aspects. Thus, participants were asked to judge the visual appearance of their prosthesis regarding resemblance with a real body part using a numerical rating scale ranging from 0 (artificial) to 10 (like an actual body part), assessing *visual realism* of the device. This feature of appearance was chosen (cf., Baars et al., 2018), since there is empirical evidence that visual realism can facilitate the experimental induction of embodiment experiences (Tsakiris et al., 2010).

Mobility was assessed using the German 12-item version of the Prosthetic Limb Users Survey of Mobility (PLUS-M-12; Hafner et al., 2017), a self-report instrument assessing mobility of lower limb amputees. The PLUS-M-12 asks for the perceived ability to perform given everyday actions (e.g., "Are you able to walk a short distance in your home?"), using a response scale ranging from 0 (without any difficulty) to 4 (unable to do). Raw sum scores were converted to T-values, representing a standardized score with a mean of 50 and an SD of 10 (according to the guidelines; University of Washington Center on Outcomes Research in Rehabilitation, 2014). For the purpose of intuition, the scores were reversed so that a higher score indicates a higher level of mobility.

Finally, participants were asked whether or not the prosthesis caused stimulations at the stump and if so, how these stimulations were evaluated, using a Likert scale ranging from −5 (negative) to +5 (positive). For this *residual limb stimulation* measure, negative ratings were recoded to −1, neutral (i.e., 0) or absent stimulations to 0, and positive ratings to +1.

Operationalization of Criterion Variables

Prosthesis Embodiment

The *Prosthesis Embodiment Scale for Lower Limb Amputees* (PEmbS-LLA; Bekrater-Bodmann, 2020) consists of ten items targeting the dimensions of *Ownership/Integrity* (a sense of belongingness for the prosthesis), *Agency* (a sense of being in control of the prosthesis), and *Anatomical Plausibility* (referring to spatial-structural properties of the prosthesis in respect to the amputee's body). These dimensions correspond to the earlier identified embodiment components in the rubber hand illusion paradigm (*Ownership*, *Agency*, and *Location*; Longo et al., 2008), and thus quantify the degree to which a prosthesis is cognitively and perceptually integrated as a part of the amputee's body, rather than a mere tool (cf., Makin et al., 2017). Participants were asked to look at or walk with the prosthesis before indicating their agreement or disagreement with given statements (for example "The prosthesis is part of my body"), using a Likert scale ranging from −3 (strongly disagree) to +3 (strongly agree). The total score of the PEmbS-LLA, representing an overall measure of perceived prosthesis embodiment, was calculated by averaging all valid items (up to one missing item was allowed in the present study, which was the case in $n = 4$ participants; another four participants had more than one missing value or were not able to walk with their prosthesis and were thus excluded from the subsequent analyses), with higher scores indicating higher prosthesis embodiment. The *Prosthesis Embodiment Scale* has previously been shown to have good to excellent reliability (Bekrater-Bodmann, 2020), and results on implicit effects suggest validity of the instrument (Fritsch et al., 2020).

Prosthesis Satisfaction

Prosthesis satisfaction was assessed with a German translation of the *Trinity Amputation and Prosthesis Experience Scales—Revised* (TAPES-R; Gallagher et al., 2010), provided by the Center for Orthopedic and Trauma Surgery, Heidelberg University Hospital, Heidelberg, Germany. The TAPES-R satisfaction sub-scale measures two dimensions of prosthesis satisfaction: *aesthetic prosthesis satisfaction* is measured with three items targeting the satisfaction level with color, shape, and appearance of the device; and *functional prosthesis satisfaction* is operationalized by five items focusing on satisfaction with weight, usefulness, reliability, fit, and comfort. Each item was answered using the response scale 1 (not satisfied), 2 (satisfied), and 3 (very satisfied). In order to enhance comparability of scores, the means of the items representing a scale (in contrast to summing them up) were calculated (ranging from 1 to 3 each).

Statistical Analysis

All analyses were performed with IBM SPSS v26. First, descriptive analyses of the included variables were performed, and prevalence, means, standard deviations (SD), medians, and/or interquartile ranges are provided, based on the scaling level.

In order to check whether the statistical assumptions for performing regression analyses were fulfilled, the author initially checked (a) for violation of the residuals' normal distribution using Shapiro–Wilk tests, (b) the absence of multicollinearity, which was assumed if tolerances >0.20 and variance inflation factors (*VIF*) < 4.0 (Hair et al., 2010), (c) the absence of heteroscedasticity using the Breusch-Pagan test (given that kurtosis of all residual distributions was < ±2; George and Mallery, 2010), (d) absence of auto correlations (checking visually the Q-Q plot; Golberg and Cho, 2010), and (e) absence of endogeneity (all correlations between residuals and regressors $r < 0.001$, all $p > 0.999$). Each model (described below) fulfilled the assumptions; statistical details are provided in the **Supplement**.

In order to test for associations between prosthesis embodiment and amputation- and prosthesis-related factors, hierarchical multiple regression analyses were performed. Separately for amputation- (models I and II) and prosthesis-related factors (models III and IV), first-level (objective-descriptive) and second-level (subjective-evaluative) regressors were entered block-wise (simultaneous entry). The regressors which emerged to be significant in models II and IV were then simultaneously entered in model V along with the demographic variables *sex* and *age*. Finally, the model-V-set of regressors was used to explain variance in aesthetic (model VI) and functional prosthesis satisfaction (model VIII). In a second hierarchical level each, prosthesis embodiment was entered (models VII and IX). The analytic strategy is visualized in **Figure 1**. For each model, the analysis of variance testing for significance of R^2 and/or its increase in hierarchical models is reported. Further, the author reports on the adjusted R^2. For each regressor, the unstandardized coefficient *B* and its standard error *SE* were reported, along with the standardized regression coefficient β and the respective *p*-value. Note that the number of participants included in the regression analyses varies between $n = 159$ and 161, depending on the availability of valid data (cf., **Table 2**).

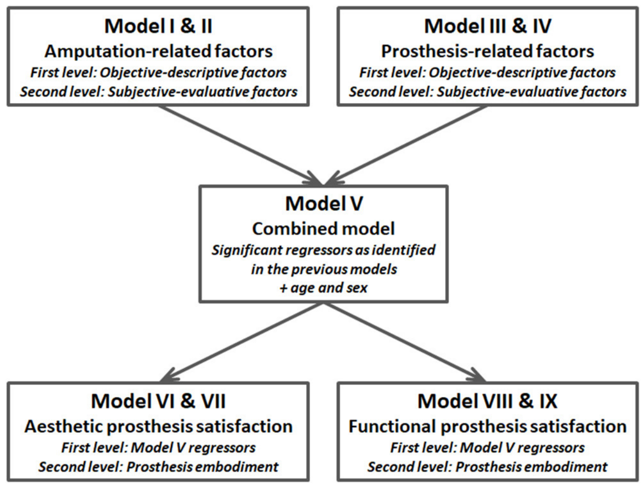

FIGURE 1 | Block diagram visualizing the analytic strategy. Regressors are described in detail in the main text.

Since the PEmbS-LLA total score distribution differed significantly from normality (Shapiro–Wilk test, $W_{162} = 0.92$, $p < 0.001$) and was characterized by positive skewness, reverse square root transformation was applied to positivize values (re-reversed score ranged from 0 to $\sqrt{6}$, i.e., ≈2.45, with higher values still describing higher prosthesis embodiment), which normalized data distribution ($W_{162} = 0.99$, $p = 0.13$). For the subsequent regression analyses, this normalized transformed score was used. Note that the initial use of the non-transformed PEmbS-LLA total score as criterion variable in the regression analyses for models I–IV resulted in residuals significantly differing from normal distribution ($W_{159-161} = 0.94$–0.97, all $p \leq 0.003$), which represents a violation of requirements for the use of multiple regression analyses (see above). This was avoided by the use of the transformed PEmbS-LLA score (for the respective statistics, see the **Supplement**). For aesthetic and functional prosthesis satisfaction as assessed with the TAPES-R, residual distribution was normal and all other assumptions required for regression analyses were fulfilled (see **Supplement**), so that no transformation procedure was applied to these data.

RESULTS

Descriptive Analyses

The descriptive details for the used variables can be found in **Table 2**. High and low amputation levels were equally distributed, and the amputation dated back more than 25 years on average (range: 0–72 years). About 56% of amputees indicated a traumatic event as the only reason for their amputation. Prevalence of PLA, PLP, and RLP in the last three months was 64.46, 53.01, and 31.33%, respectively (no missing data). Mean intensity in the last 4 weeks in the whole sample was low to medium; in those participants who reported the respective phenomenon,

TABLE 2 | Descriptive details of the included variables ($N = 166$).

Variables	*M* (*SD*)	*Mdn* (*IQR*)	%	*n* missing data
Objective-descriptive amputation-related variables				
Level of amputation (high/low)	–	–	50.00/50.00	0
Time since amputation (years)	27.35 (16.11)	–	–	0
Etiology of amputation (traumatic / other reasons or combinations)	–	–	56.02/43.98	0
Subjective-evaluative amputation-related variables				
PLA intensity (0–10)	3.06 (3.48)	–	–	1
PLP intensity (0–10)	2.95 (3.44)	–	–	0
RLP intensity (0–10)	1.41 (2.49)	–	–	0
Objective-descriptive prosthesis-related variables				
Time with current prosthesis (years)	4.14 (5.72)	–	–	0
Frequency of prosthesis use (rank 1–9)	–	9.00 (0.00)	–	2
Subjective-evaluative prosthesis-related variables				
Visual realism (0–10)	4.10 (3.02)	4.00 (5.00)	–	0
Mobility (reversed *T* scores)	59.12 (8.17)	60.00 (9.70)	–	1
Residual limb stimulation (−1—negative/0—neutral or absent/+1—positive)	–	0.00 (1.00)	40.96/43.37/15.66	0
Criterion variables				
Prosthesis embodiment (non-transformed; −3 to +3)	1.44 (1.16)	1.60 (1.30)	–	4
Prosthesis embodiment (transformed; 0 to $\sqrt{6}$, i.e., ≈2.45)	1.31 (0.49)	1.27 (0.57)	–	4
Aesthetic prosthesis satisfaction (1–3)	2.25 (0.48)	2.00 (0.67)	–	0
Functional prosthesis satisfaction (1–3)	2.28 (0.47)	2.20 (0.60)	–	0

PLA, phantom limb awareness; PLP, phantom limb pain; RLP, residual limb pain; M, mean; SD, standard deviation; Mdn, median; IQR, interquartile range; N / n = number.

however, mean intensity was 6.01 (SD = 2.45) for PLA, 5.63 (SD = 2.73) for PLP, and 4.68 (SD = 2.31) for RLP, representing medium levels. *Time with current prosthesis* averaged more than 4 years, with a wide range in the individuals from 0 to 34 years. *Frequency of prosthesis use* was high, which is expectable for lower limb amputees (Raichle et al., 2008). With an average rating of about 4, *visual realism* was rated medium. Participants rated *mobility* with their device as high (compared to norm data from a representative sample of lower limb amputees; cf., University of Washington Center on Outcomes Research in Rehabilitation, 2014). About 41% of the sample stated that the prosthesis caused negative stimulations on their residual limb, and more than 43% described these stimulations as neutral or being absent. A minority of about 16% described the residual limb stimulations as positive. About 87% of participants reported some degree of prosthesis embodiment (PEmbS-LLA score > 0, non-transformed data). With an average rating of about 2.3 each, aesthetic and functional prosthesis satisfaction was high in the present sample.

Multiple Regression Analyses

Hierarchical Regression Analyses for Amputation- and Prosthesis-Related Factors

Hierarchical Regression Analysis for Amputation-Related Factors (Models I and II)

Model I, entering objective-descriptive amputation-related factors, was characterized by a significant determination coefficient [$F_{(3,157)} = 3.483$, $p = 0.017$], with *level of amputation* emerging as significant regressor. This model explained $R^2 = 6.2\%$ of variance of prosthesis embodiment. Model II, adding subjective-evaluative amputation-related factors also was significant [$F_{(6,154)} = 4.495$, $p < 0.001$], with *level of amputation* and *RLP intensity* as individual significant regressors. This indicates that a lower amputation level, i.e., a longer residual limb, and less severe residual limb pain are significantly associated with prosthesis embodiment. Model II explained in total $R^2 = 14.9\%$ of prosthesis embodiment variance, with the increase in the determination coefficient from model I to model II being significant [$F_{(3,154)} = 5.225$, $p = 0.002$]. Details of the analysis are given in **Table 3**.

Hierarchical Regression Analysis for Prosthesis-Related Factors (Models III and IV)

Model III, including objective-descriptive prosthesis-related factors, had a significant determination coefficient of $R^2 = 5.3\%$ [$F_{(2,156)} = 4.348$, $p = 0.015$], with *frequency of prosthesis use* emerging as a significant regressor, indicating that the more often the prosthesis is actively used, the higher is the perceived embodiment for the prosthesis. The determination coefficient of model IV, to which subjective-evaluative prosthesis-related regressors were added, again was highly significant [$F_{(5,153)} = 14.713$, $p < 0.001$], with *visual realism*, *mobility*, and *residual limb stimulation* being significant regressors. This indicates that a higher degree of the prosthesis' visual similarity to a real limb, higher levels of prosthesis functionality, and the absence of negatively perceived stimulation caused by the prosthesis are positively related to prosthesis embodiment. The initially identified regressor *frequency of prosthesis use*, however, did no longer emerge as being significant in this extended model. In total, model IV explained $R^2 = 32.5\%$ of the variance in

TABLE 3 | Hierarchical regression analysis (simultaneous entry of regressors) on prosthesis embodiment with objective-descriptive (model I) and objective-descriptive + subjective-evaluative amputation-related factors (model II) in $n = 161$ lower limb amputees.

Model	Regressors	*B*	*SE*	*β*	*p*	R^2	Adjusted R^2	*p* for R^2	*p* for R^2 increase by including subjective-evaluative regressors
I— Objective-descriptive amputation-related regressors	(Constant)	1.396	0.107		<0.001	0.062	0.044	0.017	–
	Level of amputation[a]	−0.198	0.078	−0.202	0.012				
	Time since amputation	0.002	0.003	0.056	0.507				
	Etiology of amputation[b]	−0.073	0.085	−0.074	0.395				
II— Objective-descriptive + subjective-evaluative amputation-related regressors	(Constant)	1.533	0.115		<0.001	0.149	0.116	<0.001	0.002
	Level of amputation[a]	−0.198	0.077	−0.201	0.011				
	Time since amputation	0.001	0.003	0.020	0.809				
	Etiology of amputation[b]	−0.075	0.082	−0.076	0.363				
	PLA intensity	<0.001	0.012	−0.001	0.992				
	PLP intensity	−0.009	0.013	−0.065	0.456				
	RLP intensity	−0.055	0.015	−0.279	<0.001				

[a]0, low; 1, high; [b]0, accidents or injuries; 1, other reasons or combinations; PLA, phantom limb awareness; PLP, phantom limb pain; RLP, residual limb pain.

prosthesis embodiment, with the increase in the determination coefficient from model III to model IV being highly significant [$F_{(3,153)} = 20.534$, $p < 0.001$]. Details of these analyses are given in **Table 4**.

Combined Regression Analysis (Model V)

For the combined regression analysis, the regressors identified to individually explain prosthesis embodiment in the previous analyses (i.e., *level of amputation*, *RLP intensity*, *visual realism*, *mobility*, and *residual limb stimulation*) were entered simultaneously, along with *sex* and *age*. The model's determination coefficient of $R^2 = 36.3\%$ was highly significant [$F_{(7,153)} = 12.430$, $p < 0.001$], with all entered variables emerging as individual regressors for prosthesis embodiment, each in the previously described direction. *Sex* and *age* were not significantly associated with prosthesis embodiment. Details of this analysis are provided in **Table 5**.

Hierarchical Regression Analyses on Prosthesis Satisfaction (Models VI–IX)

For the hierarchical regression analyses on aesthetic (for statistical details see **Table 6A**) and functional prosthesis satisfaction (for statistical details see **Table 6B**), the regressors used in model V were entered (first-level regressors, models VI and VIII) and hierarchically complemented by prosthesis embodiment (second-level regressors, models VII and IX; see **Figure 1**).

Model VI was characterized by a significant determination coefficient [$F_{(7,153)} = 3.658$, $p = 0.001$], with *sex*, *age*, and *visual realism* significantly regressing on aesthetic prosthesis satisfaction. This indicates that the younger the prosthesis user and the more realistic the appearance of the device, the more satisfying the aesthetic aspects of the prosthesis were evaluated. Furthermore, male amputees were more satisfied with the aesthetics of the prosthesis than female amputees. This model explained $R^2 = 14.3\%$ of variance in aesthetic prosthesis satisfaction. Model VII added prosthesis embodiment to the regressors, and also had a significant determination coefficient of $R^2 = 18.6\%$ [$F_{(8,152)} = 4.353$, $p < 0.001$], representing a significant increase compared to the former model [$F_{(1,152)} = 8.040$, $p = 0.005$]. Besides *sex* and *age*, prosthesis embodiment emerged as the only significant regressor, indicating that higher prosthesis embodiment is associated with higher aesthetic prosthesis satisfaction, while concurrently absorbing explanatory power of *visual realism*. The association between the levels of aesthetic prosthesis satisfaction for each item of the respective TAPES-R sub-scale is given in **Figure 2A**.

Model VIII, regressing on functional prosthesis satisfaction and involving the same set of regressors as in model VI, again had a significant determination coefficient [$F_{(7,153)} = 4.818$, $p < 0.001$], with *RLP intensity* and *mobility* having individual and significant associations with the criterion. This suggests that less residual limb pain and higher functionality are significantly related to a higher degree of functional prosthesis satisfaction. Interestingly, compared to the previous regression on aesthetic prosthesis satisfaction, sex, and age did not emerge as significant regressors in this model, which in total explained $R^2 = 18.1\%$ of the criterion's variance. As before, model IX added prosthesis embodiment to the regressors, and again its determination coefficient was characterized by significance [$F_{(8,152)} = 5.958$, $p < 0.001$]. In total, this model explained $R^2 = 23.9\%$ of variance in functional prosthesis satisfaction, which again represented a significant increase in the determination coefficient [$F_{(1,152)} = 11.601$, $p = 0.001$]. Besides *RLP intensity*, only *prosthesis embodiment* emerged as a significant regressor for higher functional prosthesis satisfaction, canceling out the explanatory power of *mobility*. The association between the levels of functional prosthesis satisfaction for each item of the respective TAPES-R sub-scale is visualized in **Figure 2B**.

TABLE 4 | Hierarchical regression analysis (simultaneous entering of regressors) on prosthesis embodiment with objective-descriptive (model III) and objective-descriptive + subjective-evaluative prosthesis-related factors (model IV) in $n = 159$ lower limb amputees.

Model	Regressors	*B*	*SE*	*β*	*p*	R^2	adjusted R^2	*p* for R^2	*p* for R^2 increase by including subjective-evaluative regressors
III—Objective-descriptive prosthesis-related regressors	(Constant)	0.589	0.246		0.018	0.053	0.041	0.015	–
	Time with current prosthesis	0.003	0.007	0.035	0.658				
	Prosthesis use frequency	0.082	0.028	0.229	0.004				
IV—Objective-descriptive + subjective-evaluative prosthesis-related regressors	(Constant)	−0.507	0.304		0.097	0.325	0.303	<0.001	<0.001
	Time with current prosthesis	−0.005	0.006	−0.056	0.409				
	Prosthesis use frequency	0.044	0.025	0.122	0.076				
	Visual realism	0.053	0.011	0.332	<0.001				
	Mobility	0.021	0.004	0.334	<0.001				
	Residual limb stimulation[a]	0.145	0.046	0.210	0.002				

[a]*-1, negative; 0, neutral or absent; +1, positive.*

TABLE 5 | Regression analysis (model V, simultaneous entering of regressors) on prosthesis embodiment with identified amputation- and prosthesis-related factors, controlling for sex and age, in $n = 161$ lower limb amputees.

Regressors	*B*	*SE*	*β*	*p*	R^2	Adjusted R^2	*p* for R^2
(constant)	−0.015	0.360		0.967	0.363	0.333	<0.001
Sex[a]	−0.103	0.078	−0.095	0.189			
Age	0.002	0.003	0.047	0.505			
Level of amputation[b]	−0.139	0.068	−0.142	0.042			
RLP intensity	−0.038	0.013	−0.190	0.005			
Visual realism	0.048	0.011	0.297	< 0.001			
Mobility	0.021	0.005	0.325	< 0.001			
Residual limb stimulation[c]	0.137	0.046	0.198	0.003			

[a]*0, female; 1, male;* [b]*0, low; 1, high;* [c]*-1, negative; 0, neutral or absent; +1, positive; RLP, residual limb pain.*

DISCUSSION

The present study sought to identify amputation- and prosthesis-related factors significantly associated with prosthesis embodiment experiences in lower limb amputees. A hierarchical regression analytical approach was used, and variables were grouped dependent on their objective-descriptive (e.g., amputation level or time with current prosthesis) or subjective-evaluative character (e.g., residual limb pain intensity or rated mobility). Entering significant regressors in a combined regression model revealed that a lower level of amputation, less severe residual limb pain, more realistic visual appearance of the device, higher mobility, and more positive valence of prosthesis-induced residual limb stimulations individually and significantly explained variance in prosthesis embodiment. Together with demographic variables, this model explained more than 1/3 of prosthesis embodiment variance in the present sample. Using the identical set of regressors, hierarchically complemented by prosthesis embodiment, on different forms of prosthesis satisfaction revealed that prosthesis embodiment adds a significant amount of explanatory power to models on both aesthetic and functional prosthesis satisfaction. These findings emphasize the importance of psychological factors for the integration of a prosthesis into the amputee's body representation, which itself might represent a crucial factor associated with prosthesis satisfaction.

These results might be of crucial interest for shaping theoretical concepts on prosthesis embodiment as well as for prosthetic rehabilitation. Thus, the results add to the large body of literature investigating the mechanisms underlying embodiment experiences, since Botvinick and Cohen (1998) introduced the rubber hand illusion paradigm. This seminal experiment involves a setup to induce embodiment experiences (particularly *Ownership*, *Agency*, and spatial-structural aspects referred to as *Location*; Longo et al., 2008) for a visible artificial limb in non-amputated individuals by applying synchronous visuotactile stimulation to the rubber hand and the participant's hidden hand. Since even upper limb amputees can be induced to perceive the rubber hand illusion—by the

TABLE 6 | Hierarchical regression analysis (simultaneous entering of regressors) on aesthetic prosthesis satisfaction **(A)** and functional prosthesis satisfaction **(B)**, with identified factors (model VI and VIII, respectively) and additionally added prosthesis embodiment (model VII and IX, respectively), controlling for sex and age, in $n = 161$ lower limb amputees.

Model	Regressors	*B*	*SE*	*β*	*p*	R^2	adjusted R^2	*p* for R^2	*p* for R^2 increase by including prosthesis embodiment
(A)—criterion: aesthetic prosthesis satisfaction									
VI—Identified regressors	(Constant)	2.404	0.409		<0.001	0.143	0.104	0.001	–
	Sex[a]	0.234	0.089	0.220	0.009				
	Age	−0.008	0.004	−0.181	0.027				
	Level of amputation[b]	−0.038	0.077	−0.039	0.627				
	RLP intensity	−0.027	0.015	−0.140	0.072				
	Visual realism	0.034	0.012	0.217	0.006				
	Mobility	0.001	0.005	0.015	0.865				
	Residual limb stimulation[c]	0.072	0.052	0.106	0.171				
VII—Identified regressors + prosthesis embodiment	(Constant)	2.408	0.400		<0.001	0.186	0.144	<0.001	0.005
	Sex[a]	0.260	0.087	0.244	0.003				
	Age	−0.008	0.003	−0.193	0.016				
	Level of amputation[b]	−0.002	0.076	−0.002	0.978				
	RLP intensity	−0.018	0.015	−0.091	0.224				
	Visual realism	0.022	0.013	0.140	0.084				
	Mobility	−0.004	0.006	−0.070	0.433				
	Residual limb stimulation[c]	0.037	0.052	0.054	0.485				
	Prosthesis embodiment	0.255	0.090	0.260	0.005				
(B)—criterion: functional prosthesis satisfaction									
VIII—Identified regressors	(Constant)	1.596	0.386		<0.001	0.181	0.143	<0.001	–
	Sex[a]	0.090	0.084	0.087	0.285				
	Age	−0.001	0.003	−0.032	0.686				
	Level of amputation[b]	−0.072	0.073	−0.078	0.321				
	RLP intensity	−0.040	0.014	−0.214	0.005				
	Visual realism	0.018	0.011	0.117	0.124				
	Mobility	0.012	0.005	0.202	0.017				
	Residual limb stimulation[c]	0.086	0.049	0.132	0.082				
IX—Identified regressors + prosthesis embodiment	(Constant)	1.601	0.373		<0.001	0.239	0.199	<0.001	0.001
	Sex[a]	0.119	0.081	0.116	0.145				
	Age	−0.002	0.003	−0.046	0.548				
	Level of amputation[b]	−0.033	0.071	−0.035	0.647				
	RLP intensity	−0.029	0.014	−0.157	0.039				
	Visual realism	0.004	0.012	0.027	0.728				
	Mobility	0.006	0.005	0.104	0.228				
	Residual limb stimulation[c]	0.047	0.049	0.072	0.339				
	Prosthesis embodiment	0.285	0.084	0.302	0.001				

[a]0, female; 1, male; [b]0, low; 1, high; [c]-1, negative; 0, neutral or absent; +1, positive; RLP, residual limb pain.

application of visuotactile stimulation to an artificial hand together with the amputee's residual limb (Ehrsson et al., 2008)—it has been proposed that this kind of illusion could be an experimental model for prosthesis embodiment as well (Giummarra et al., 2008; Niedernhuber et al., 2018). Empirical evidence for psychometric similarity between non-amputated individuals experiencing the rubber hand illusion and lower limb amputees using a prosthesis was recently provided (Bekrater-Bodmann, 2020). Contrary to the rubber hand illusion, in which multimodal sensory input leads to the integration of the artificial limb into the amputees body representation, prosthesis embodiment could be achieved by sensorimotor (cf., Kalckert and Ehrsson, 2012) or phantom-prosthesis interactions (Giummarra et al., 2010), although the actual processes still remain unknown. The present study, however, describes factors that extend beyond active sensory

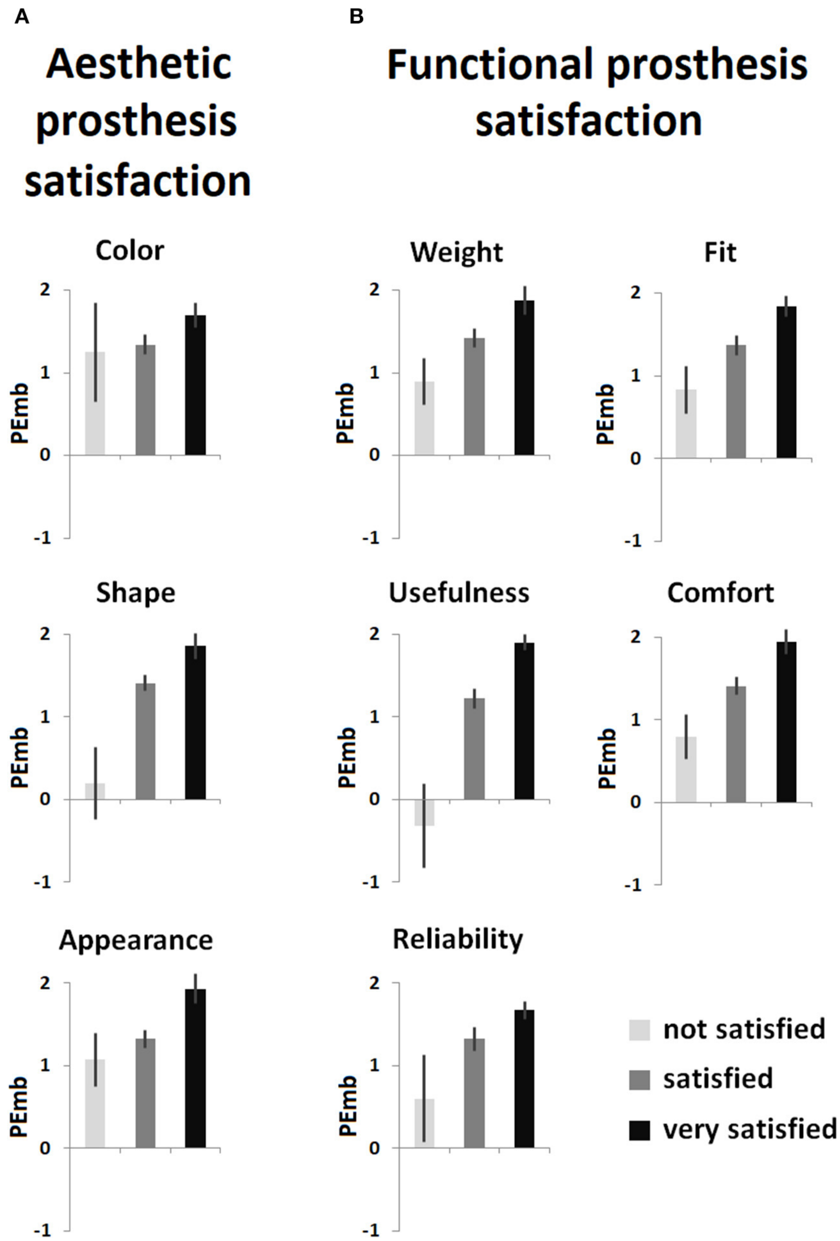

FIGURE 2 | Item-wise relationship between levels of prosthesis satisfaction as measured with the prosthesis satisfaction sub-scales of Trinity Amputation and Prosthesis Experience Scales—Revised questionnaire and prosthesis embodiment (PEmb) as measured with the Prosthesis Embodiment Scale (non-transformed scores with a potential range from −3 to +3). **(A)** Aesthetic prosthesis satisfaction; **(B)** functional prosthesis satisfaction. Given are the mean values; error bars indicate the standard error of the mean.

feedback and neural-machine-interfaces, which are the main foci of current prosthesis embodiment literature (e.g., Marasco et al., 2011; Tabot et al., 2013; Clites et al., 2018; Petrini et al., 2019; Rognini et al., 2019), potentially guiding future prosthetic developments.

Results suggest that objective-descriptive amputation- and prosthesis-related variables can only explain a small amount of the variance in prosthesis embodiment in the present sample. Entering subjective-evaluative variables significantly enhanced the explanatory power of the models. The combination of significant regressors explained the greatest amount of variance in prosthesis embodiment (R^2 = 36.3%). Thus, the level of amputation emerged as a significant regressor in this model which might be indicative of higher perceptual barriers associated with more severe limb loss. This could be due to the longer prosthesis which has to be incorporated in higher amputation levels. A longer prosthetic device might represent a mismatch to the body representation which hinders its incorporation. Previous results suggested that there are distortions of the peripersonal space representation around the residual limb of amputees (Canzoneri et al., 2013). The peripersonal space, however, marks the barrier within which the induction of embodiment experiences is successful (Lloyd, 2007). Consequently, for prosthetic limbs outside these representational boundaries (which is about 70 cm for the lower limbs; Stone et al., 2018) the experience of embodiment might be reduced.

Results further indicate that residual limb pain is negatively associated with prosthesis embodiment. Together with the like-wise significant, but individual, regressor *residual limb stimulation*, this is an interesting finding which emphasizes the importance stump health and proper fit of the device might have for eliciting prosthesis embodiment experiences. On a psychological level, adverse stump experiences, which can be exaggerated by bad prosthesis fit, might reduce the acceptance of the device and thus its embodiment. Previous studies revealed the relevance of socket properties for prosthesis satisfaction (Ali et al., 2012), so that prospective studies should focus on its importance for prosthesis embodiment as well.

Mobility emerged as significant regressor for prosthesis embodiment in the present study, emphasizing the importance of prosthesis functionality for the incorporation of the device. Imaizumi et al. (2016) argued that motor learning and subsequent internal body model updates are consequences of long-term prosthesis use and thus contribute to prosthesis embodiment. However, since neither *time since amputation* nor *time with current prosthesis* were significantly associated with prosthesis embodiment, and *frequency of prosthesis use* only emerged as a significant regressor when *mobility* was not included, the results suggest that the quality of prosthesis use, rather than passive or active use alone, is crucial for inducing embodiment experiences. However, it has to be kept in mind that the present study only assessed the subjective evaluation of mobility; prospective studies should substantiate this finding by implementing objectifiable measures of prosthetic function and the quality of its use. In this context, it might be particularly interesting to further elucidate the satisfaction with usefulness of the device (see **Figure 2**) which showed particularly strong associations with prosthesis embodiment.

The positive correlation between perceived visual realism of the prosthesis and its embodiment suggests that prosthesis appearance might play a role for incorporation of the device. A similar effect has been previously shown for the experimental induction of embodiment (Tsakiris et al., 2010). It is remarkable, however, that this effect plays a role for lower limb prostheses, whose users—compared to users of upper limb prostheses—are less often directly faced with the device. It could be that prosthetists therefore implicitly assume that realism is of secondary importance which would explain the often-implemented technical appearance of lower limb prostheses. The present results, however, suggest that prostheses that are aesthetically designed in accordance to the user's body perception might facilitate its embodiment. This might particularly be true for the shape of the prosthesis resembling a real limb, since satisfaction with this feature seems to be specifically associated with prosthesis embodiment (see **Figure 2**). The shape of the prosthesis resembling a real limb could be of particular importance for amputees who habitually have an unfavorably low manifestation of the perceptual trait underlying embodiment experiences (cf., Bekrater-Bodmann et al., 2012). More research is required to elucidate the importance of visual prosthesis characteristics and its interaction with the user's embodiment experiences.

Interestingly, prosthesis embodiment emerged as an important factor associated with both aesthetic and functional prosthesis satisfaction, independently of the other identified variables. This is an extension of findings reported before: using a sub-sample of the present one, the univariate relationship (as revealed by Spearman correlations) between prosthesis satisfaction and prosthesis embodiment has already been reported (Bekrater-Bodmann, 2020). However, the present multivariate analytical approach substantiates this finding, emphasizing that prosthesis embodiment significantly contributes to prosthesis satisfaction even if the association of other relevant factors is statistically controlled for. This emphasizes the relevance prosthesis embodiment might have for prosthesis acceptance. Besides prosthesis embodiment, only sex and age emerged as significant regressors for aesthetic prosthesis satisfaction, probably emphasizing the technical affinity in younger and male persons (Edison and Geissler, 2003). The analyses for functional prosthesis satisfaction further revealed the importance of residual limb pain, supporting previous results (Baars et al., 2018). Thus, although prosthesis embodiment appeared to explain a substantial amount of both aesthetic and functional prosthesis satisfaction, demographic and medical conditions should also be taken into account as moderating variables. It is remarkable, however, that the relationship between prosthetic feature satisfaction and prosthesis embodiment was found for each item of the TAPES-R prosthesis satisfaction sub-scales (**Figure 2**). Besides classical aesthetic and functional features, satisfaction with the device's weight might be of particular importance (Sinha et al., 2014), since it directly relates to the constructional design of the prosthesis. The relationship between single features of the prosthesis and its embodiment might thus be of crucial interest for prosthesis developers.

The findings indicate that the interaction between body and prosthesis perception should be considered in addition to cosmetic and functional aspects of the prosthesis. The identification of perceptual deficits related to the prosthesis at an early stage might help to fix user problems which might be easily overlooked otherwise. Further, the literature on embodiment experiences in normally-limbed persons suggest that incorporation of an artificial body part into one's body representation can be facilitated by reducing multimodal sensory or sensorimotor conflicts in relation to a cortically stored body model (for reviews see Tsakiris, 2010; Riemer et al., 2019). For limb amputees, characterized by an altered body representation, these factors might even increase in importance. The present results emphasize that a prosthesis which successfully interacts with the user's body perception could enhance prosthesis acceptance and thus reduce the risk of prosthesis abandonment.

Moreover, recent advances suggest that sensory feedback might further enhance lower limb prosthesis embodiment (Petrini et al., 2019), which has been earlier reported also for upper limb prostheses (Rognini et al., 2019). How these technical innovations might interfere with the factors identified in the present study, however, remains unknown.

It has to be noted that some of the present results (e.g., the positive association between the level of amputation and prosthesis embodiment) support previous studies, while others do not (e.g., the non-significant association between time since amputation and prosthesis embodiment; cf., Bekrater-Bodmann et al., 2020). This might be due to the fact that the earlier study assessed only a subcomponent of prosthesis embodiment (i.e., ownership; cf., Longo et al., 2008), while the PEmbS-LLA assesses prosthesis embodiment multidimensionally. The differences in sample size might further cause different levels of statistical power. Future studies have to evaluate the differential relationships to other components of prosthesis embodiment (Murray, 2008; Makin et al., 2017).

There are several limitations of the present study. Thus, regression analyses can identify associations, but cannot reveal causal relationships. For instance, it remains open whether visual realism of the prosthesis enhances its embodiment, or whether embodiment experiences lead to perceived similarity of the prosthesis to an actual body part (cf., Longo et al., 2009). Likewise, prosthesis embodiment could lead to satisfaction with the device, but it could also be the other way around, that is, satisfaction could cause the device's incorporation. For other objective-descriptive characteristics, such as the level of amputation, the direction of relationship appears clearer. It is likely that there are complex interactions between different variables. Prospective experimental studies, manipulating identified factors by keeping others constant, are necessary to answer the question of causality. These studies should also systematically compare technical properties of the prosthesis. For instance, recent results indicate that rather naturalistic designs might be associated with higher prosthesis embodiment (Bekrater-Bodmann et al., 2020), and other results emphasize the importance of socket liner characteristics for prosthesis satisfaction (Ali et al., 2012).

In general, the results of regression analyses highly depend on the entered variables. The selection of regressors in the present study was guided by previous findings and theoretical considerations on prosthesis embodiment; however, technical properties of the prosthesis were excluded. Thus, the present results have to be seen as starting point for prospective studies on prosthetic properties and their impact on prosthesis embodiment. These studies could elucidate the large amount of unexplained prosthesis embodiment variance, which was nearly 2/3 in the present study. A recent study estimated the effects of prosthetic features on embodiment experiences at about 40%; endogenous constraints, in terms of relatively stable perceptual traits related to the degree of flexibility of the body representation system, might account for another 30% of the unexplained variance (Bekrater-Bodmann, 2020). The quantification of effects of intra-individually invariant characteristics and external open-to-influence features has to be performed by future studies.

Further, it has to be noted that prosthesis-using participants might represent a particular sample of lower limb amputees. Most of the participants in the present study lost their leg by accidents, which is different to the general population of lower limb amputees (Moxey et al., 2010) who display a higher percentage of peripheral vascular diseases. Since amputations caused by the latter reason are at a higher risk to develop post-amputation pain (Larbig et al., 2019), the found relationship between RLP (which had a relatively low prevalence; cf., Ehde et al., 2000) and prosthesis embodiment has to be further elucidated in the future. Finally, the present results cannot be generalized to other clinical samples characterized by limb loss, such as arm amputees or persons with congenitally absent limbs, and should also be replicated in an independent sample of lower limb amputees. In those future studies, implicit or behavioral measures should be considered to operationalize the factors identified in the present sample.

CONCLUSION

Objective-descriptive and subjective-evaluative factors contribute to the embodiment of a lower limb prosthesis, complementing current technical approaches that focus on the effects of multimodal sensory and sensorimotor feedback. In addition to cosmetic and functional aspects of the prosthesis, prosthesis embodiment has been identified as contributing to the user's satisfaction with the prosthetic device. Future studies have to elucidate the underlying neurocognitive processes in order to translate the findings into practical recommendations for prosthesis developers and professionals working in prosthetic rehabilitation.

DATA AVAILABILITY STATEMENT

The dataset analyzed for the current study is available from the corresponding author on reasonable request.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by ethics commission II, Heidelberg University. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

RB-B wrote the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnbot.2020.604376/full#supplementary-material

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Decision-Making in the Human-Machine Interface

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If our choices make us who we are, then what does that mean when these choices are made in the human-machine interface? Developing a clear understanding of how human decision making is influenced by automated systems in the environment is critical because, as human-machine interfaces and assistive robotics become even more ubiquitous in everyday life, many daily decisions will be an emergent result of the interactions between the human and the machine – not stemming solely from the human. For example, choices can be influenced by the relative locations and motor costs of the response options, as well as by the timing of the response prompts. In drift diffusion model simulations of response-prompt timing manipulations, we find that it is only relatively equibiased choices that will be successfully influenced by this kind of perturbation. However, with drift diffusion model simulations of motor cost manipulations, we find that even relatively biased choices can still show some influence of the perturbation. We report the results of a two-alternative forced-choice experiment with a computer mouse modified to have a subtle velocity bias in a pre-determined direction for each trial, inducing an increased motor cost to move the cursor away from the pre-designated target direction. With queries that have each been normed in advance to be equibiased in people's preferences, the participant will often begin their mouse movement before their cognitive choice has been finalized, and the directional bias in the mouse velocity exerts a small but significant influence on their final choice. With queries that are not equibiased, a similar influence is observed. By exploring the synergies that are developed between humans and machines and tracking their temporal dynamics, this work aims to provide insight into our evolving decisions.

Keywords: mouse tracking, embodied cognition, decision-making, eye tracking, drift diffusion

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INTRODUCTION

Human-machine interfaces of various kinds are now ubiquitous in everyday life. For example, purchasing of products frequently takes place via computer, some restaurants use touch screens for ordering from the menu, many voting machines are now electronic, and people spend an inordinate amount of time using their smart phones to interact with their social world (Samaha and Hawi, 2016). In fact, the technology for allowing one's eye movements to be tracked from a smart phone's camera has recently been developed (Valliappan et al., 2020). Clearly, a variety of mundane human choices and decisions are no longer being made purely *inside* a human anymore but instead at the *interface* between a human and some form of technology (Clark, 2004). Also, a variety of laboratory human choices and behaviors are now being studied with human-machine interfaces to uncover the mechanics of embodied cognition (Pezzulo et al., 2013; Beckerle et al., 2019). Here, we examine exactly how those choices and decisions can be influenced by that interface.

Decades ago, Gibson (1979) developed the theoretical framework of ecological psychology, which holds at its core the notion that intelligent behavior emerges not from inside an organism but from the interaction between organism and environment (see also, Neisser, 1976; Järvilehto, 1998; Turvey and Shaw, 1999). Thus, the environment surrounding an organism is partly responsible for that organism's intelligent behavior. If one places that same organism in a different environment, it will produce somewhat different behavior. Around that same time, philosophers of mind were developing the theoretical framework of externalism (Putnam, 1974), which describes mental content as consisting of more than just the information encoded by an organism's nervous system but also information encoded in the relations that the organism builds with its environment (Clark and Chalmers, 1998; Gallagher, 2017). More recently, cognitive scientists have been developing the theoretical framework of embodied cognition, which includes the brain, the body, and its connections with objects and people in the environment, as the engine of cognitive activity (Barsalou, 1999, 2016; Spivey, 2007; Chemero, 2011). When studying the generation of intelligent behavior, these theoretical traditions encourage one to analyze not just the organism itself but instead the organism-environment system.

When viewed through this theoretical lens, a human reporting a decision via the use of a machine interface is not making that decision inside some encapsulated decision-making module (uninfluenced by context) and then merely recording it (in unaltered fashion) via the machine interface. It is not the case that the organism first makes the decision completely on its own and then reports it via the machine interface. Rather, the dynamic process by which the human interfaces with that machine can influence the decision that eventually gets reached. The decision is not being made by the organism; it is being made by the organism-environment system.

A concrete demonstration of this comes from a study by Pärnamets et al. (2015b), where they presented participants with moral quandaries such as "Is murder ever justifiable?" and gave them response options on a computer screen such as "sometimes justifiable" and "never justifiable." By recording participants' eye movements, Pärnamets et al. (2015b) found that participants often fixated one response option and then the other response option and then perhaps back again. Importantly, the amount of time that participants spent looking at their two response options could be used as an indicator of what decision they were about to make before they made it. In Experiment 2, Pärnamets et al. (2015b) further demonstrated that the computer's timing of its response prompt could slightly influence the choice that the participant made in the end. For each trial, the computer randomly selected a "target" response. Once the participant had fixated that "target" response option for at least 750 ms and had also fixated the non-target response option for at least 250 ms, the computer then urgently prompted a decision from the participant. Thus, at a moment in time when the participant was likely to have been spending more time looking at the "target" response, the computer interrupted the participant's deliberation and demanded a choice. Without that interruption, it is possible that the participant may have eventually wound up fixating the non-target response option more and finally choosing it. In a decision process that wavers between the two options, "leaning" one way and then the other way, and perhaps back again, this gaze-contingent response-timing manipulation is able to "catch" that decision process at a pre-determined state and trigger a choice based on that state.

In their Experiment 2, Pärnamets et al. (2015b) found that their gaze-contingent response-timing manipulation caused participants to choose the computer's randomly chosen "target" response option 58% of the time – well above chance. This result suggests that the 2–3 s that a person spends engaged in a wavering decision process while deliberating among two moral choices can be substantively influenced by the manner in which the system they are interfaced with interacts with them. The decision is not being made solely by the human; it is being made by the human-machine interface.

In fact, even with human-human interfaces, this kind of adventitious influence can happen in a way that alters people's decisions, even moral ones. Consider, for example, a woman who has made a moral commitment to not eating veal anymore, despite the fact that veal parmigiana is her favorite dish. She sits down at her favorite Italian restaurant and peruses the menu. Her eyes flit back and forth between her old favorite, veal parmigiana, and her new replacement, chicken parmigiana. She wants to adhere to her new moral code, but the veal is tempting. Just as her eyes happen to have settled on the veal for about 1 s, suddenly the waiter walks up and asks what she would like to order. If the waiter had shown up a second or two later, she might have managed to settle her eyes, and her mind, back on the chicken. But, in that moment, her decision is prompted and she caves, ordering the veal. Everyday scenarios like this are not very different from the experimental manipulation in the Pärnamets et al. (2015b) experiment.

However, in the Pärnamets et al. (2015b) experiment, a concern can be raised about the 16% of trials which were excluded from the analysis because the gaze-contingent response-timing manipulation was never triggered [see also Tavares et al. (2017) and Newell and Le Pelley, 2018]. On those time-out trials, participants never looked at both response options for the required amount of time to trigger the experimental manipulation. On many of those time-out trials, participants fixated only their internally preferred option and continued to stare at it until the trial was timed-out at 3 s, and then a decision was finally prompted. When those trials were included in the analysis, the overall effect of participants choosing the computer's randomly chosen "target" response option was reduced (54%) but still statistically significant against a chance level of 50%.

Falandays and Spivey (2020) followed up the Pärnamets et al. (2015b) study with a new set of moral items that were normed for their population to each be very close to equibiased (e.g., near 50/50) in their choices and compared them to non-normed items that were unlikely to be equibiased. This adjustment was meant to address the fact that a subtle influence of gaze on preferences may be washed out by strong, pre-existing preferences for one response option relative to the other (a prediction of the "attentional drift-diffusion model," discussed in the next section). With no exclusion of time-out trials, the gaze-contingent response-timing manipulation replicated Pärnamets et al. (2015b)'s result, where participants selected the target response 52% of the time – a small but statistically significant effect. With the non-normed stimulus items that were unlikely to be equibiased, no effect was observed.

Ghaffari and Fiedler (2018) replicated and extended the Pärnamets paradigm from moral choices to other-regarding choices. Other-regarding choices are common dilemmas that balance self-interest against the common good. In Ghaffari and Fiedler's (2018) experiment, they presented participants with pre-recorded spoken queries such as, "If I saw a stranger on the street struggling with her grocery bags, I would help her carry them." On the computer screen, participants could choose "Only if I have time" or "I would usually help." In their first experiment, they used a gaze-contingent response-timing manipulation essentially identical to experiment 3 of Pärnamets et al. (2015b), with participants allowed to respond *before* the decision prompt if they so chose. Ghaffari and Fiedler (2018) found that on 38% of trials, participants did, in fact, choose to respond before their eye movements had triggered the gaze-contingent response-timing manipulation. Moreover, 19% of the trials were time-out trials, where the participant's eye movements did not trigger the gaze-contingent response-timing manipulation over the course of a full 3 s. This left only 43% of trials to have the gaze-contingent response-timing manipulation enacted. Among those trials, the moral-choice trials clearly replicated the findings of Pärnamets et al. (2015b), but the other-regarding trials did not. However, the same concern remains, as before, regarding the exclusion of trials in which the gaze-contingent response-timing manipulation was not triggered. Analyzing only that subset of trials introduces a biased selection problem (Newell and Le Pelley, 2018).

Therefore, in Ghaffari and Fiedler (2018) second experiment, instead of a gaze-contingent response-timing manipulation, the response options turned on and off on the screen in a manner that simulated the fixation patterns of previous participants. The "target" response option, in this case, was the option that had been chosen by that previous participant. Importantly, no exclusion of trials was needed in this paradigm. Again, corroborating the pattern observed by Pärnamets et al. (2015b) and Ghaffari and Fiedler (2018) found that, in the moral-choice trials, participants chose the target option more often (53% of the time). However, with other-regarding trials, no effect was observed.

With moral-choice items, at least, Ghaffari and Fiedler (2018) concluded that while the majority of the variance in a decision-making process may rest in the hands of top-down cognitive processes, some portion of that variance is controlled by events that take place in the perception-action cycle of a person interacting with their environment. Their preferred model for this combination of top-down and bottom-up influences is the attention-drift-diffusion model (aDDM) developed by Krajbich et al. (2010; see also Krajbich, 2019).

THE aDDM: HOW VISUAL ATTENTION INFLUENCES DECISION-MAKING

The drift diffusion model (DDM) is a standard model for simulating choices and response times in a two-alternative forced choice task, which assumes that decisions are made through the stochastic accumulation of perceptual evidence until a decision threshold is exceeded (Ratcliff and McKoon, 2008). The standard DDM represents the relative evidence for one of two alternatives at time t as $x(t)$ according to the following equation (Bogacz et al., 2006):

$$x_{t+1} = x_t + A + W \qquad (Eq.\ 1)$$

When x is 0, the two options have equal relative evidence, whereas positive or negative values indicate greater evidence for one option than the other. The change in evidence over time is the result of a constant "perceptual evidence" factor, A, plus Gaussian noise, W. For an initially undecided choice, $x = 0$ at $t = 0$, indicating equal support for each of the two response options.

An arbitrary upper and lower bound are set, such that when x crosses either boundary, a decision is made in favor of the corresponding response option. For example, if the reference option is coded as a +1 and the alternative option is coded as −1, if x crosses the boundary at −1 the model is treated as having chosen the alternative option. Due to the presence of noise, DDMs offer an account for why participants will sometimes choose response options with lower relative value. When the magnitude of A is small (one option is only slightly preferable to the other) and/or W is large, drift due to noise can dominate the decision.

While the standard DDM is designed to represent perceptual decisions based on a single stimulus, Krajbich et al. (2010; see also Pärnamets et al., 2014) adapted this model to the context of choosing between two displayed stimuli through visual sampling. Their attention-drift-diffusion-model (aDDM), which provided a close fit to human data, allowed the rate of evidence accumulation to vary as a function of the currently fixated option. This represents a cognitive discounting of the value of currently un-fixated options. The simple intuition here is that a response option that is "out of sight" is also (at least partially) "out of mind." For this version of the model,

$$x_{t+1} = \begin{cases} x_t + d(A_{left} - \theta A_{right}) + W, & \textit{left is fixated} \\ x_t + d(\theta A_{left} - A_{right}) + W, & \textit{right is fixated} \end{cases} \qquad (Eq.\ 2)$$

where θ is a value between 0 and 1, which discounts the value of the currently unfixated option, d represents the rate of information accumulation, and W represents Gaussian noise.

Given the reasonable assumption that visual attention biases information accumulation, and that decision outcomes depend upon accumulated information, it follows that one can influence decision outcomes by influencing the gaze. Because an advantage is conferred upon fixated response options, options that are fixated for longer should be more likely to be chosen. Importantly, however, this effect is dependent upon both the magnitude of cognitive discounting on non-fixated options, as well as the relative values of the two response options. Examining Equation 2, we can see that if the value of $A_{\text{unfixated}}$ is large relative to A_{fixated}, discounting would need to be substantial (θ *near* 0) in order for gaze to change the direction in which preferences evolve. Under normal circumstances, we can assume that participants at least momentarily fixate, and therefore have some awareness of, both response options, so we would expect discounting to be less than complete. As such, the aDDM only predicts a meaningful role of gaze when the two response options are roughly equal in value (see also Tavares et al., 2017).

To demonstrate how a human-machine interface may influence decisions by exploiting the dynamics of visual attention, in this section we present a simplified simulation of the experimental task in Pärnamets et al. (2015b), using an adapted version of the aDDM. To provide a point of comparison, we also conducted a replication of Pärnamets et al. (2015b) with human participants, with the only change being that our moral stimuli were normed to be equibiased in our population (obtaining 50 ± 10% agreement), while our non-moral stimuli were taken directly from the set used in Pärnamets et al. (2015b) and were not normed for our population, and therefore were unlikely to be equibiased[1].

Methods

Our adapted version of the aDDM begins with the equation introduced by Krajbich et al. (2010; Equation 2). In modeling gaze behavior, we adopted the following simplifying assumptions: (1) one alternative is fixated at any given time, (2) the first fixation on any trial is random, (3) there is a minimum fixation length, after which fixation switches are determined by competition between current preferences and attentional fatigue, and (4) saccades are instantaneous. The minimum fixation time was set at 200 timesteps, representing 200 ms, which is approximately the time required to plan and launch a saccade (Salthouse and Ellis, 1980). After this period, attentional fatigue f begins to accumulate at a constant rate d_f:

$$f_{t+1} = \begin{cases} 0, & \textit{consecutive fixations} < 200 \textit{ timesteps} \\ f_t + d_f, & \textit{consecutive fixations} >= 200 \textit{ timesteps} \end{cases} \qquad (Eq.\ 3)$$

Attention, a, was modeled as deviating from the value of current preferences, toward the alternative option, by the current magnitude of f until the 0-line is crossed, inducing a switch in gaze:

$$a_t = \begin{cases} x_t - f_t, & x_t > 0 \\ x_t + f_t, & x_t < 0 \end{cases} \qquad (Eq.\ 4)$$

For the first 200 timesteps of any fixation, a is exactly equal to x, but after this time, attentional fatigue causes a to move toward zero. When a crosses the zero-line and changes sign, this represents an attentional switch, and gaze is directed toward the previously unfixated option. Because a is coupled to x (attention is coupled to current preferences), greater magnitudes of x can offset the decay from f, such that the model looks longer at options that it "prefers," despite some attentional fatigue. Similar attentional parameters are commonly used in dynamical systems models of bi-stable perceptual phenomena, such as the Necker cube, to account for perceptual reversals (Ditzinger and Haken, 1995; Fürstenau, 2014). The red lines in **Figures 1**, **2** show how attention decays as compared to decision preference (black lines), leading to gaze-changes (alterations between blue and yellow regions). Note that, while attentional fatigue can lead to gaze switches, unless there is a corresponding switch of preferences, gaze will switch back to the preferred option after the minimum fixation time (e.g., in **Figure 1**, the second blue section, a brief period of fixating the target from ∼1400 to 1600 ms).

On each simulated trial, the pre-designated target was randomly assigned to one of the two response options. Each trial was run for a maximum of 3000 timesteps, analogous to the 3 s time limit in the Pärnamets paradigm. We recorded the number of timesteps spent "fixating" each alternative. If at least 750 timesteps of gaze accumulated on the target side and at least 250 timesteps on the alternative side (analogous to the 750 ms/250 ms threshold in the experiment), the trial was ended, and a positive x value resulted in choosing the reference option (coded as +1) while a negative x value resulted in choosing the other option (coded as −1). **Figure 1** shows an example trial where the simulation met the gaze-time thresholds after 2500 timesteps and selected the target option (because x was >0 at the end of the trial). **Figure 2** shows an example trial where the simulation did not fixate the target for long enough to satisfy the gaze-contingent response-timing criteria, leading to a time-out after 3000 ms, after which the simulation selected the non-target alternative.

Results

This simple model was not intended to precisely characterize psychometric variables in our population, but rather to show that drift diffusion models straightforwardly predict the pattern of results obtained when using biased or equibiased stimuli. Thus, to avoid overfitting, no parameter tuning was done. The gaze-bias parameter (θ) was set to 0.5, such that the currently unfixated option was discounted by half. The rate of information accumulation (d_A) was set to 0.001 and the gaussian noise (W) was set to a mean of 0 and a standard deviation of 0.01. The rate of attentional fatigue accumulation (d_f) was set to 0.0005. To simulate our normed equibiased stimuli, we set the values of both options to 0.5. To simulate biased stimuli, we set the values of one option to 0.8 and the other to 0.2, randomly assigned on each trial. 50000 simulated trials were run for each set of values. For each trial, we recorded the choice made by the model (determined by the sign of x when the trial terminated) as well as whether or not the trial "timed-out" by reaching 3000 ms without meeting the gaze-time criteria.

The general behavior of this simulation approximates the data in Falandays and Spivey (2020) remarkably well, especially given that we have not systematically explored the parameter space with this model. The results summarized in **Table 1** show

[1]This simulation and replication were previously reported in a conference proceedings paper (Falandays and Spivey, 2020). The full stimulus selection procedure is reported below in the "Method" subsection of our current experiment, but the results of the prior human experiment are only described, for considerations of space.

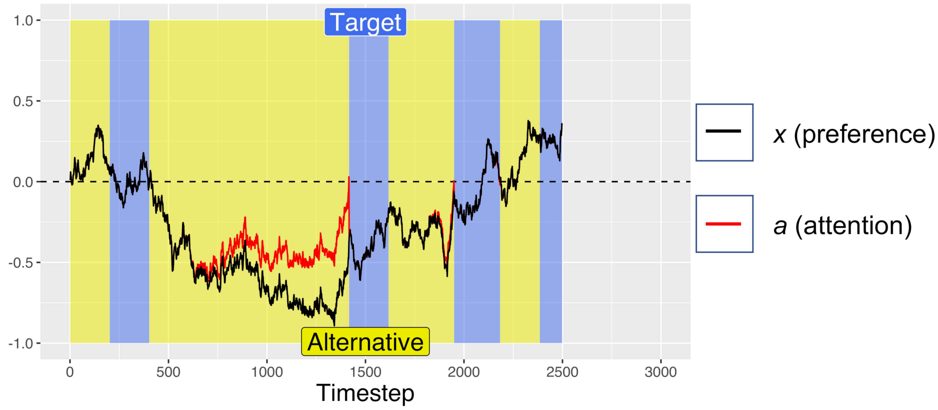

FIGURE 1 | An example simulate dtrial with no initial preference (A_{target} = $A_{alternative}$ = 0.5) in which the model was trending toward preferring the non-target alternative, but once it satisfied the gaze-contingent response-timing criteria, it selected the target. Periods of fixating the target are marked in blue, with fixations to the alternative in yellow. After a minimum fixation time of 200 timesteps, attention begins to decay toward the currently unfixated option (clearly visible between ∼500 and 1400 timesteps), triggering a switch in gaze when crossing the zero-line. Also note how accumulation of preference is biased toward currently fixated options (e.g., the strong trend toward the alternative option from ∼500 to 1400 ms, while fixating the alternative). For this simulation: d = 0.001, d_f = *0.0005*, and W was Gaussian noise with mean 0 and s.d. of 0.01.

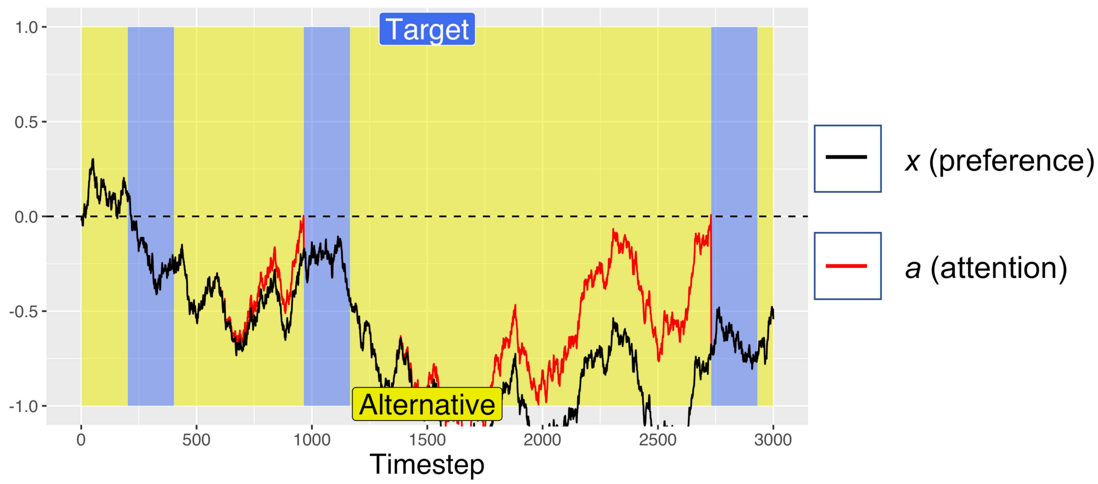

FIGURE 2 | An example simulated trial with no initial preference (A_{target} = $A_{alternative}$ = 0.5) on which the simulation "timed-out" after 3 s (because cumulative target fixation time <750 timesteps), then selected the non-target alternative. Periods of fixating the target are marked in blue, with fixations to the alternative in yellow. For this simulation: d = 0.001, d_f = *0.0005*, and W was Gaussian noise with mean 0 and s.d. of 0.01.

that the differences across equibiased or biased stimuli in the simulation are in the same direction and have similar magnitudes to the trends across moral and non-moral stimuli in the human experiment, despite some differences in absolute values.

Discussion

The results of this simple drift diffusion model provide a close approximate match to the results obtained from human participants. The relatively uncertain moral stimuli, exhibiting minimal intrinsic cognitive bias toward either of the response options, produced time-out trials less than half of the time, whereas the intrinsically biased filler stimuli produced time-out trials more than half of the time. When these time-out trials were excluded from analysis, both moral and filler stimuli exhibited strong choice preferences for the pre-designated target response, just as seen in our human data. However, when time-out trials were included in the analysis, only the moral items showed a reliable preference for the pre-designated target response – again, just as seen in the human data. Thus, results from the human data (Falandays and Spivey, 2020), and from this aDDM simulation, demonstrate that the gaze-contingent response-timing manipulation is most effective with queries that have relatively equibiased options, and less effective with queries that have substantial pre-existing biases.

A novel theoretical contribution of this model concerns the role of attentional fatigue. Given that attentional fatigue can result in switches of gaze, and gaze discounts non-fixated options, it follows that attentional fatigue can slow the accumulation

TABLE 1 | Summary results from the aDDM simulation and human experiment.

	Simulation results		Human results	
	Equibiased	**Biased**	**Moral**	**Non-moral**
Prop. timeout trials	40.57%	75.84%	23.59%	64.87%
Prop. target choices, all trials	56.13%	52.03%	52.3%	49%
Prop. target choices, non-timeout trials	79.69%	89.02%	62.67%	65.67%
Prop. target choices, timeout trials	21.63%	40.25%	20.18%	40.16%

of evidence toward a higher-valued option. For example, if a participant prefers option A, and therefore fixates option A, attentional fatigue may eventually divert their gaze to option B. Given a minimum fixation time before launching a saccade, option A will be temporarily cognitively discounted. If the options are relatively equibiased, temporary gaze switches due to attentional fatigue may be enough to tip the scales of evidence/preference toward option B.

THE mDDM: HOW MOTOR COSTS CAN INFLUENCE DECISION-MAKING

Importantly, from the theoretical position we are advancing here, visual attention is by no means a privileged influence upon decision-making. In this section, we address the influence of an entirely different factor in the decision-making process: the relative costs, in terms of time and/or effort, associated with making different response options. Consider the example of perusing a shelf at the grocery store, looking for ingredients for a recipe. You may notice that a cheaper, generic brand of ingredient is positioned on the top-most shelf, and would be a bit difficult to reach. If you're in a rush, you instead might choose to grab the slightly more-expensive version directly in front of you, even though you know the quality is no better. Marketers are of course well aware of phenomena such as this, and compete to put their products in the most visible, convenient locations (Gidlöf et al., 2017). There is no reason to think that similar biases couldn't be implemented in human-machine interfaces, including the increasingly ubiquitous case of making decisions with a computer mouse.

A key insight of work using "process-tracing" techniques to study decision-making – techniques which take many samples of a behavioral variable over a short period of time, such as motor movements or gaze position – is that mental representations, such as attitudes and preferences, do not spring to the mind as fully formed, discrete entities (Spivey, 2007). Instead, explicit reports of attitudes are merely the discrete output at the end of a continuous cognitive process, one that dynamically evolves on the scale of milliseconds and seconds in decision-making (Wojnowicz et al., 2009), or over longer periods in development (Smith and Thelen, 2003). For example, Wojnowicz et al. (2009) presented participants with various nouns and had them indicate whether they "like" or "dislike" the presented stimulus, using their mouse-cursor to select their response. In some cases these nouns were things that most people uncontroversially like, such as "sunshine," or dislike, such as "murderers." But the key stimuli probed participants' implicit biases: they were "white people" and "black people." The authors proposed that, if participants had implicit biases against the latter group, the unfolding movements toward the chosen response option would show evidence of some cognitive dissonance, even when the end result of the decision process was the same for both stimuli (reporting "like" for both groups). Indeed, the authors found that the trajectories of the mouse-cursors made relatively straight paths toward "like" when the stimulus was "white people," but curved more toward "dislike," before eventually landing on "like," when the stimulus was "black people." Beyond the disheartening evidence of implicit racial biases, this result also shows that multiple, conflicting attitudes may be simultaneously "competing" for control of the decision-making process as it unfolds over time.

Response deadline procedures (Dosher, 1976) also provide some insight into these partially active representations that are simultaneously active at early moments of the unfolding decision-making process. For example, McElree et al. (2006) induced speeded True-False responses to sentences such as "Water pistols are harmless," using response deadlines of 300, 500, 700, 900, 1500, and 3000 ms. They found that the short deadlines elicited a substantial number of incorrect responses with d-prime increasing non-linearly over time. Similarly, Spivey et al. (2002) induced speeded sentence completions for fragments such as "The patient cured. . ." and "The judge sentenced. . .," using response deadlines of 300, 600, 900, and 1200 ms. They found that the short deadlines elicited a greater proportion of the rare relative clause completion, e.g., "The patient cured by the doctor was happy." By contrast, with those sentences, the longer deadlines elicited almost exclusively the common main clause completion, e.g., "The patient cured himself" (Spivey, 2007, chapter 7). For decades, results like these have suggested that multiple competing representations are simultaneously partially active early on during a cognitive process and this activation pattern evolves into singular decision over the course of several hundred milliseconds.

The dynamic evolution of decisions on a short time scale is represented in the DDM as the accumulation of evidence or preference. This process can of course be *willfully* biased by the decision-maker, for example by adopting a liberal or conservative response criterion under differing task demands. For example, Kloosterman et al. (2019) found that liberal response criteria are associated with a suppression of alpha band activity, relative to conservative criteria, which appears to systematically bias the direction of evidence accumulation toward a "target present" response in a go/no-go task (see also: Kloosterman et al., 2020). But given the logic of the DDM, influencing neural activity through explicit task demands is only one method of introducing systematic bias into the decision-making process, and other mechanisms may be external to the cognitive dynamics of evidence accumulation entirely. For example, the experimental manipulation of Pärnamets et al. (2015b) works by using gaze to probe the likely balance of evidence over time in the evidence accumulation process, and requiring a decision when evidence is expected to favor a pre-chosen "target" option. Another mechanism would be to introduce asymmetrical costs in making different response options, which may consciously or unconsciously factor into response criteria. The grocery store example mentioned above is one flavor of this: individuals may systematically discount the value of options that are more difficult to choose.

There is already some evidence that *perceptual* decisions can be influenced by the motor cost of responding. Hagura et al. (2017) instructed participants to move either a left or a right lever to indicate the direction of coherent motion using standard random-dot motion stimuli. During training, the researchers gradually increased the resistance on one lever relative to the other, such that one response required more force and thus became more costly. The authors found that participants then required *greater* perceptual evidence before making the more difficult response. Interestingly, based on a comparison of model fits, the authors concluded that the motoric cost of action directly influenced the perceptual stage, rather than influencing the participants' response criterions.

The study by Hagura et al. (2017) can be seen as an extension to the domain of perceptual decision-making of prior work on motor control by Shadmehr et al. (1993) and Shadmehr and Mussa-Ivaldi (1994). In this earlier work, participants held a robotic manipulandum that either displaced the hand from an equilibrium starting position (Shadmehr et al., 1993) or altered the forces acting on the hand through some regions of space during reaching movements (Shadmehr and Mussa-Ivaldi, 1994). The forces acting to displace the hand constitue a motoric "force field." Shadmehr and colleagues found that participants adapted to the displacing force fields of the robotic manipulandum through restorative movements, which defined a *postural* force field complementary to the one applied by the manipulandum. Furthermore, Shadmehr and Mussa-Ivaldi (1994) found that with a substantial amount of training, participants were able to adapt to the presence of a displacing force field during reaching movements, achieving movement trajectories similar to those seen in the absence of a force field prior to training. However, after some training with the force fields, when these fields were suddenly removed, participants "over-corrected" in their movements, applying restorative forces when none were needed. Based on these results, (Shadmehr and Mussa-Ivaldi, 1994) concluded that participants accomplish this reaching task by adjusting an internal model of the movement dynamics of the hand, arm, and shoulder, which predicts the forces that will be encountered over the course of a movement.

But motor costs need not be explicitly calculated nor implicitly learned in order to influence the outcome of decisions. Given the logic of the DDM, it follows that merely increasing the time it takes to reach one outcome relative to another can also bias outcomes (under the additional assumption that individuals continue to accumulate evidence, rather than endogenously stopping the process). Because noise plays a role in the accumulation of preference over time, decision outcomes that take longer to achieve (therefore drawing out the evidence accumulation process) allow more time for noise to tip the scales toward alternative outcomes. To show how this may be the case, in this section we present another variant of the DDM, which we will call the motor-drift-diffusion-model (mDDM). Using this model, we consider the case of an individual making a decision using a mouse cursor, but where a subtle bias in the cursor operation makes it easier to move in one direction than another.

Methods

The present model made one small change to the standard DDM (Eq. 1) with the inclusion of a second variable, m, representing the current position of a mouse cursor (or it could represent a hand, or an entire body) moving along a single dimension toward one of two response options. The model was treated as having made a decision only when m, rather than x (the evidence or preference variable), reached the upper or lower bound of ± 1, which represents a participant moving the mouse to the left or right top corner of a screen, and concluding a trial by clicking one response option. Meanwhile, x was bounded between the values ± 1 and, unlike in the aDDM, x reaching either boundary had no effect on terminating the trial. This means that the model could attain maximum preference for one response option, yet the preference accumulation process would not terminate until an *action* threshold was also met.

The position variable m was computed by integrating the preference variable x at rate d. This results in the m moving toward the currently preferred response option with a velocity determined by the magnitude of current preferences. As can be seen in **Figures 3–5**, this simple mechanism produces smoothly changing position curves from the noisy preference signal, which are reminiscent of the movement trajectories seen in mouse-tracking studies with similar designs (e.g., Spivey et al., 2005). As in our previous model, on each simulated trial, one of the two response options was designated as the "target" option – the option that the software "wants" the simulated participant to choose. For simplicity, the target was always designated as +1, and the alternative was designated as −1. Meanwhile, the relative values of the target and alternative options were allowed to vary from trial to trial.

Critically, the m variable was also influenced by a directionally dependent velocity bias. When x was on the side associated with the target (i.e., the model currently prefers the target and therefore is moving toward it), the change in m was equal to x. On the other hand, when x was closer to the non-target alternative, the change in m was equal to x multiplied by s, a velocity squashing factor. Formally stated:

$$m_{t+1} = \begin{cases} m_t + dx_t, & x_t > 0 \\ m_t + sdx_t, & x_t < 0 \end{cases} \qquad (Eq.\ 5)$$

Based on these functions, the magnitude of current preferences determines the velocity toward the preferred option (see also, Abrams and Balota, 1991). However, the velocity is squashed by some proportion for movements in the direction of the computer's pre-designated non-target alternative, making movements toward the non-target slower (see **Figure 7**; also see **Figure 8** for a schematic illustration of this mechanism for

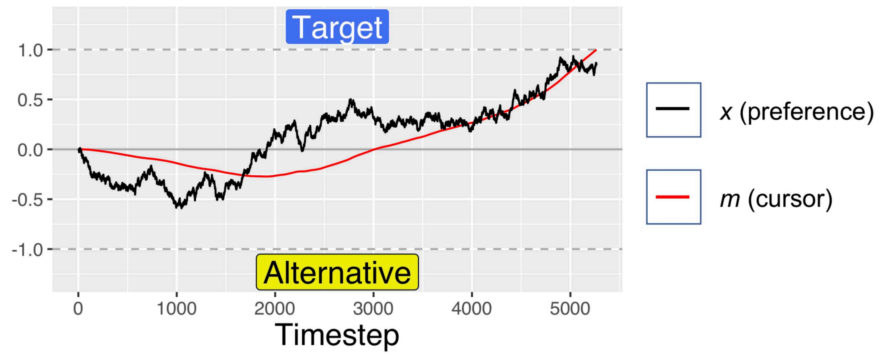

FIGURE 3 | A simulated trial with no initial preference for either response option. The evolution of the decision value is driven only by noise, but the velocity squashing effect makes movements toward the alternative slightly slower. This makes it more likely for noise to result in movements drifting toward the target. For these simulations, $d = 0.001$, $s = 0.45$, and W was Gaussian noise with mean 0 and s.d. of 0.01.

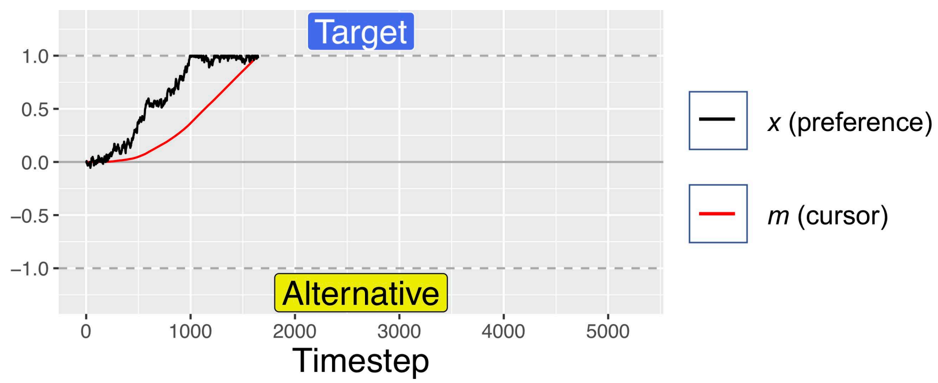

FIGURE 4 | A simulated trial where the target is fully preferable to the alternative. Notice how the black trajectory (representing evolving preference) in this figure and **Figure 5** below reach the boundary at approximately the same time, but the red line (representing the cursor) reaches the boundary faster here than below. For these simulations, $d = 0.001$, $s = 0.45$, and W was Gaussian noise with mean 0 and s.d. of 0.01. For comparison of response times, this figure uses the same x-axis as **Figure 3**, but note that this trial ended at ~1500 timesteps.

the human experiment). Because the relative decision value variable x is bounded between −1 and +1, velocity is bounded at d units per time step.

We explored three different sizes of the velocity squashing effect, s, in the simulation:0.45, 0.66, and 0.90. We also simulated the case of no effect (or a velocity squashing factor of 1) as a control. While varying the velocity squashing parameter can be informative as to the general patterns that occur as the effect varies in strength, it is important to note that real time and space do not map clearly onto simulated time and space in these models, nor are we using a highly realistic model of movement generation. As such, it is not necessarily the case that a squashing factor of 0.45 will produce the exact same effects in the simulation as in the human experiment that follows in the next section.

To explore how the effect size varies as a function of how balanced of a stimulus set is used (meaning whether the two response options in each pair tend to be near equally preferable), we varied the distribution from which the A parameter was drawn. Recall that the A parameter determines the preferability of the target reference option relative to the non-target alternative. We defined this as a value between −1 and +1, where positive relative preference value indicate preference for the response option coded as +1, while negative values indicate preference for the option coded as −1. On each simulated trial, the value of A was drawn from a uniform distribution bounded within some range. We explored ranges from ±0 to ±1 in increments of 0.2; such as 50/50, 60/40, and up to 100/0. Examples of simulated trials with no difference in preferability of the options, maximum preference for the target, and maximum preference for the alternative are shown in **Figures 3–5**. For readers interested to get a greater sense of how the velocity squashing parameter influences movement dynamics in each of these cases, the **Supplementary Material** contains GIF files plotting dynamic time series for 10 random trials with each of the parameter settings used for **Figures 3–5**.

At the start of each simulated trial, either the +1-coded or −1-coded response option was randomly designated as the target option. Thus, when the target was the +1 option, movements in the negative direction were squashed by s, and vice versa when the −1 option was the target. Each trial proceeded until m crossed the upper or lower limits of ±1, and the model

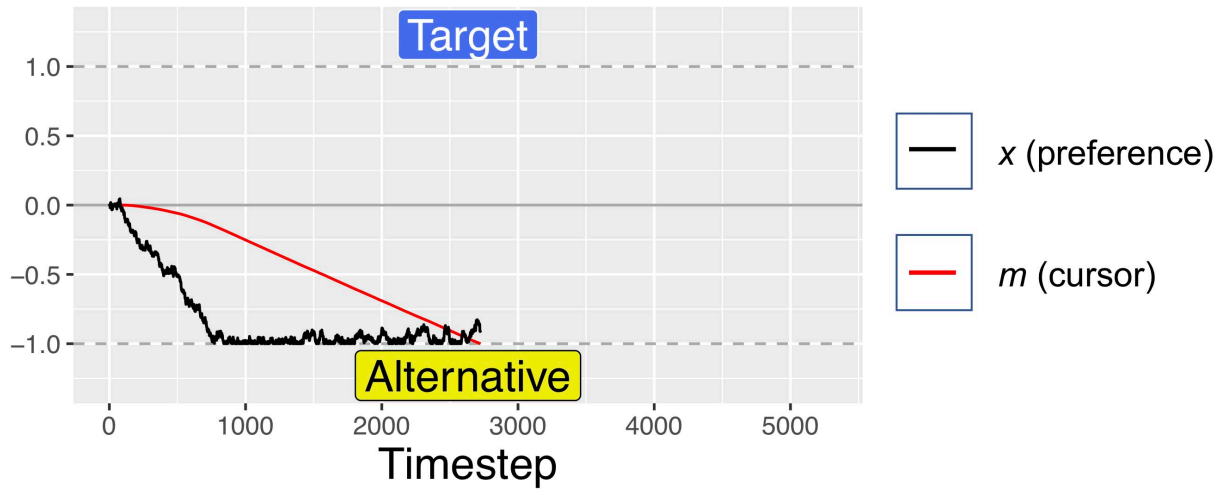

FIGURE 5 | A simulated trial where the alternative is fully preferable to the target. Notice how the black trajectory in this figure and **Figure 4** above reach the boundary at approximately the same time. However, here the red line lags further behind the black trajectory as a result of the velocity squashing effect, because movements are toward the alternative. For these simulations, $d = 0.001$, $s = 0.45$, and W was Gaussian noise with mean 0 and s.d. of 0.01. For comparison of response times, this figure uses the same x-axis as **Figure 3**, but note that this trial ended at ∼2750 timesteps.

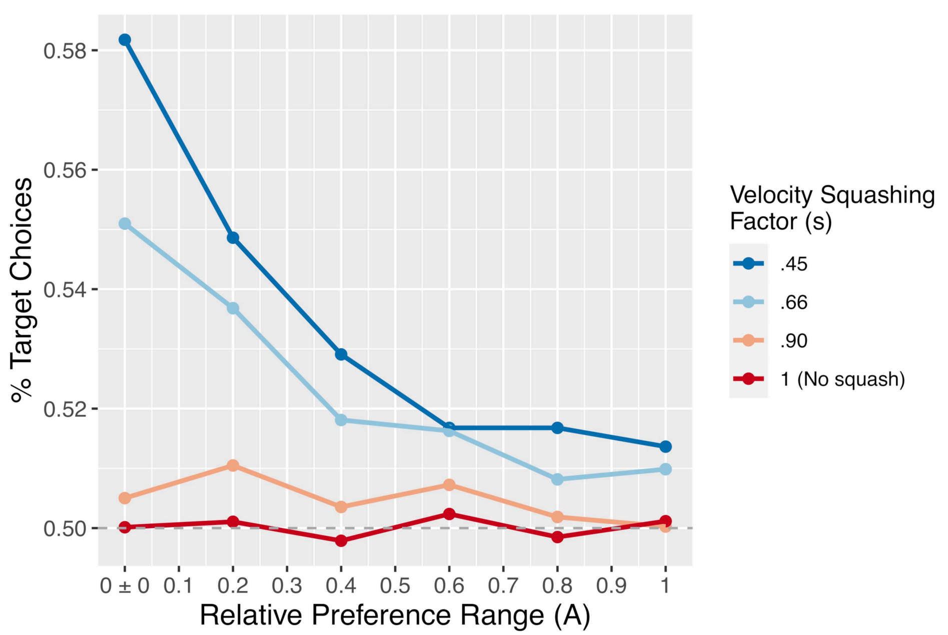

FIGURE 6 | The proportion of trials on which the simulation chose the target option as a function of the velocity squashing factor and the width of the distribution from which preferences, A, were drawn. Each data point is the result of 50,000 simulated trials.

was treated as having chosen the response option with the corresponding code. For example, when the model crossed the upper boundary, it was treated as having chosen the +1 coded option. These choices were then compared against the target option on that trial and recoded as a target or non-target choice. In keeping with our previous implementation of the aDDM presented earlier, the rate of information accumulation d was set to 0.001, and gaussian noise W was introduced at each time step, with a mean of 0 and standard deviation of 0.01. The model was run for 50,000 simulated trials for each combination of stimulus parameters, and each trial was allowed to proceed until m crossed the upper or lower boundary.

Results

The primary results of the simulation experiment are shown in **Figure 6**. As the figure shows, there is a clear main effect of the velocity squashing factor, with a greater likelihood of choosing the pre-designated target option seen when movements away

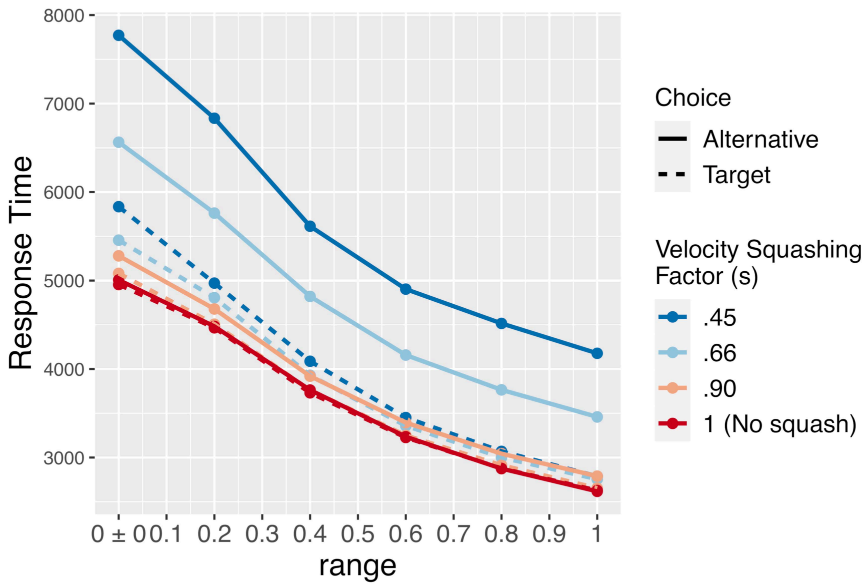

FIGURE 7 | Mean response times for the simulation (in timesteps, roughly equivalent to ms) by the size of the velocity-squashing manipulation and whether thee model chose the target or alternative option. Response times are faster when choosing the target due to the velocity squashing manipulation slowing movements toward the alternative.

from the target are reduced by a greater proportion (i.e., as they are multiplied by a smaller squashing factor). Importantly, the choices are at chance (50%) when the velocity squashing manipulation is turned off ($s = 1$, the red line in **Figure 6**). There is also an effect of the width of the distribution from which the relative preferences were drawn – the A parameter in our model – whereby the effect size of the squashing manipulation diminishes as the range of A values increases, meaning as stimuli become more biased with respect to initial preferences. Finally, there is an interaction between these two parameters such that the effect of s diminishes more quickly for smaller values of s (stronger manipulations).

Importantly, motor costs are not calculated and factored into decisions in this model. Instead, the effect of the manipulation is attributable to a bias in the accumulation of noise in preference, as it is mapped onto movements. When noise induces a change in preferences toward the target option, movements in that direction are faster, which increases the likelihood of reaching the target and terminating the trial. This is evident in the faster response times of the simulation when selecting the target vs. the alternative (solid vs. dashed lines in **Figure 7**). The response times also show a clear effect of the bias in initial preferences (the width of the distribution from which A is drawn). When A is small and stimuli are relatively equibiased, the signal-noise ratio becomes weaker, and when $A = 0$, the evolution of preferences is driven entirely by noise. This increases the mean time required to reach a response, and thereby increases the opportunity for noise to accrue in movements toward the target.

Discussion

This simple model demonstrates how, by slowing down movements away from the target option, our manipulation biases the effect of drift due to noise in the direction of the target, resulting in more trials on which the simulation ultimately chooses the target.

As **Figure 6** illustrates, while the effect diminishes in size as pairs of response options become less equibiased (i.e., increasing the range of A), the effect does not disappear completely even for a subtle velocity squashing effect and relatively biased stimuli. This result can be contrasted to the findings of Falandays and Spivey (2020) regarding the gaze-based timing manipulation, which showed that the effect may disappear completely when the response options are not equibiased. The difference between these two manipulations may be explained by the fact that the gaze-based response-timing manipulation, used by Pärnamets et al. (2015b) and others, is imposed only when participants spend time fixating both response options, whereas the present motoric manipulation is active on all trials. As such, this velocity bias may be able to subtly influence decisions even when one response option is strongly preferred relative to the other. Note, however, that the strongest effect observed in the simulation, a ∼58% preference for the pre-designated target, is obtained only with a perfectly equibiased stimulus and an extreme velocity squashing. In a human experiment with stimuli that are *approximately* equibiased (but not perfectly so) and velocity squashing that is mild enough to go undetected, the effect may be substantially smaller than that.

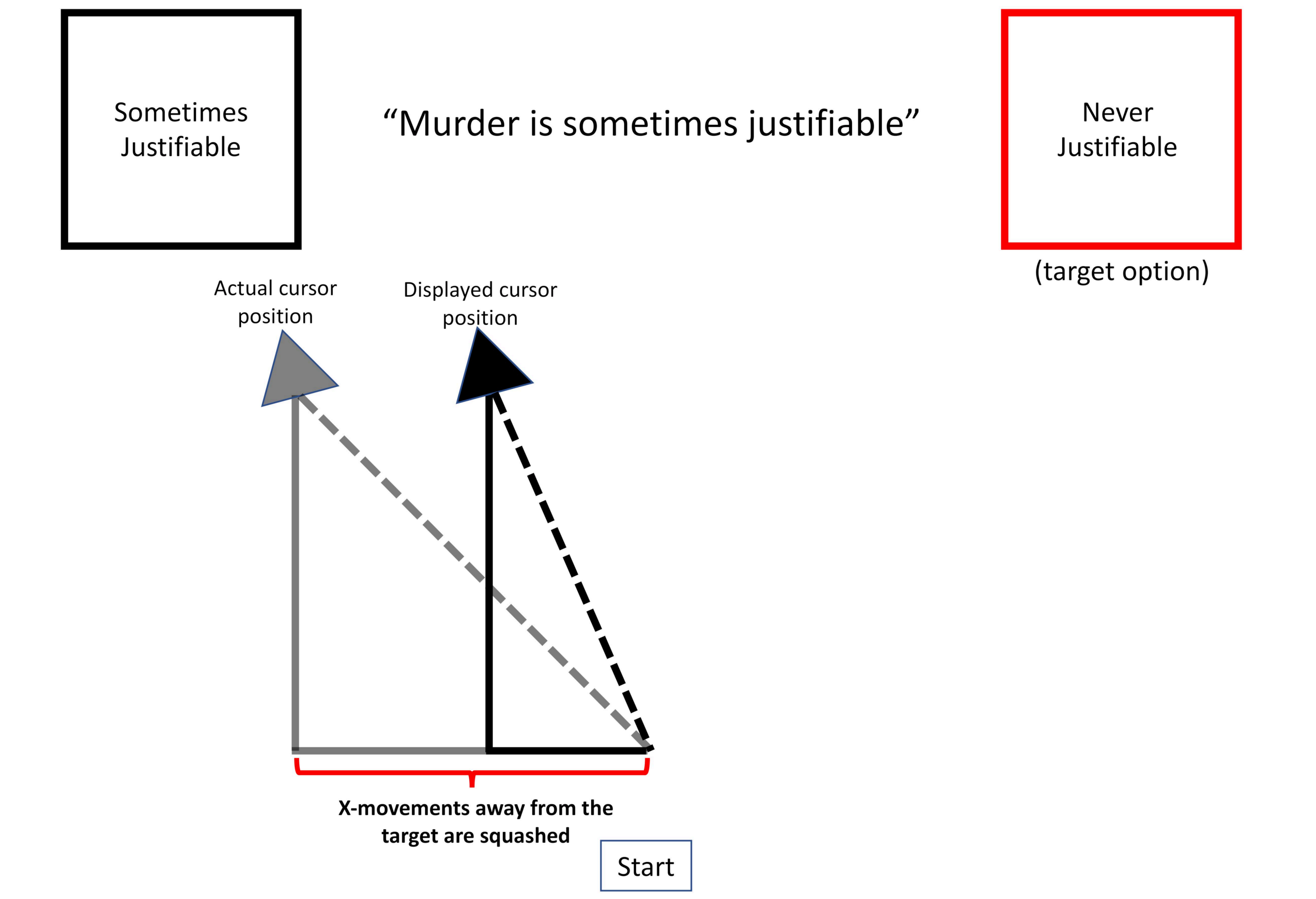

FIGURE 8 | A schematic of the operation of the velocity-squashing manipulation. The change in x-position for movements *away* from the target are squashed by a factor of 0.45 and the cursor is reset to a new position. For example, on this trial, a cursor movement of 10 pixels to the left would result in a displayed movement of 4.5 pixels to the left. Movements *toward* the targets are unperturbed.

EXPERIMENT: MANIPULATING DECISIONS WITH MOUSE CURSOR VELOCITY

We next sought to test the predictions of our mDDM in a human-subjects experiment. In this experiment, we asked whether a subtle bias in the movement of a mouse cursor could push decisions toward a randomly pre-selected option. The present experiment was a conceptual replication of Pärnamets et al. (2015b), and used the same stimuli as a recent replication of that experiment, Falandays and Spivey (2020). On each trial, participants first heard a moral or non-moral (factual, opinion) statement or question, then two possible response options appeared in boxes in the top-left and top-right corners of the screen, respectively. In those previous experiments, participants responded after a prompt screen appeared, using one of two key presses to respond. However, in the current study, participants responded with the mouse cursor by moving it from a central starting point near the bottom of the computer screen to click on their chosen response option at the upper corners of the computer screen. The response options remained on screen until one was selected. As before, on each trial, one response option is randomly pre-designated as the "target" – the option we are trying to bias their decision toward. Unbeknownst to the participant, the experiment software acted to subtly decrease the velocity of the mouse cursor for any movements *away* from the target option (or toward the non-target), such that the mouse moved slightly slower toward one option than toward the other. Based on the mDDM simulation above, we predicted that this motoric manipulation would result in participants choosing the target option slightly more often than chance and would influence even stimuli for which the response options were not equibiased.

As we briefly discussed earlier, our velocity squashing manipulation is similar to the "force fields" used by Shadmehr et al. (1993) and Shadmehr and Mussa-Ivaldi, 1994 to investigate human motor control. In light of the adaptation to force fields observed by Shadmehr and Mussa-Ivaldi (1994), it might be predicted that human participants could also adapt to our motor perturbations, resulting in no effect of the manipulation on choices. However, a key difference between our paradigm and that of Shadmehr et al. (1993) and Shadmehr and Mussa-Ivaldi (1994) as well as that of Hagura et al. (2017) is that the direction of the force field was randomized across trials, which would likely preclude a generalized adjustment of an internal model of reaching dynamics. For this reason, our model did not include any calculation of motor costs or adaptation on that basis. Instead, we propose that force-field-like manipulations can also bias decision-making in the absence of adaptation, simply by increasing the time it takes to reach one response option relative to the other, and thereby allowing greater opportunity for noise to push decisions toward the target option.

Method

Participants

Eighty healthy undergraduate students (61 female, 18 male; age: mean $\pm$ s.d. = 19.3 $\pm$ 1.37) were recruited from the subject pool at the University of California, Merced. Participants provided informed consent in accordance with IRB protocols and received course credit for their participation. Participation was restricted to those who reported being right-handed, having normal or corrected-to-normal vision and hearing, and not having a reading disorder or physical disability that would prevent simple actions with the hands.

Materials

The stimuli consisted of 72 prompts with two response options per prompt. The stimulus selection procedure is reported in Falandays and Spivey (2020), and the full set of stimuli is available on our preregistration page on the Open Science Framework[2]. Half of the prompts consisted of a statement expressing an opinion on some moral or ethical issue (e.g., "Murder is sometimes justifiable." Or "Hunting for sport is OK if it doesn't harm the ecosystem"). These stimuli were normed to generate 50 $\pm$ 10% agreement in our population. Because these stimuli were designed with the explicit goal of generating uncertainty and conflict in choosing, response options did not necessarily represent the extreme endpoints of an opinion spectrum. For example, in response to the statement "Murder is sometimes justifiable," the extreme opinion endpoints might be "Never justifiable" and "Always justifiable," but in this case the latter response is expected to be universally undesirable, and therefore these two options would be unlikely to generate uncertainty and conflict.

The other half of the prompts were non-moral filler questions regarding opinions or facts (e.g., "Do people respect selflessness?" or "Can bacteria live in boiling water?") on which no norming was conducted. Response options to these stimuli were always "Yes" or "No." As they were in the studies of Pärnamets et al. (2015b) and Newell and Le Pelley (2018), these non-moral items are considered "filler" items and are included mainly to prevent participants from focusing exclusively into a mindset of moral reasoning. In principle, the filler items may also show an effect of the gaze-based timing manipulation. However, given that these stimuli were not normed to be near 50/50 uncertainty, given that the word length of the response options is much shorter than those in the moral condition, and given that the response options are identical for all filler items, we expected these items to be relatively far from equibiased (represented in the DDM as $A >> 0$). In Falandays and Spivey (2020), these items showed no effect of the gaze-contingent response-timing manipulation (once time-out trials were included). However, based on our mDDM simulations above, these items may nonetheless be susceptible to this computer-mouse velocity manipulation and may reveal a subtle preference for the pre-designated target response option.

Stimulus queries were presented auditorily over headphones at the participants' preferred volume. Response options consisted of white text centered in a 300 $\times$ 300 pixel white box on a black background. Boxes were placed in the top left and top right corners of a 1920 $\times$ 1200 pixel screen, with a 30 pixel buffer between each box and the closest edge of the screen. Text was displayed in Times New Roman size 70 font.

Procedure

Participants completed the experiment individually in the lab, in a single session taking approximately 30 min. Participants were seated in front of a computer and wearing headphones with the volume set to their most comfortable level. The experiment was run using the Psychophysics Toolbox package (Brainard, 1997) in Matlab. On each trial, a white fixation dot was displayed in the center of the screen while the audio prompt played over the headphones. During this time, the mouse cursor was made invisible. Once the auditory prompt finished playing, the two response options would appear in the top-left and top-right corners of the screen. Upon completion of the query and appearance of the response options, the mouse cursor was reset to the bottom center of the screen, and participants moved the mouse to click on their choice. Participants had no time limit to make a selection. The left or right position of each response option was randomized. On 36 randomly selected trials, the left option was selected as the target, while the right option was selected on the remaining 36. After each trial, participants rated their confidence in their choice as well as their understanding (the degree to which they read and understood both response options) on a 1–7 scale.

In order to manipulate the motor cost of responding in an asymmetric fashion, the computer program made it slightly more difficult for participants to move the mouse cursor away from the target than toward it. This was accomplished by doing a fast re-draw of the mouse cursor position. Every 10 ms, the change in the x-position was sampled. Changes in the direction away from the target were squashed by a factor of 0.45, such that the mouse cursor was repositioned closer to its origin (along the x-axis) than it had actually traveled. This resulted in a decreased velocity when moving in one direction, though which direction was impacted was random across trials.

After completion of the main phase of the experiment, participants were presented with two free-response questions designed to probe for detection of the experimental manipulation in the experiment. The first question asked "What do you think was being manipulated in this experiment?" The second

[2]https://osf.io/z9r47/

question asked "Did you notice anything unusual about the functioning of the computer program used in this experiment?" An experimenter was present to offer participants clarification on the meanings of the questions, when necessary.

Data and Code Availability

All code and data from this experiment and preceding simulations are available are available on the Open Science Framework[3].

Results

Our analysis excluded any trial with a response time greater than 2 standard deviations from the mean. 3.6% of trials were excluded on this basis. After exclusions, the mean overall response time was 4012 ms (SD = 2082 ms). The mean response time by item type and choice (target vs. alternative) is plotted in **Figure 9**. Response times were analyzed using linear mixed effects regression with the log-transformed response times as the dependent variable. A backward-fitting procedure was used to select the maximal random-effects structure justified by the data (Barr et al., 2013). The full model included item type (moral/normed vs. non-moral/un-normed), choice (whether the participant clicked the target or the alternative), and their interaction as fixed effects. Random-intercepts were included for participants and items, as well as by-subject random slopes for the effect of item-type. Model comparison revealed that moral items elicited slower response times than non-moral items [$b = 0.2$, $SE = 0.04$, $t = 5.254$, $X^2(1) = 23.54$, $p < 0.001$], and that response times were slower when choosing the alternative relative to the target [$b = -0.08$, $SE = 0.006$, $t = -14.533$, $X^2(1) = 207.03$, $p < 0.001$]. There was no interaction between item type and choice.

Figure 10 shows the proportion of trials on which participants chose the target for each item type. Participants selected the target option 51.4% of the time overall, 51.06% of the time for our normed, moral items, and 51.9% of the time for our un-normed, non-moral items. The data were analyzed using logistic mixed-effects analysis. Again, a backward-fitting procedure was used to determine the maximal random-effects structure justified by the data. The full model included a single fixed effect, the intercept term. Random intercepts were included for participants and items, as well as random slopes for the effect of item type (normed/moral vs. unnormed/non-moral) by-participant. This analysis revealed a significant effect of adding the intercept term [$\alpha = 0.06$, SE = 0.03, $z = 2.03$, $X^2(1) = 3.97$, $p < 0.05$] and no significant effect of item-type, indicating that participants selected the target option more often than chance, and that this effect did not differ between moral items and filler items.

The overall mean rating for understanding was 6.52 (on a 1–7 scale; SD = 0.955), indicating that participants were able to read and understand both response options on most trials. For moral items, the mean understanding rating was 6.505 (SD = 0.92), for non-moral items it was 6.504 (SD = 0.99). Again using mixed effects linear regression, we analyzed the effects of item type, choice, and their interaction on confidence ratings. The full model included random intercepts for participants, and by-participant random slopes for the effect of item type. This analysis indicated no significant main effects or interactions.

The mean confidence rating was 5.28 (SD = 1.68) overall, 4.93 for non-moral items (SD = 1.81), and 5.64 for moral items (SD = 1.45). Using the same fixed and random-effects structure as noted above for the understanding ratings, we analyzed the effect of item type and choice on confidence. This analysis revealed a significant effect of item-type only, such that confidence was

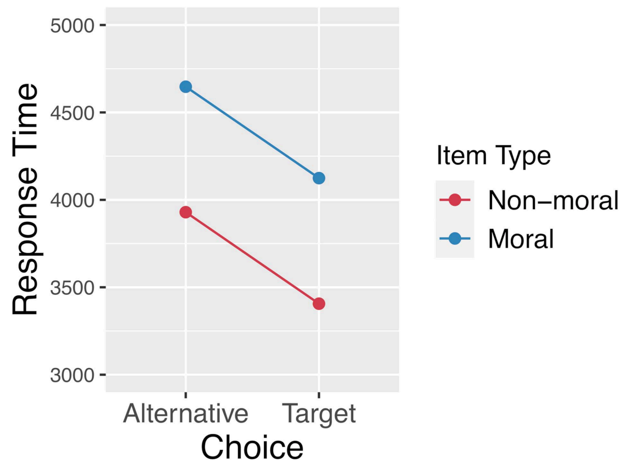

FIGURE 9 | Response times by item type and whether the participant chose the target response option or the alternative. This plot reveals a main effect of item type, which is consistent with the fact that the moral stimuli were normed to be relatively equibiased with respect to initial preferences. There is also an effect of the velocity squashing manipulation, whereby movements toward the alternative are made slower than movements toward the target.

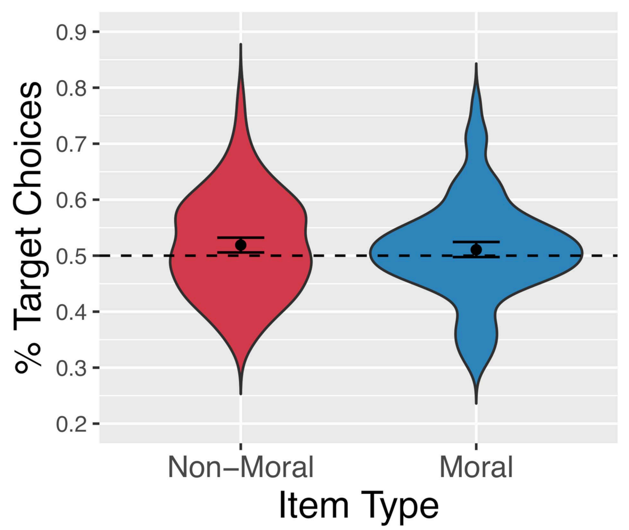

FIGURE 10 | Percentage of trials on which participants selected the randomly pre-selected target option for non-moral (red, left) and moral (blue, right) statements.

[3] https://osf.io/w26k3/

higher for moral items than for non-moral items [$b = 0.644$, $SE = 0.046$, $t = 14.04$, $X^2(1) = 100.8$, $p < 0.001$].

To probe for detection of the mouse-cursor manipulation, the answers to the two post-experiment free-response questions were qualitatively explored. Several participants reported thinking that the mouse-cursor moved slower than normal in general – and indeed, the baseline cursor speed was already diminished below the default computer values (on a 2019 iMac Pro) to require participants to use overt arm movements rather than slight flicks of the wrist. However, no participants reported noticing a bias in the speed of movement toward one side or another.

Discussion

In this experiment, we introduced a subtle, direction-specific bias in the velocity of the mouse cursor while participants decided which of two equidistant response options to click on. Although the effect is small, our results show that this manipulation was sufficient to bias decisions toward a randomly pre-determined target option, indicating that even moral decisions are sensitive to irrelevant influences on the motor system. Furthermore, no participants reported noticing this directional bias in cursor gain, so it is certainly possible that the strength of the manipulation could be increased further before becoming reliably detectable.

Response times also show the predicted effect of slower responses when choosing the non-target option, given the nature of the velocity squashing manipulation. The fact that response times were longer for the normed, moral stimuli is consistent with these stimuli being more equibiased than the un-normed, non-moral stimuli, and therefore requiring greater deliberation time. However, it should be noted that, in our experimental design, actual preferences cannot be assessed independently of the effect of the manipulation. This points to a potential weakness of our design, in that the statistical average of preferences in our population was used as a proxy for individual preferences. This leaves open the possibility that our normed stimuli were not actually less biased than the un-normed stimuli (although the results of Falandays and Spivey, 2020, and the main effect of item type on RTs are inconsistent with this possibility).

One notable finding was the presence of an effect of the manipulation on choices in *both* the moral stimuli, which had been normed such that response options themselves were relatively equibiased, and the non-moral stimuli, which had not been normed. Falandays and Spivey (2020), and our aDDM simulation above, suggest that – with Pärnamets et al. (2015b) gaze-contingent response-timing manipulation – only equibiased items (those where $A \approx 0$) may be influenced by the manipulation. However, our mDDM presented above straightforwardly accounts for the presence of an effect in both biased (those where $A >> 0$) and equibiased queries, in light of the motoric manipulation used here. While the gaze-contingent response-timing manipulation is only imposed when participants fixate both response options for a sufficient amount of time, which may not occur when response options are not equibiased, this motoric manipulation is imposed on all trials, leading to detectable effects even with a relatively weak velocity squashing factor and a relatively biased stimulus set. The more surprising finding that the normed stimuli did not show a *stronger* effect of the manipulation indicates either that our normed stimuli were not substantially less biased than our un-normed stimuli, or, more likely, that our experimental manipulation was rather subtle in practice, compared to the same velocity squashing factor in simulated space (see **Figures 6**, **7**). This issue will need to be addressed by a follow-up study using a stronger velocity-squashing manipulation, with the predicted outcomes being a greater proportion of target choices and a greater difference in response times between target-choice trials and alternative-choice trials. It is also worth reiterating that our moral and non-moral stimuli differed in textual complexity, length, and other psycholinguistic dimensions. While this was a purposeful choice (Falandays and Spivey, 2020), future work will also need to account for the role of these differences in determining effect sizes in each stimulus condition.

GENERAL DISCUSSION

For decades, pollsters and psychologists have known that the way a question is worded can have a subtle but detectable influence on the response it induces (Schwarz, 1999). Once people make a choice (which is unavoidably biased by the way the question was delivered), their preferences tend to shift in favor of their chosen alternative (Sharot et al., 2010). In fact, even when those final choices are misrepresented in a sleight-of-hand, people will often fail to notice the misrepresentation and happily defend those choices as if they were actually their own (Pärnamets et al., 2015a; Strandberg et al., 2018).

Recent experiments that recorded eye movements during moral decision-making further show that a response can be manipulated by the timing and delivery of the response prompt. Inducing a response while the eyes are revealing a (potentially temporary) bias toward a particular option can have a subtle but detectable influence on choice (Pärnamets et al., 2015b; Ghaffari and Fiedler, 2018; Falandays and Spivey, 2020). In addition to that kind of *timing* perturbation, a *motor movement* perturbation can also influence choice, either through learning about movement costs (Hagura et al., 2017), or through "online" perturbations such as our velocity squashing manipulation. The present experiment and simulations suggest that the timing manipulation may depend significantly on the intrinsic preference among the choices being relatively equibiased, whereas a motor movement manipulation may be able to exert its subtle influence even on choices that start out far from equilibrium.

Although the effect on choice in our human experiment is small, the results of both the human and simulation experiments suggest that it is robust even with queries that are far from equilibrium. This finding shows that our decisions can be slightly influenced by even small biases present in the interface to a decision, even when those decisions deal with complex and personal issues like morality. If a bias of 1–2% above chance seems negligible at first, one need only consider the countless number of micro-decisions that most of us make each day with the help of a technological interface, and it quickly becomes apparent that these small nudges could add up to a massive difference over a relatively short period of time. The mouse cursor manipulation we used in our experiment was apparently undetected by *any* of our participants and is something that could be established on any website or phone application with nothing more than a few lines of code.

Furthermore, the points we are making should not be taken as applying strictly to decisions made using a mouse cursor or even a screen-based interface of any kind. Rather, it is the case that *every* decision occurs in the context of some constraints, whether it be a time pressure, a difference in the location of options or effort required to select them, or a bias in the accumulation of noise in preferences onto motor output. However, the degree to which these influences on our decisions can be *controlled* is certainly much greater in the case of human-machine interactions. As such, we hope these results will encourage our readers to understand the interface of a decision as being a potentially critical constituent of the decision itself, rather than a separate step that takes place after cognition has done its work.

Given the small size of this motoric influence on choice, if one was imagining that machine interfaces could be designed to substantially manipulate a specific decision by a specific person – for the common good or for selfish reasons – these results do not provide much support for that approach. Encouraging humans to support the common good, even when it means some degree of self-sacrifice, will still require training those humans to have good moral reasoning skills. There is no quick fix for that. Rather than interpreting these findings as evidence for a dystopian future where some particular high-stakes decision will be reliably manipulated by a smart phone that tracks a politician's eye movements, there is a more realistic and scientific way to interpret these results.

At a theoretical level, it should be clear that these results simply could not happen so systematically if moral decisions were generated exclusively inside a neural module dedicated to moral reasoning – or even a network of such modules (e.g., Casebeer and Churchland, 2003). Instead, the evidence suggests that moral decisions (and potentially any difficult dilemma) emerge as a result of a human interfacing with their environment. While the majority of the statistical variance in those decisions is indeed determined by the human's intrinsic preferences (Ghaffari and Fiedler, 2018), some portion of that variance is also determined by adventitious biases that take place in the interface itself. With human-machine interfaces becoming so ubiquitous, many of our everyday decisions – and some of our high-stakes decisions – are emergent results of this interaction between human and machine.

Our results can be situated within the vast literature on embodied cognition, which focuses on the important roles of the body, action, and motor systems of the brain in cognition more generally (Barsalou, 1999; Anderson, 2003; Clark, 2008; Shapiro, 2019). Work on decision-making in this framework has emphasized the role of "irrelevant" sensory information on judgments, such as the way that holding a heavier clipboard results in increased assessments of the importance of decisions (Jostmann et al., 2009), or the way that exposure to bad smells or disgusting rooms increases judgments of moral disgust with respect to crimes (Schnall et al., 2008; see also: Prinz, 2007).

Thus, as urged by Gibson (1979) and others, the domain of analysis when studying the human mind should not be solely the human organism itself but, instead, the entire organism-environment system. A human's cognitive operations, their moral choices, their sense of self, perhaps even their consciousness, may be processes that are generated by the interaction of physical material both inside the skull and outside the skull (O'Regan and Noë, 2001; Clark, 2004; Aspell et al., 2009; Kirchhoff and Kiverstein, 2020; Spivey, 2020).

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in https://osf.io/z9r47/ and https://osf.io/w26k3/.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the University of California, Merced IRB. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

JF and SS conducted the experiment. JF conducted the simulations. All authors contributed to the writing of the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2021.624111/full#supplementary-material

Supplementary Video 1 | 10 simulated trials plotted over time, using the same parameter settings as in **Figure 3** (no preference). Timesteps have been approximately made equivalent to milliseconds.

Supplementary Video 2 | 10 simulated trials plotted over time, using the same parameter settings as in **Figure 4** (maximum target preference). Timesteps have been approximately made equivalent to milliseconds.

Supplementary Video 3 | 10 simulated trials plotted over time, using the same parameter settings as in **Figure 5** (maximum alternative preference). Timesteps have been approximately made equivalent to milliseconds.

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Bringing Together Robotics, Neuroscience, and Psychology: Lessons Learned From an Interdisciplinary Project

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The diversified methodology and expertise of interdisciplinary research teams provide the opportunity to overcome the limited perspectives of individual disciplines. This is particularly true at the interface of Robotics, Neuroscience, and Psychology as the three fields have quite different perspectives and approaches to offer. Nonetheless, aligning backgrounds and interdisciplinary expectations can present challenges due to varied research cultures and practices. Overcoming these challenges stands at the beginning of each productive collaboration and thus is a mandatory step in cognitive neurorobotics. In this article, we share eight lessons that we learned from our ongoing interdisciplinary project on human-robot and robot-robot interaction in social settings. These lessons provide practical advice for scientists initiating interdisciplinary research endeavors. Our advice can help to avoid early problems and deal with differences between research fields, prepare for and anticipate challenges, align project expectations, and speed up research progress, thus promoting effective interdisciplinary research across Robotics, Neuroscience, and Psychology.

Keywords: interdisciplinarity, human-robot interaction, social robotics, collaboration, robotics, social intelligence, cognitive neurorobotics, diversity

INTRODUCTION

Interdisciplinary collaborations are becoming an increasingly important ingredient for successful research in many fields (Van Noorden, 2015). Combining the expertise of different disciplines helps to address societal challenges (Beckerle et al., 2019) by bringing more comprehensive perspectives and solutions to pressing global issues. This also holds in Robotics, as the need to develop robots apt for interacting with humans is growing (Breazeal, 2004; Wiese et al., 2017) and is among the ten greatest challenges of Robotics (Yang et al., 2018). To build socially intelligent robots fit for bidirectional exchange with other agents, joining forces with other fields such as Neuroscience and Psychology is paramount. However, initiating collaboration between disciplines might not be straightforward, as these fields have different long-standing research traditions and practices. Here, we share eight lessons we learned from initiating our interdisciplinary project across these three fields within the Cluster of Excellence "Science of Intelligence."

Our research aims at extracting core principles of human interactions from Neuroscience and Psychology experiments for transferring into robot platforms to build communicative robots fit for social interactions where humans and robots exchange information adapting to the environment and to each other (Kirtay et al., 2020). Upon project initiation, we experienced various challenges due to diversity in our backgrounds, training, and discipline cultures, including: divergent project expectations, lack of common terminology, technical misconceptions, varied research procedures, as well as differences in desired research outlets.

Here, we put forward important principles we distilled when facing these challenges. We emphasize especially the integration with Robotics as a promising direction for innovation and advance in Human Neuroscience. Although other researchers have published insights regarding interdisciplinary research teams, they have either reviewed attributes of established successful teams (Lakhani et al., 2012), proposed frameworks to deal with challenges of interdisciplinary research in general (Wright Morton et al., 2015; Tobi and Kampen, 2018), focused on single aspects of the collaboration (e.g., methodology, Smaldino and O'Connor, 2020), or offered examples from collaborations between other disciplines (e.g., Campbell, 2005). Here, we offer a novel contribution by addressing the challenges of bringing together Robotics, Neuroscience, and Psychology, focusing on the most problematic project phase (i.e., initiation), and provide advice that extends to other collaborations involving technical (e.g., engineering) and human-centered (e.g., psychology) disciplines. Additionally, we provide concrete examples to help other researchers picture common problems and anticipate similar challenges. We encourage scientists establishing research collaborations across Robotics, Neuroscience, and Psychology to capitalize on these principles to make their collaboration smoother and more productive and to spare setbacks and frustration.

EIGHT LESSONS LEARNED THROUGH AN INTERDISCIPLINARY PROJECT AT THE INTERSECTION OF ROBOTICS, NEUROSCIENCE, AND PSYCHOLOGY

Lesson 1: Align Project Expectations

When researchers plan to bridge to a new discipline, they will likely start by gathering information about the new field and will form expectations on how fruitful such a collaboration could possibly be. Expectations about what is feasible in research fields where they themselves are not experts may be disproportionate. When scientists eventually actively exchange ideas with colleagues from those disciplines, they may realize that the outcome they envisaged is far from what is achievable. For example, availability of robots able to display predefined repertoires of social behavior (e.g., Pepper and NAO) may lead psychologists and neuroscientists to envisage a certain level of autonomy, flexibility, and variety in robots' behavior. This may induce the expectation that such robots can engage in smooth interactions with humans. Yet, despite using advanced technologies, robots' social skills are still quite limited. Conversely, roboticists may assume that a measurement of brain activity will lead to mechanistic models of cognitive functions that could be transferred into robots. In fact, most measurements of brain activity in humans reflect the physiological processes underlying cognitive functions only indirectly. Moreover, although advanced computational models have acquired a high level of precision in reproducing multiple aspects of low-level cognitive processes (e.g., perception; Voulodimos et al., 2018; Rankin and Rinzel, 2019), an accurate computational description of higher-level functions (e.g., complex social perception) is far from being reached. Prior expectations developed by roboticists, neuroscientists, and psychologists may diverge also due to the different levels they refer to (i.e., specific actions vs. complex behavior). It is, therefore, crucial to share expectations early on and re-scale them to a level of complexity that can be achieved by all disciplines.

Lesson 2: Agree on a Common Goal

Researchers' goals can be distinct across disciplines as what represents a successful outcome varies across fields. Moreover, what seems interesting for one discipline may appear trivial to another. When starting an interdisciplinary project, a crucial step is to clarify everyone's goals as much as possible to identify discrepancies and points of convergence. Once these have been identified, definitions of new goals may be needed that integrate these different demands. For example, during our first team meeting, two main goals were put forward: on the one hand, Psychology and Neuroscience collaborators aimed to assess whether the same cognitive mechanisms involved in human-human interaction would be involved in human-robot interaction; on the other hand, roboticists focused on reproducing complex behavior in artificial agents to derive testable hypotheses. This discrepancy reflects the difference between the exploratory character of Robotics' experiments and the confirmatory nature of Psychology and Neuroscience studies (Floreano et al., 2014). It took us some time to figure out that these individual goals could converge into the common goal of endowing robots with biologically inspired computational models.

Lesson 3: Discuss and Understand Different Research Practices

We experienced a number of challenges due to different research practices across our fields. While Psychology and Neuroscience share many practices, these might be unfamiliar to roboticists. Similarly, research practices in Robotics might appear unconventional to colleagues from Psychology and Neuroscience. Taking the time to understand the respective research procedures is crucial to envisage *how*, and especially *how fast,* the project will develop.

For example, obtaining Ethics approval is standard practice in Psychology and Neuroscience and is mandatory for studies involving human data collection. Therefore, all research projects require Ethics application and approval before data collection can commence. In Robotics, instead, most studies do not require Ethics approval as experiments are carried out on hardware (e.g., the iCub robot) or software platforms (e.g., the Neurorobotics Platform, Falotico et al., 2017) (although there might be exceptions for studies in human-robot interaction and cognitive developmental Robotics). Preparing Ethics proposals and awaiting their approval might take a considerable time and require revisions. Therefore, all team members shall be well-informed about this step when planning the project timeline.

Another increasingly common practice in Psychology and Neuroscience is pre-registration of studies (e.g., Bakker et al., 2020). This refers to the process of registering methods and analysis plans before a study commences. The purpose is to minimize the opportunity for research malpractice (e.g., data fabrication/selection) and to improve reproducibility of research results (e.g., Ioannidis, 2005; Eklund et al., 2016; Renkewitz and Heene, 2019). Pre-registration has the great advantage of carefully pre-planning various experimental features such as hypotheses, data collection and analysis (Botvinik-Nezer et al., 2020), and exclusion criteria in advance. One disadvantage is that considerable time is needed when starting a project to carefully plan each experimental feature. This might be unfamiliar to roboticists who are ready to start collecting data soon after project ideation. Lately, interest in designing reproducible studies is growing in Robotics as well (Bonsignorio and del Pobil, 2015).

Psychology and Neuroscience put special care to assure maximal experimental control, which will allow drawing sound conclusions. Pre-testing procedures, counterbalancing experimental stimuli, and scripting experimental protocols are just a few examples of steps necessary to avoid experimental confounds, achieve robust results, and draw solid conclusions. Roboticists might be surprised by this obsession for "details" and shall be prepared for anticipating these compulsory procedures and the time they require.

Another common practice in Psychology and Neuroscience implemented to assure good-quality data and minimize experimental design flaws is piloting data acquisition. Piloting refers to a preliminary data collection on a small sample of participants conducted to assess the feasibility of a study and to improve experimental details prior to the full-scale data collection. Although extensive piloting is not required in Robotics, some of its practices are comparable to this process. For example, it is common to validate a new model (e.g., deep learning models for reaching and grasping) on robot simulators before deploying it on an actual robot platform. This way, the researchers can fine-tune model parameters for the actual robot and avoid potential hardware problems during experiments. Agreeing with your team on the importance of the piloting phase is thus advisable.

Finally, to reach sufficient statistical power to reliably detect experimental effects, Psychology and Neuroscience studies often require a large number of participants. Sample sizes are usually calculated through power analysis, which estimates the number of participants required to detect an effect of a certain size. Generally, robotics experiments involve none or just a few participants, especially when assessing the effectiveness of developed demonstrators. As sufficient statistical power is fundamental for sound conclusions, the interdisciplinary team should familiarize with this procedure and consistently adopt it. Larger sample sizes affect the project timeline, as data collection will take longer, especially if access to lab space (e.g., fMRI facilities) is limited because shared with other projects run at the facility.

As many factors may affect the project timeline, it is important that the team discusses what might be a possible starting date and how fast the project is expected to proceed, anticipating possible constraints. For example, although psychologists and neuroscientists may be eager to test robots displaying specific social behaviors, it might take considerable time for roboticists to generate such behaviors on the platform. Here, constraints posed by delivering the research output of one discipline reflect on a minor experimental detail of another.

Lesson 4: Agree on Terminology

Interdisciplinary research projects inevitably host diverse terminology that plays a non-negligible role at various stages of the project, including grant proposal writing, conducting experiments, analyzing data, and disseminating the results. Agreeing on a common terminology early on will facilitate team communication and thus project success.

For example, our research project investigates how different modalities are integrated to enrich social interaction and communication. At first, it was challenging for us to understand what "modality" refers to, as the term has different meanings across our fields. In Robotics, this term indicates the type of sensory data associated with different aspects of the observed phenomenon, such as depth and color data recorded by sensors in an object-recognition experiment (see Ramachandram and Taylor, 2017). However, in Psychology and Neuroscience, "modality" refers to a sensory system (e.g., vision and touch). Thus, in robotic studies, color and depth of an object refer to two different modalities, albeit they are perceived through the same sensory system in biological agents (e.g., the eyes). Note that in Neuroscience modality has yet another meaning as it also refers to the measurement technique (e.g., fMRI or PET).

One way to establish a common terminology is to develop a project-specific dictionary to preserve the project know-how for future team members. Reading project members' previous publications and gaining knowledge of their respective fields is necessary to identify conflicting concepts and terms whose meaning needs to be agreed upon for effective communication. Mutual understanding in interdisciplinary teams improves with the detail and precision of the communication. Researchers should not assume common knowledge nor be afraid of repeating themselves; redundancy is helpful in interdisciplinary projects to understand each other.

Lesson 5: Get on the Same Page

Nowadays, still a negligible number of truly interdisciplinary degrees are offered. In most cases, interdisciplinary projects bring together experts from different disciplines who are knowledgeable about different topics and are familiar with disparate literature. Therefore, establishing a functional ground of shared knowledge may be challenging. What helped us immensely in the first months of our interdisciplinary project, was not only sharing literature and discussing research ideas but also jointly engaging in a literature review project. Through this review article (Kirtay et al., 2020), we were able to converge our perspectives and discuss the main findings of our respective fields. Not only were we able to build upon our expertise from three different fields, but we were also able to familiarize ourselves with the key findings of our colleagues' respective disciplines and develop a shared vision for the project. Finally, it provided us with the chance to develop a good dynamic for working together early on. Hence, engaging in a common literature review project might also help others to get on the same page with literature, key research findings, and form a shared long-term vision for their project.

Lesson 6: Transfer Essential Technical Knowledge

Overcoming technical challenges is a critical factor to obtain results and finish projects on time. Working with robots in interdisciplinary experiments might pose additional challenges. Sharing essential technical knowledge is crucial to minimize them. Technical aspects of the platform and their official documentation should be introduced to colleagues without a robotics background. Safety-related information, such as handling and cleaning of the robot, monitoring of charging level, the meaning of the light-emitting diodes are also important, as robot misuse could harm both people and itself.

The procedure for generating robot behavior (e.g., processing visual stimuli for object recognition) should be presented step-by-step, including technical details: charging levels, communication protocols, software interface, etc. The robot skills, such as dexterous manipulation, should be illustrated with simple demos. For example, robots' pointing, reaching, and grasping skills could be displayed through a small-scale experiment where the robot groups objects on the table. These demos should describe the robot sensors (e.g., cameras, touch sensors) employed to carry out the experiments. Basic information on robot control, data processing, and simple troubleshooting should be also provided to the project partners.

Similarly, technical knowledge from the complementary fields should be transferred to roboticists. For example, when planning interdisciplinary experiments that use functional magnetic resonance imaging sharing safety-related information is crucial. A description of practical limitations that may affect experimental design is also necessary. For example, highlighting the need for minimizing movements inside the scanner is important as this constrains what type of tasks can be performed.

Knowledge transfer allows collaborators to correct erroneous expectations and to plan feasible experiments. It should happen on a basic level that enables the partners to understand relevant functioning principles and to anticipate and handle potential issues when running their experiments. The challenges introduced here are just illustrative; setting up novel experiments brings always unknown challenges. However, sharing essential knowledge in advance reduces potential issues before, during, and after the experiments.

Lesson 7: Agree on the Desired Research Outlets

Different publication venues appeal unequally to different disciplines. In Robotics, conference proceedings are a preferred way to disseminate research. Papers submitted therein undergo rigorous peer-reviewing. These usually have higher impact than journal publications (e.g., Meyer et al., 2009) and are often preferential reads in Robotics. Dissemination at conferences provides more visibility to early-career researchers and has greater impact, as engagement of attendees is high, promoting collaborations with researchers from different Robotics subfields.

At Psychology and Neuroscience conferences, researchers typically present their newest (and usually preliminary) results. Abstracts submitted to conferences do not commonly undergo extensive peer-review as happens for journal submissions. As a consequence, a journal publication in these fields is more valuable, as reflected by higher Impact Factors for journals as compared to conferences. Although this is a questionable metric (Paulus et al., 2018; Larivière and Sugimoto, 2019), it is still widely used in academic evaluations (Else, 2019).

The time necessary to disseminate research outputs is also an important factor to consider when choosing a proper publication venue. To provide robust, reliable results and make the generalizable claims required for journal articles, running additional experiments may be necessary. This adds to the lengthy review-revision cycle that takes at best several months. Instead, conference papers are usually short, present a single study, and the review process is completed within a few months.

Identifying a proper publication venue for interdisciplinary research may carry additional complications. For example, brief research reports of interdisciplinary experiments are generally welcomed by both disciplinary and interdisciplinary conferences. In our experience, such a format is more often unsuccessful when targeting field-specific journals, which are inclined to consider interdisciplinary studies for publication only when submitted as lengthy manuscripts with detailed descriptions and simplified prose.

To manage the expectations of publishing the results of interdisciplinary experiments, the project partners should openly discuss the possible publication venues to balance interests of colleagues from different disciplines. For example, psychologists and neuroscientists may prefer not to publish research results at conferences, as some journals do not consider work already published elsewhere. However, publication of preliminary results at conferences often does not violate this requirement, therefore it is desirable for all counterparts. To accommodate the wishes of the project partners, they should all agree on the publication strategy, ideally at an early stage of the project.

Lesson 8: Diversity Is an Asset

Interdisciplinarity brings diversity, which is an asset for teamwork. People from different fields likely develop different skills during their careers that could come in handy in joint projects. For example, researchers with a computer science background are usually fluent in programming while psychologists are typically less so. On the other end, psychologists and neuroscientists are typically more trained in experimental design and advanced statistics than roboticists are. Therefore, interdisciplinary teams span a broader range of skills that can be combined to overcome setbacks more effectively.

Additionally, interdisciplinary teams are often more diverse in terms of cultures, genders, and personalities. Such diversity further enriches the research collaboration by bringing in different perspectives and improving problem-solving, flexibility, and innovation of the team (see Schrouff et al., 2019). For example, during our first project retreat, people from fields with unequal gender proportions engaged in common projects. Different gender representations emerged, producing unbalanced communicative exchanges. To promote inclusive discussions, later we made moderation of the debate mandatory for each talk. This measure encouraged participation and facilitated the emergence of different perspectives and, eventually, of innovative ideas.

SUMMARY AND CONCLUSION

Interdisciplinary collaborations can seem challenging at first, but when collaborators are informed about intricacies of the contributing fields and varied research practices, they can become highly rewarding and can significantly enrich the project and the research field (e.g., Rognini and Blanke, 2016). We believe the eight lessons we presented here will help researchers with a smooth initiation and implementation of projects at the intersection of Robotics, Neuroscience, and Psychology, thus promoting effective interdisciplinary research across these fields.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

OW, MK, and DP conceptualized the manuscript and wrote the original draft of the manuscript. DP and AK provided supervision. DP administered the project. RA, J-DH, and VH acquired funding. All authors contributed to manuscript revision and editing, and approved the submitted version.

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Embodied Cooperation to Promote Forgiving Interactions With Autonomous Machines

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During every waking moment, we must engage with our environments, the people around us, the tools we use, and even our own bodies to perform actions and achieve our intentions. There is a spectrum of control that we have over our surroundings that spans the extremes from full to negligible. When the outcomes of our actions do not align with our goals, we have a tremendous capacity to displace blame and frustration on external factors while forgiving ourselves. This is especially true when we cooperate with machines; they are rarely afforded the level of forgiveness we provide our bodies and often bear much of our blame. Yet, our brain readily engages with autonomous processes in controlling our bodies to coordinate complex patterns of muscle contractions, make postural adjustments, adapt to external perturbations, among many others. This acceptance of biological autonomy may provide avenues to promote more forgiving human-machine partnerships. In this perspectives paper, we argue that striving for machine embodiment is a pathway to achieving effective and forgiving human-machine relationships. We discuss the mechanisms that help us identify ourselves and our bodies as separate from our environments and we describe their roles in achieving embodied cooperation. Using a representative selection of examples in neurally interfaced prosthetic limbs and intelligent mechatronics, we describe techniques to engage these same mechanisms when designing autonomous systems and their potential bidirectional interfaces.

Keywords: embodiment, human–machine interaction, autonomous machine, bidirectional interface, perception, cooperation

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INTRODUCTION

From smartphones to self-driving vehicles to advanced artificial limbs, cooperative machines are becoming increasingly integrated into our society. As they continue to grow in their level of sophistication and autonomy, so does the complexity of human-machine relationships. When engaging with technology, frustration is never far away and negative emotions may shape our disposition to using a technology (Klein et al., 2002). Sometimes these emotions are merited by the poor performance of the technology, but we often misjudge technologies and place unfair expectations on them (Jackson, 2002) simply because of the way they communicate with us. Like the way the glimmer of a smile or the touch of a hand can change our reception of hard news, the way that technologies interface with us is imperative to accepting their capabilities. As humans, we are quick to distinguish between ourselves and cooperating machines, and to blame them for errors (Serenko, 2007). However, the perception that our bodies and our actions are our own is incredibly malleable and this malleability provides a pathway to improved human-machine interactions. Our brains and our bodies host a variety of conscious and non-conscious perceptual mechanisms to perceive ourselves as separate from our environments, and these mechanisms may be targeted through bidirectional machine-interfaces. In doing so, we may assume ownership of cooperative machines and their collaborative actions to promote more forgiving interactions, a concept we call embodied cooperation.

OUR ACTIONS AND OUR BIASES

How do we know that we are "ourselves"; autonomous agents that have physical bodies, and act within an external environment? Although various forms of this age-old question have long been explored across disciplines including philosophy, phenomenology, psychology, and cognitive neuroscience; a single unifying theory of self-awareness has yet to be developed (Braun et al., 2018). Rather, there are several neurocognitive theories that hypothesize varying degrees of influence from the brain integrating multisensory information and internal representations of the body (Tsakiris, 2010; Braun et al., 2018). What is clear, is that our brains readily and constantly distinguish ourselves as separate from our environments, the tools we use, and the people around us. These distinctions of "self or other" shape our perceptions of nearly every action we perform.

There is a spectrum of control that we have over the outcomes of our actions that spans the extremes from full to negligible correlation. In between, our *perceived* role in an outcome is directly linked to the brain's distinction of self or other. As individuals, our locus of control describes the degree to which we believe that *we* control the events around us, as opposed to *external forces* (Rotter, 1966). There are many factors that may shape this perception including age, gender, and cultural differences (Strickland and Haley, 1980; Berry et al., 1992; Hovenkamp-Hermelink et al., 2019); however, there are inherent biases in our perceived control of events. The term self-serving bias describes the larger group behavior in which we tend to disproportionately credit ourselves for positive outcomes of actions while blaming negative outcomes on things beyond our control (Davis and Davis, 1972). This behavior has been observed in numerous contexts including competitive sports (Lau and Russell, 1980; Riess and Taylor, 1984; De Michele et al., 1998), perceptions of one's own employability (Furnham, 1982), and academic performance (McAllister, 1996), among many others (Gray and Silver, 1990; Sedikides et al., 1998; Farmer and Pecorino, 2002). Self-serving bias is highly relevant to human-machine interactions as people tend to not only blame technology for mistakes but are also less likely to attribute positive outcomes to machine-partners and even take credit for themselves (Friedman, 1995; Moon, 2003; You et al., 2011).

Autonomous machines have an even more troublesome relationship with self-serving biases. This behavior is observed during interactions with artificial intelligence (Vilaza et al., 2014) and amplified as the degree of machine autonomy increases (Serenko, 2007). Further, in the event of an inappropriate interaction, frustration and emotional consequences are never far away. Negative emotional states are linked to more extreme self-serving behaviors (Jahoda et al., 2006; Coleman, 2011) and frustrating interactions can leave users negatively disposed to technologies (Klein et al., 2002). Here, there is a difficult "blame cycle" in which systems of increasing autonomy receive increased blame for errors and these errors can promote negative emotional states that further reinforce the displacement of blame. Rather than blaming and becoming frustrated with our technological partners, we need to develop more forgiving relationships to break this blame cycle. As humans, we do have the capacity to form these forgiving relationships. For example, individuals are more inclined to assist a computer to complete a cooperative task if that same computer has previously assisted the user (Fogg and Nass, 1997). Further, Mirnig et al. performed a study in which participants were provided simple task instructions by an anthropomorphized social robot. Participants described the robot as more likable when minor non-task-related errors were made, suggesting that like perceptions of other humans, minor imperfections carry the potential of increasing likability (Mirnig et al., 2017). Therefore, we argue that natural human tendencies and biases also provide opportunities rather than just barriers to improve interactions with autonomous machines. We further suggest that if a technology (and/or its actions) can be perceived as belonging to the user, many of our existing biases may be flipped to the benefit of more effective and forgiving cooperation.

One might think that autonomous machines would be more easily accepted and forgiven, given that our brains are hardwired to cooperate with the autonomous processes in our own bodies. For instance, a single motor task may be achieved by nearly infinite combinations of joint motions and timings (Bernstein, 1967). To be completed without attending to every muscle's action, the central nervous system appears to rely on repertoires of autonomous movement patterns (Bizzi et al., 1991; Wolpert et al., 2001; Giszter and Hart, 2013). Although we feel in complete control of our limbs and bodies, when we move our bodies or manipulate objects, the specifics of those motions are executed through autonomous sensorimotor control loops outside of our conscious control. It is this biological-autonomous framework that cooperative machines should seek to engage. To do this, carefully constructed bidirectional interfaces may be employed. Like our biological bodies, these devices will need to consistently and accurately trigger a machine to perform cooperative actions while also returning relevant and temporally appropriate information to the user.

THE MECHANISMS OF EMBODIMENT

In nearly all interactions with cooperative machines, we perceive ourselves and our actions as separate from the machine. This distinction is a product of our sense of embodiment. Here, we adopt the definition of embodiment as the combined experiences of owning and controlling a body and its parts (Matamala-Gomez et al., 2019; Schettler et al., 2019). Embodiment emerges from the integration of our intentions, motor actions, and sensory outcomes (Braun et al., 2018; Schettler et al., 2019). More specifically, it integrates perceptions and mental constructs built around vision, cutaneous sensation, proprioception, interoception, motor control, and vestibular sensations (Maselli and Slater, 2013). The sense of embodiment is malleable and manipulating these channels can extend the perceived borders and capabilities of our bodies to include non-bodily objects and even cooperative machines (Botvinick and Cohen, 1998; Braun et al., 2018; Schettler et al., 2019). In this context, there are three key experiences that a machine may engage with, these are: (1) the sense of self-location, experienced as the volume in space where one feels their body is located; (2) the sense of ownership, the experience of something being a part of the body; (3) and the sense of agency, the experience of authoring the actions of one's body and the resulting sensory outcomes (De Vignemont, 2011; Kilteni et al., 2015). **Figure 1** illustrates the relationship between actions, intentions, sensations, and the experiences that summate to the sense of embodiment. In this paper, we discuss varying degrees in which machines may engage these experiences to create a spectrum of perceptions that spans between operating a tool as an extra-personal extension of the body through the complete embodiment of a machine.

Self-Location and Tool-Incorporation

In literature, the larger concept of embodiment is often confounded with tool-incorporation which is the extra-personal experience of operating a tool as an extension of the body (rather than a part of the body). Promoting tool-incorporation in autonomous machines may be achieved by simply providing appropriate sensory feedback to the user. In doing so, users may develop a keen awareness of the tool's physicality as the brain adapts its geometric representation of the body and surrounding workspace (peripersonal space) (Iriki et al., 1996; Schettler et al., 2019). For example, the haptic feedback provided through canes used by visually impaired individuals can promote tool-incorporation. This results in an expansion of peripersonal space and an acute awareness of the area around the cane's tip (Serino et al., 2007). Similar effects are observed in numerous tools spanning the complexities of a rake through an automobile (Iriki et al., 1996; Sposito et al., 2012; Moeller et al., 2016). However, at no point do these users perceive their tools as a part of their bodies as they do not engage all the key mechanisms of embodiment. Here, peripersonal space and the sense of self-location are closely linked and may be influenced by tool use (Noel et al., 2015). Further, tool use may even promote a sense of external-agency (described below). However, these tools do not provide visually collocated feedback, which is required to form a sense of ownership, the distinguishing factor in this case. Of further relevance to human-machine cooperations, there appears to be a link between tool-use proficiency and the changes in peripersonal space that accompany tool-incorporation (Sposito et al., 2012; Biggio et al., 2017). For instance, experienced drivers underestimate distances in front of their vehicles (Moeller et al., 2016), and skilled archers perceive their targets as larger (Lee et al., 2012). Therefore, further exploring tool-incorporation and how cooperative machines may engage the requisite sensorimotor mechanisms may be an important avenue to accelerating user proficiency.

The Sense of Ownership

The sense of ownership is the experience of our body and body parts belonging to ourselves and describes the feeling of "mineness" that we experience (Braun et al., 2018). It is the feeling that is captured in statements such as "this is 'my' hand," and it often occurs at the fringe of consciousness (De Vignemont, 2011; Braun et al., 2018). There is strong evidence suggesting the sense of ownership is a product of the integration of visual and (most commonly) tactile sensory channels (Botvinick and Cohen, 1998; Kilteni et al., 2015; Braun et al., 2018; Schettler et al., 2019). Much of our current understanding originates from the rubber hand illusion in which participants report experiencing a rubber hand as a part of their bodies with strategic manipulation of what they see and feel (Botvinick and Cohen, 1998). This well-known experimental paradigm demonstrates that our experience of body ownership is dynamic, adaptable, and is not constrained to our biological body parts. Not only does the rubber hand illusion influence participants' sense of ownership, but it also influences the sense of self-location. When participants are asked to close their eyes and point to the location of their hand, their estimates are typically shifted toward the rubber hand (Botvinick and Cohen, 1998; Tsakiris and Haggard, 2005). This finding suggests that the brain is updating its body representation at conscious and non-conscious levels, with other non-conscious temporary physiological changes being observed, including hand temperature (Moseley et al., 2008), touch and pain sensitivity (Folegatti et al., 2009; Fang et al., 2019), skin conductance (Ehrsson et al., 2007), and cortical excitability (Della Gatta et al., 2016).

The rubber hand illusion is of specific relevance to human-machine embodied cooperation. It is one of the more encouraging pieces of evidence suggesting that non-bodily objects and even cooperative machines such as a robotic prosthesis (described below) can engage the brain's mechanisms that distinguish self or other. Yet here, the appropriateness of bidirectional human-machine communication becomes a key element. The rubber hand illusion is diminished in cases where visual and tactile stimulation are asynchronous, demonstrating that the congruency of multisensory inputs is vital to the illusion (Botvinick and Cohen, 1998). Therefore, for a cooperative machine to engage one's sense of ownership, the sensory feedback from that system must be strategically designed and tuned. The rubber hand illusion has found many applications throughout human-machine cooperative literature and purposefully developing a sense of ownership has been a goal in prosthetic limbs (discussed below) (Niedernhuber et al., 2018), chronic pain treatment (Martini, 2016), and virtual reality avatars (Matamala-Gomez et al., 2019).

The Sense of Agency

The sense of agency is distinct from the sense of ownership and can be thought of as the feeling of "mineness" for our

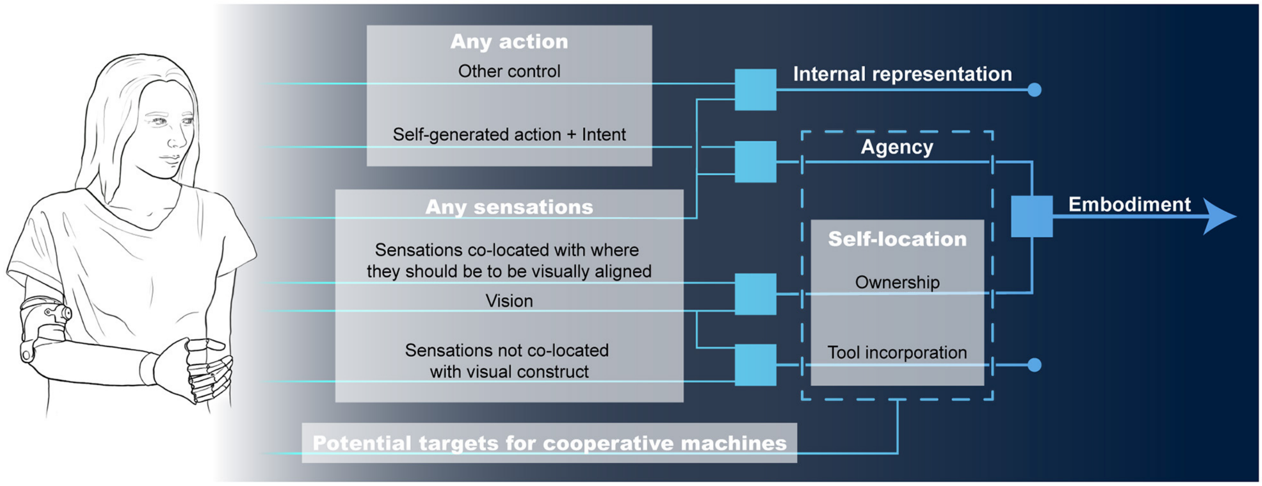

FIGURE 1 | The pieces of embodiment and potential targets for cooperative human-machine interactions.

actions. It distinguishes our self-generated actions (and their outcomes) from those generated by others (David et al., 2008). It accounts for the experience of authoring our actions and is captured in statements such as "I moved my leg" or "I pressed the button and made that happen" (Jeannerod, 2003; Braun et al., 2018). The sense of agency emerges when the motor and sensory outcomes of our actions align with our brain's predictions of the body acting in its environment (internal models) (Gallagher, 2000; Wolpert et al., 2001; Van Den Bos and Jeannerod, 2002; Legaspi and Toyoizumi, 2019). There are two levels of agency (Wen, 2019), both of which have implications in cooperations with autonomous machines. The first emerges during the control of our bodies (internal-agency). As humans, we trust our bodies to perform the actions we intend; when this is achieved, we establish an intrinsic sense of agency that is closely coupled, yet distinct from the sense of ownership (Gallagher, 2000). This sense is largely influenced by the intentions and brain's predictive models of a movement as well as the sensory experiences generated in our bodies (Gallagher, 2000; Marasco et al., 2018). The second level describes the experience of controlling external events (external-agency) (Wen et al., 2019). Pressing buttons, pulling levers, and even operating complex machinery falls into this category (Wen et al., 2019). Internal- and external-agency are both highly relevant to the perception of authoring outcomes during human-machine cooperations. Importantly, it only forms when user actions and internal models align with the sensory information returned from the machine and environment, an important goal when designing a machine's bidirectional interface.

Promoting a sense of agency during autonomous human-machine cooperation is important as it allows the user to assume authorship over cooperative actions; and therefore, may promote more forgiving interactions. The sense of agency is heavily influenced by our perceptions of self or other, and when achieved, individuals will explicitly judge themselves as responsible for the outcomes of actions (Dewey and Knoblich, 2014; Braun et al., 2018; Schofield et al., 2019). Not only does it influence explicit perceptions, but also subconscious processes. When an action produces an appropriate sensory outcome, the action and outcome are perceived as closer together in time, a phenomenon known as intentional binding (Haggard et al., 2002). Of further relevance, the sense of agency may be formed during cooperative actions. In human-human cooperations, a joint sense of authorship may be formed (Obhi and Hall, 2011; Sahai et al., 2017). Yet, these effects are diminished if a human partner is replaced with a machine (Obhi and Hall, 2011; Sahai et al., 2017; Grynszpan et al., 2019), and increasing autonomy in machine-partners reduces the sense of agency (Berberian et al., 2012). Relevant to interactions with autonomous machines, we suggest that the communicative potential of cooperating with our own bodies, another human, or a machine is dramatically different and reflected in our brain's models of these partnerships. The sense of agency is important in achieving embodied cooperation, and cooperative machines have the potential to form a joint sense of agency (or even external or internal agency) through careful construction of bidirectional interfaces. Consistent and accurate contributions of the machine will be necessary, and relevant temporally-appropriate sensory feedback will be required to allow the brain to build robust internal models.

INTEGRATING MACHINES AS A PART OF OURSELVES

There are numerous examples of bidirectional human-machine interfaces that promote embodied cooperation. Some of the more prominent work has emerged in the active field of advanced artificial limbs [for reviews see (Niedernhuber et al., 2018; Sensinger and Dosen, 2020)]. Robotic upper limb prostheses are computerized machines, and here embodiment may be an intuitive goal as they are often prescribed to augment or return function after limb loss. Like many other cooperative technologies, control and sensory feedback remain a driving factor influencing device abandonment (Biddiss and Chau, 2007; Østlie et al., 2012; Schofield et al., 2014). However, experimental prosthetic sensory interfaces that provide (most commonly) touch-based feedback have become widely investigated. Studies have shown that various modalities of feedback including vibration, skin-based pushing forces, and electrical stimulation of relevant nerves can be integrated into the brain's sensorimotor control loops and even promote a sense of ownership over an artificial limb (Ehrsson et al., 2008; D'Alonzo et al., 2015; Blustein et al., 2018; Graczyk et al., 2018; Valle et al., 2018; Cuberovic et al., 2019).

Recently, bidirectional neural-machine interfaces have been established for robotic prosthesis users. One such example leverages targeted reinnervation (TR) surgery to provide prosthetic control through users thinking about moving their missing limbs (Kuiken et al., 2004), and can even restore the senses of touch (Kuiken et al., 2007) and movement (Marasco et al., 2018). Working with individuals that received TR surgery, Marasco et al. used a modified version of the rubber hand illusion to demonstrate that ownership over a prosthesis can be readily achieved (Marasco et al., 2011). When participants viewed touch to a prosthetic hand while receiving synchronous sensations of touch to their missing hands, a strong sense of ownership was formed and captured across multiple independent measures. Since, Schofield et al. have reported on a long-term trial of similar touch-enabled prostheses (Schofield et al., 2020). Restoring touch sensation improved participants' grasping abilities, and over time participants tightly integrated touch into their prosthesis control strategies. Participants demonstrated long-term adaptations, developing a strong sense of ownership only when feedback was temporally and spatially appropriate (Schofield et al., 2020). Individuals who received TR surgery can also form an internal sense of agency over their prostheses. Vibration of muscles and/or tendons can induce illusory perceptions of limb movement (Goodwin et al., 1972), and vibration of participants' reinnervated muscles can induce perceptions of missing hand movements (Marasco et al., 2018). Marasco et al. demonstrated that these sensations of missing hand movement can be integrated with visual information of a prosthesis moving to influence perceptions of self-generated actions and develop a strong sense of internal-agency (Marasco et al., 2018).

Beyond these studies, prosthetic embodiment has been a rapidly growing area of interest. In fact, a PubMed search of the terms prosthetic, (or) prosthesis, (or) artificial limb, (and) embodiment, returned 195 research articles in the 30 years between 1989 and 2019. Nearly 80% of these articles were published in the last 10 years. Here, we are reaching a critical mass and beginning to reshape the way we view the relationship between a prosthesis and user. As robotic prostheses continue to advance, we are beginning to depart from simply evaluating these devices as tools for improved function and starting to assess their influence on the mechanisms that drive embodiment, an important next step.

DISCUSSION

The distinction of self or other shapes our perceptions of nearly every action we perform and drives our propensity to blame cooperative technologies when errors are made. Autonomous systems are becoming increasingly integrated into our society, and we need to reframe how we approach our cooperative relationships such that they engage the fundamental mechanisms that distinguish self or other. Neurally interfaced prostheses provide a strong example of how we may begin achieving this goal; however, they are far from the only technology in which embodied cooperation is desirable. Other assistive devices such as orthotic exoskeletons and powered mobility aids may also benefit. In these applications, the goal of bidirectional interfaces may be two-fold: the first being effective control to improve the user's physical capabilities, and the second being the embodiment of the technology. If such devices are truly embodied, the capabilities they afford the user become perceived as body function. This is a significant shift for the user as they depart from feelings of dependance on a machine to feelings of being more independent and physically capable with their bodies. It is important to note that ethical considerations will grow increasingly important as we move closer to seamless partnerships and even begin to augment human capabilities. We will need to be cognizant of the relationships and dependencies we create with machines; their implications to the user and society; as well as their accessibility and equity, especially in medical care contexts; among many others.

Full embodiment of every cooperative machine is an incredibly ambitious goal. However, as our society and our relationships with autonomous machines continues to evolve, cooperative embodiment may provide meaningful pathways to promote effective control, foster forgiving interactions, and encourage device adoption. The experience of embodiment arises from the senses of self-location, ownership, and agency, all of which cross a spectrum of workspaces that may be targeted by various cooperative machines. Just as it is valuable in prostheses, we will need to begin shifting how we evaluate interactions with cooperative machines to include assessments of cooperative embodiment. In doing so we can begin carefully constructing contextually appropriate bidirectional interfaces that leverage our inborn distinctions of self or other, and flip our natural biases to accept cooperative machines and their actions as indistinguishable from our own.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

JS participated in the preparation of the figure. PM participated in writing, figure generation, and shaping the scientific direction of the manuscript. All authors contributed to the writing, reviewing, and editing processes as well as figure generation.

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A Framework for Optimizing Co-adaptation in Body-Machine Interfaces

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The operation of a human-machine interface is increasingly often referred to as a two-learners problem, where both the human and the interface independently adapt their behavior based on shared information to improve joint performance over a specific task. Drawing inspiration from the field of body-machine interfaces, we take a different perspective and propose a framework for studying co-adaptation in scenarios where the evolution of the interface is dependent on the users' behavior and that do not require task goals to be explicitly defined. Our mathematical description of co-adaptation is built upon the assumption that the interface and the user agents co-adapt toward maximizing the interaction efficiency rather than optimizing task performance. This work describes a mathematical framework for body-machine interfaces where a naïve user interacts with an adaptive interface. The interface, modeled as a linear map from a space with high dimension (the user input) to a lower dimensional feedback, acts as an adaptive "tool" whose goal is to minimize transmission loss following an unsupervised learning procedure and has no knowledge of the task being performed by the user. The user is modeled as a non-stationary multivariate Gaussian generative process that produces a sequence of actions that is either statistically independent or correlated. Dependent data is used to model the output of an action selection module concerned with achieving some unknown goal dictated by the task. The framework assumes that in parallel to this explicit objective, the user is implicitly learning a suitable but not necessarily optimal way to interact with the interface. Implicit learning is modeled as use-dependent learning modulated by a reward-based mechanism acting on the generative distribution. Through simulation, the work quantifies how the system evolves as a function of the learning time scales when a user learns to operate a static vs. an adaptive interface. We show that this novel framework can be directly exploited to readily simulate a variety of interaction scenarios, to facilitate the exploration of the parameters that lead to optimal learning dynamics of the joint system, and to provide an empirical proof for the superiority of human-machine co-adaptation over user adaptation.

Keywords: co-adaptation, human-machine interface, use-dependent learning, model-free learning, reinforcement, dimensionality reduction, subspace learning, body-machine interface

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INTRODUCTION

Interfaces between human and a machine are at the forefront of research in human augmentation [e.g., supernumerary limbs (Prattichizzo et al., 2014; Parietti and Asada, 2016; Yamen Saraiji et al., 2018), myoelectric prostheses (Antuvan et al., 2014; Wright et al., 2016; Dyson et al., 2018)], assistance [e.g., brain-computer interfaces (Santhanam et al., 2006; Millán et al., 2010; Nicolas-Alonso and Gomez-Gil, 2012; Jarosiewicz et al., 2015), brain-machine interfaces (Collinger et al., 2013), body-machine interfaces (Antuvan et al., 2014; Farshchiansadegh et al., 2014; Chau et al., 2017; Fall et al., 2017; Aspelund et al., 2020; Rizzoglio et al., 2020)], and rehabilitation (Rohm et al., 2013; Pierella et al., 2014; Donati et al., 2016).

In the majority of these applications, human-machine interfaces (HMIs) are expected to provide support to their users for prolonged periods of time. However, extensive usage requires interface stability, which is at present a considerable challenge both due to technological characteristics of the device, and due to physiological and functional processes active at the user's level (Young et al., 2011; Barrese et al., 2013; Orsborn et al., 2014; Downey et al., 2018). Co-adaptive algorithms for HMIs have been developed to address the issue of decoder instability (Vidaurre et al., 2011; Kao et al., 2017; Yeung et al., 2019; Degenhart et al., 2020; Silversmith et al., 2020) and to compensate for performance degradation due to the emergent closed-loop dynamics during use (Orsborn et al., 2012; Dangi et al., 2013; Shenoy and Carmena, 2014; Hahne et al., 2015; De Santis et al., 2018). One goal of these strategies is to reduce reliance on user adaptation to compensate for imperfections in the interface, a process that can be lengthy and cognitively demanding, besides being often insufficient for guaranteeing efficient control (Sadtler et al., 2014; Golub et al., 2018).

Despite the growing body of research, the majority of the efforts have been devoted to improving the decoding power of the algorithms while still little work has addressed the mechanisms that enable the user to learn an efficient control strategy to interact with the interface (Héliot et al., 2010; Kübler et al., 2014; Couraud et al., 2018; Perdikis and Millán, 2020). A few studies proposed to investigate user-interface co-adaptation through mathematical models in a two-learners setting as a viable way to study the system's learning trajectory. These models share the assumptions that (i) the user intention is known, (ii) the task goal is defined and accessible, (iii) the user and the interface act as independent agents that work together either to minimize some joint cost function (Müller et al., 2017), to minimize closed-loop error through joint stochastic optimization (Merel et al., 2013), to minimize an individual cost function in a game-theoretic formulation (Madduri et al., 2020), or to maximize the expected reward via reinforcement learning (DiGiovanna et al., 2009). These models are particularly suited for guiding and interpreting co-adaptation in the context of brain-machine interfaces. However, the requirements of knowing user intentions and task goals limits their application to situations when explicit information regarding the task objectives might not be directly accessible or user intentions cannot be reliably estimated. Moreover, there is no knowledge whether these models can be generalized to a task different from the one they have been trained on.

In order to tackle these limitations, here we propose a novel framework for studying co-adaptation in a human-machine interface setting when explicit information regarding the tasks goal might not be directly accessible. We draw inspiration from the field of body-machine interfaces, which have traditionally adopted what we may call general purpose-decoders and aim to identify a suitable low-dimensional encoding of the user's body signals to use for control in a variety of tasks. We propose a framework where the user and the interface are non-independent agents that co-adapt toward maximizing the interaction efficiency rather than optimizing task performance. We believe our approach is novel also in that it addresses the problem of non-stationarity in the user behavior together with learning through data that is not independently identically distributed, as it is generally the case in practical applications (Perdikis and Millán, 2020).

The framework defines a mathematical model of a user learning and a model of an adaptive body-machine interface. User learning is implemented through a strategy based on reward-weighted use-dependent learning (Diedrichsen et al., 2010) with the goal of generating actions that maximize the coherence with the associated sensory feedback over time. We use experimental data obtained from a previous study where participants interacted with a body-machine interface (De Santis and Mussa-Ivaldi, 2020) to validate the plausibility of the model. The interface, on the other hand, is modeled as a linear compression map from high-dimensional actions to low dimensional feedback, that adapts to minimize transmission loss through an unsupervised learning procedure (De Santis et al., 2018). We simulate the models in different scenarios to study the final performance and convergence of the system as a function of the learning time scales of both the user and the interface.

In the following sections, we provide a mathematical formulation for framing the problem of co-adaptation in the context of body-machine interfaces. In the first section, we provide details of the mathematical models for a generic interface user, a model for an adaptive interface, and of their interaction. We then describe the simulation scenarios developed to test the plausibility of the proposed model for the user and to evaluate the effect of the learning time scales of the user and the interface on the ability of the system to converge to a joint solution.

We provide a thorough interpretation of the results to show that this novel framework can be directly exploited (i) to readily simulate a variety of interaction scenarios, (ii) to facilitate the exploration of the parameters that lead to optimal learning dynamics of the joint system, and (iii) to provide an empirical proof for the superiority of human-machine co-adaptation over user adaptation.

PROBLEM FORMULATION

The control problem in a human-machine interface (HMI) scenario can be formulated as follows. The user has to control some physical or virtual device in order to perform a certain task. The interface implements a continuous map B, between a certain n-dimensional vector of inputs $\boldsymbol{q}$ generated by the user, and an m-dimensional output vector of controls to the machine, $\boldsymbol{p}$.

$$\boldsymbol{p} = B(\boldsymbol{q}),\ B : \mathbb{R}^n \to \mathbb{R}^m \tag{1}$$

For instance, we may consider a user wanting to bring a computer cursor to a certain location on a screen. In this scenario, an interface may implement a map from body postures to the {x,y} location of the cursor on a screen (Mosier et al., 2005). Equivalently, another interface may define a transformation between the activity of neurons in the motor cortex and the velocity of the cursor (Santhanam et al., 2006).

As is often the case for HMI applications, we will assume that the dimensionality of the space of input signals recorded from the user is greater than the dimensionality of the signals necessary to control the device, $m < n$. This implies that not all inputs that the user generates will be equally effective in driving the device, as only vectors lying in the potent space of the map will determine a change in the output. Hence, when learning to operate the interface, a user is faced with both an explicit goal—to satisfy specific task requirements—and an implicit objective—to generate control signals that produce a change in the state of the device. We will call the space of all possible low dimensional vectors $\{\boldsymbol{p}\}$ different from the zero vector the *latent space* of the map.

For the sake of clarity, we will develop our formulation with application to body-machine interfaces, where B implements *a linear map and,* in particular*, an orthogonal transformation* between body postures and the state of the device (Farshchiansadegh et al., 2014). These particular properties allow us to derive a simplified and tractable mathematical formulation for the problem and to highlight interesting properties of the human-machine system that can extend beyond our particular case.

Considering the subset of linear orthogonal maps, for any given input vector $\boldsymbol{q}$ the corresponding set of output vector $\boldsymbol{p}$ can be defined as the orthogonal projection of $\boldsymbol{q}$ onto $\mathbb{R}^m$:

$$\boldsymbol{p} = B\boldsymbol{q} + B^{\perp}\boldsymbol{q} \tag{2}$$

Where $B^{\perp}$ denotes the orthogonal complement of B, that maps the vector $\boldsymbol{q}$ into the zero vector or null space of B. Here B effectively defines an m-dimensional hyperplane embedded in $\mathbb{R}^n$. Because the dimension of the null space is $n - m > 0$, the problem of identifying the inverse transformation of B is ill posed. Thus, we may expect the user to learn one out of the possible infinite particular solutions to the forward-inverse problem (Pierella et al., 2019).

Note that out of the possible generalized right-inverses of B, the pseudoinverse, also known as the Moore-Penrose inverse, $B^{\dagger} = B^T \left(BB^T\right)^{-1}$ represents the minimum norm solution in a least-square sense. In particular, for matrices with orthonormal columns, $B^{\dagger} = B^T$.

Figure 1 summarizes the individual components of the proposed framework that will be described in the following sections. Section A Model for the User details the proposed model for a body-machine interface user that learns to interact with a static interface through a strategy based on reinforcement and use-dependent learning. Section A Model for an Adaptive Interface summarizes the proposed algorithm for implementing an adaptive body-machine interface. Finally, section A Model for User-Interface Coadaptation describes the algorithm for implementing user-interface co-adaptation within the proposed framework.

A Model for the User

Let us assimilate a generic user to a generative process characterized by a probability distribution, $\mathcal{P}_u$, over the inputs $\boldsymbol{q}$. We will assume that the user is initially naïve to the interface, and that, with practice, will learn to control the interface up to a certain degree of proficiency. We then assume that learning will be reflected into a change in time of the probability of generating certain inputs based on the feedback received by the device (e.g., visual feedback of the cursor position).

Let us consider the case of $\mathcal{P}_u$ following a multivariate Normal distribution with mean $\boldsymbol{\mu} \in \mathbb{R}^n$ and covariance matrix $\Sigma \in \mathbb{R}^{n\times n}$. To account for time-dependency, we then assume that the distribution is non-stationary and can be summarized by a mean $\boldsymbol{\mu_k}$ and a covariance matrix Σ_k at a certain discrete time k:

$$\mathcal{P}_u\left(k\right) \sim \mathcal{N}\left(\boldsymbol{\mu}_k, \Sigma_k\right) \tag{3}$$

In order to simulate how the probability distribution of the user's data changes with practice, we need to make certain assumptions as to what learning strategy the user might adopt. Previous work assumed the user follows an optimal control policy for directly minimizing task-related error (Merel et al., 2013, 2015; Müller et al., 2017). The authors of these studies rely on the knowledge of user intent for computing an error metric that guides an optimization routine over the model's parameters. However, the availability of the error depends on the capability to generate adequate input signals. Hence, when interacting with a system whose properties are still unknown, exploration of the input space is required (Bernardi et al., 2015; van Vugt and Ostry, 2019). Consistently, here we hypothesize learning in the early stages of interaction with the interface can be better approximated by a mechanism that acts through reinforcement and a memory of past inputs and their observed consequences. As a definition of error becomes unnecessary, the proposed approach allows framing the learning problem in a way that is task independent.

Let us assume that the user associates to every generated "action" $\boldsymbol{q_k}$ a certain reward r_k based on the feedback received from the map and that the objective of the user is to learn to generate actions that maximize the expected reward over time:

$$\{\boldsymbol{q_k}\} : max_{\Sigma,\mu,B}\left\{E\left[r_k\right]\right\} \tag{4}$$

In particular, we assume that the reward assigned to each action is proportional to the "amount of feedback" the user receives for that action. For instance, actions that lie in the null space of B will

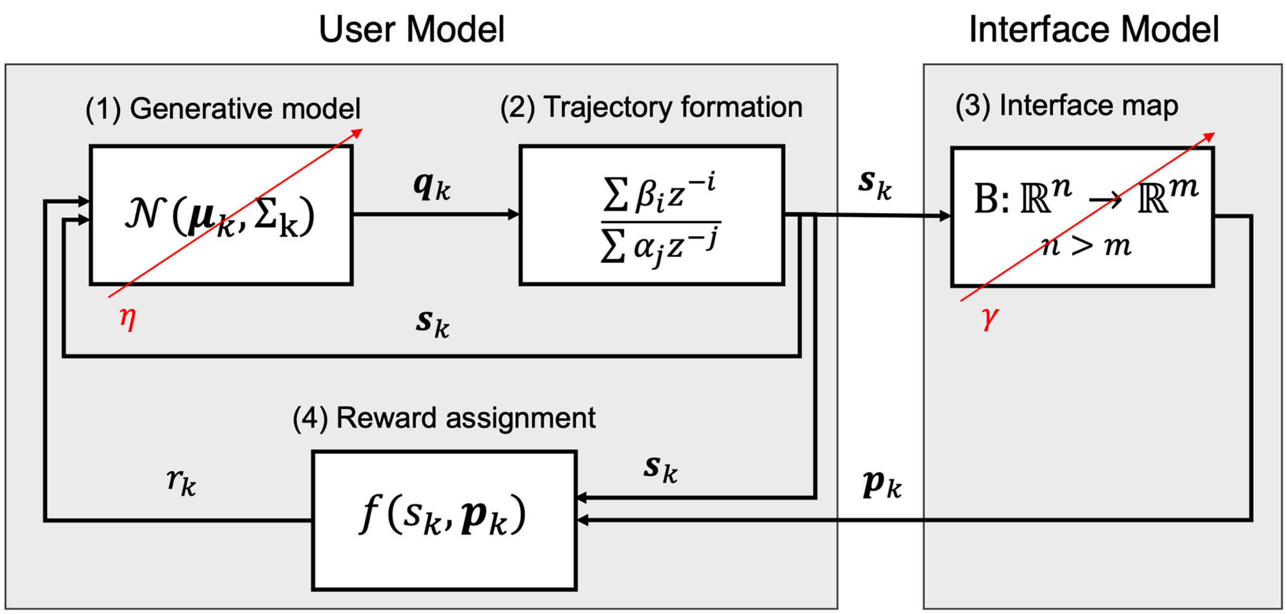

FIGURE 1 | Model components and behavior. The user is composed of a generative model (1) that describes the probability of drawing a certain n-dimensional action $\boldsymbol{q}_k$ at the instant k. The action $\boldsymbol{q}_k$ contributes to generating a smooth trajectory of control signals $\boldsymbol{s}_k$ for the interface (2). The interface map computes a vector $\boldsymbol{p}_k$ of a dimension $m < n$ and provides it to the user as feedback related to the smooth control action $\boldsymbol{s}_k$ (3). The user model processes the feedback assigning a reward for the action based on the feedback (4). After each iteration, the map recursively updates its parameters based on the distribution of the observed user commands $\boldsymbol{s}_k$ with learning rate γ. The user updates its generative model with learning rate η after a feedback is received, reinforcing the generated smooth action according to its reward.

receive zero reward, as they will produce no change in the state of the device, while actions that produce an observable change in state will receive a reward discounted by the amount of their null space component. The reward assignment rule, given (1), can be formalized as:

$$r_k = \frac{tr\left(\boldsymbol{p}_k \boldsymbol{p}_k^T\right)}{tr\left(\boldsymbol{q}_k \boldsymbol{q}_k^T\right)} = \frac{tr\left(B\boldsymbol{q}_k \boldsymbol{q}_k^T B^T\right)}{tr\left(\boldsymbol{q}_k \boldsymbol{q}_k^T\right)} \tag{5}$$

Note that the reward is a non-negative scalar, $0 \leq r_k \leq 1$:

$$\begin{aligned} tr\left(B\mathbf{q}_k\mathbf{q}_k^T B^T\right) &= tr\left(\mathbf{q}_k\mathbf{q}_k^T\right), if \ \|B\mathbf{q}_k\| = \|\mathbf{q}_k\| \\ tr\left(B\mathbf{q}_k\mathbf{q}_k^T B^T\right) &< tr\left(\mathbf{q}_k\mathbf{q}_k^T\right), if \ \|B\mathbf{q}_k\| < \|\mathbf{q}_k\| \end{aligned} \tag{6}$$

Equation (5) defines the reward as the amount of power transferred through the map and Equation (6) gives us the intuition that the reward is maximized if $\mathbf{q}_k$ lies in the potent space of B at every instant of time.

Let us now consider a set of samples $\{\overline{q}\}$ generated over a finite time horizon $[k_0, \ k_1]$ within which the generative model $\mathcal{P}_u\left(k_0 \leq k \leq k_1\right) \sim \ \mathcal{N}\left(\overline{\boldsymbol{\mu}}, \overline{\boldsymbol{\Sigma}}\right)$ can be considered approximately stationary. Given (5) and knowing that $\overline{\Sigma} = E\left[\left(\overline{q} - \overline{\mu}\right) \ \left(\overline{q} - \overline{\mu}\right)^{\mathbf{t}}\right] = E\left[\overline{q}\,\overline{q}^T\right] - \ \overline{\mu}\,\overline{\mu}^T$, we can formulate the maximization policy for the expected reward in Equation (4) as follows:

$$\begin{aligned} E\left[r_k\right] &= \frac{tr\left(E\left[\overline{\mathbf{p}}\,\overline{\mathbf{p}}^T\right]\right)}{tr\left(E\left[\overline{\mathbf{q}}\,\overline{\mathbf{q}}^T\right]\right)} \\ &= \frac{tr\left(BE\left[\overline{\mathbf{q}}\,\overline{\mathbf{q}}^T\right]B^T\right)}{tr\left(E\left[\overline{\mathbf{q}}\,\overline{\mathbf{q}}^T\right]\right)} \\ &= \frac{tr\left(B\overline{\boldsymbol{\Sigma}}B^T\right) + tr\left(B\overline{\boldsymbol{\mu}}\,\overline{\boldsymbol{\mu}}^T B^T\right)}{tr\left(\overline{\boldsymbol{\Sigma}}\right) + tr\left(\overline{\boldsymbol{\mu}}\,\overline{\boldsymbol{\mu}}^T\right)} \end{aligned} \tag{7}$$

We can find a more interesting expression for Equation (7) considering the set of input vectors centered in the mean: $\{q\} = \{\overline{q}\} - \overline{\boldsymbol{\mu}}$. Knowing that $\overline{\Sigma}$ is symmetric and positive definite, we can define two matrices, a diagonal matrix $\Lambda = diag([\lambda_1, \ldots, \lambda_n])$, where λ_n are the eigenvalues of $\overline{\Sigma}$, and an orthogonal matrix $V = [\mathbf{v}_1 | \ldots | \ \mathbf{v}_n]$ with the corresponding eigenvectors as columns such that:

$$\overline{\Sigma} = V \Lambda V^T \tag{8}$$

Using Equation (8), we can then rewrite Equation (7) in the case of random variables with zero mean:

$$E\left[r_k\right] = \frac{tr\left(B\overline{\Sigma}B^T\right)}{tr\left(\overline{\Sigma}\right)} = \frac{tr\left(BV\Lambda V^T B^T\right)}{\sum \lambda_i} = \frac{tr(C\Lambda C^T)}{\sum \lambda_i} \tag{9}$$

where $C = BV$. We can immediately see from Equation (9) that the expected reward will be maximized if $CC^T = I$, hence if $V = B^{\dagger}$. This is equivalent to say that the reward will be maximized if the user learns to generate inputs that lie in the potent space of the interface map.

We have assumed the user could be modeled as a non-stationary generative process characterized by a certain expected value and covariance matrix at a certain instant of time. In the following paragraph we will now provide a mathematical formulation for iteratively computing the parameters of the user distribution based on the feedback received by the interface and the reward.

Given that the user receives feedback as a continuous stream, the distribution parameters should be estimated following an incremental approach. In the following, we will report the formulation originally proposed by Weng and colleagues (Zhang and Weng, 2001; Weng et al., 2003) for iteratively estimating the eigenvectors and eigenvalues of the data covariance matrix, that we have modified to account for non-stationarity in the distribution that generated the data (De Santis et al., 2018; De Santis and Mussa-Ivaldi, 2020). Every time a new sample $\boldsymbol{q_k}$ is received, the sample estimates for the mean and the principal components of the covariance matrix can be updated as follows:

$$\boldsymbol{\mu}_{k+1} = (1-\eta)\,\boldsymbol{\mu_k} + \eta\boldsymbol{q_k} \tag{10}$$

$$\boldsymbol{w}_{k+1} = (1-\eta)\,\boldsymbol{w_k} + \eta\frac{(\boldsymbol{q_k}-\boldsymbol{\mu_{k+1}})(\boldsymbol{q_k^T}-\boldsymbol{\mu_{k+1}})}{\|\boldsymbol{w_k}\|}\boldsymbol{w_k} \tag{11}$$

where $\mathbf{w}_k=\lambda_k\mathbf{v}_k$ is the estimate of the eigenvector scaled by its corresponding estimated variance.

Equations (10) and (11) effectively implement a first order exponential smoothing filter with time constant $\tau = -T/\ln(1-\eta)$, where T is the sampling interval and η the *learning rate*. Hence, the η parameter describes how fast new data is incorporated in the model or, equivalently, how quickly the user is willing to discount older memories. It has been suggested that the learning rate should be chosen within the range $[10^{-5},\ 10^{-1}]$ to ensure convergence and stability of the solution (Schmitt et al., 2016). By modulating the learning rate η we can characterize processes with a variable amount of memory and sensitivity to data that lie outside the distribution. In particular, small values of η will decrease the likelihood that new data will considerably affect the distribution parameters. This may be desirable when the reward for the current action is low. Conversely, the user should reinforce actions that are highly rewarded. This can be accounted for in the model by modulating the learning rate in proportion to the reward, as suggested by Diedrichsen et al. (2010):

$$\eta_k = \eta{\cdot}r_k \tag{12}$$

According to Equation (12), at each iteration the learning rate will always be bounded between zero, whenever the current action receives zero reward, and η. It is interesting to note that for $\eta_k = \eta$ the model would effectively mimic a process that is referred to as "use-dependent" or "experience-dependent" learning (Butefisch et al., 2000; Diedrichsen et al., 2010; Huang et al., 2011), which describes the progressive consolidation of patterns of activity by repeated occurrence of a same action.

The last component of the model that has to be addressed is how the process of action selection is carried out. In a real scenario, the user would select actions directed toward a goal, for instance to reach a target position with the computer cursor or when carrying out a pursuit task. As we are not interested in modeling the behavior of the user under specific task conditions, we will only include in the model the general requirement that the samples drawn by the user ought to be statistically dependent.

In practice, we simulate data to be dependent within a certain window L by filtering successive randomly drawn inputs $\{\boldsymbol{q_k},\ldots,\boldsymbol{q_{k+L}}\}$ with a first order autoregressive exponentially weighted moving average (ARMA) model, initialized with $\boldsymbol{s}_0=\boldsymbol{q}_0$:

$$\boldsymbol{s_k} = \alpha\boldsymbol{s_{k-1}} + \beta\boldsymbol{q}_k \tag{13}$$

The parameters values $\alpha = 0.99$, $\beta = 0.15$ have been chosen to resemble the correlation encountered in experimental data sequences from upper-limb movements after centering the data in the mean (De Santis and Mussa-Ivaldi, 2020). An example of real vs. simulated data is shown in **Figure 2**.

Finally, we have to add a regularizing term that encodes some constraints on the structure of the variance of the generated action that, under conventional circumstances, would be induced by task requirements. Given that the model generates correlated data, the possibility for the simulated user to successfully learn to generate actions that increase the expected reward depends on the specific sequence of actions the user produces. In fact, it is likely that the model in the present form will learn degenerate solutions. For example, the user may learn to consistently produce actions along a line parallel to one column of the map rather than in two dimensions. Another, less intuitive, singularity relates to the magnitude of the actions the user learns. As we assume that samples generated by the user are normally distributed, actions that lie closer to the mean are more likely to be produced than actions that lie further from the mean. Consequently, we can predict from the recursiveness of Equations (10) and (11) that the user distribution will progressively shrink until the variance becomes zero.

In order to prevent the user from learning degenerate solutions and to avoid the problem of the "vanishing variance," we need to introduce two regularizing constraints on the structure of the covariance matrix used to generate data at each step. In particular, we assume here that the user is motivated in producing actions that span (at least) two dimensions. This motivation is then translated into a corrective term for the variance matrix Λ_k at each time step:

$$\hat{\Lambda}_k = diag(|\boldsymbol{\lambda}_k + \boldsymbol{\lambda}_C + \mathbf{z}|) \tag{14}$$

where λ_C is a n-dimensional vector of corrective factors and $\mathbf{z}$ is a n-dimensional vector of random noise.

The first constraint, formalized in Equation (15), imposes that the vigor of the user's actions in the task dimensions over time has

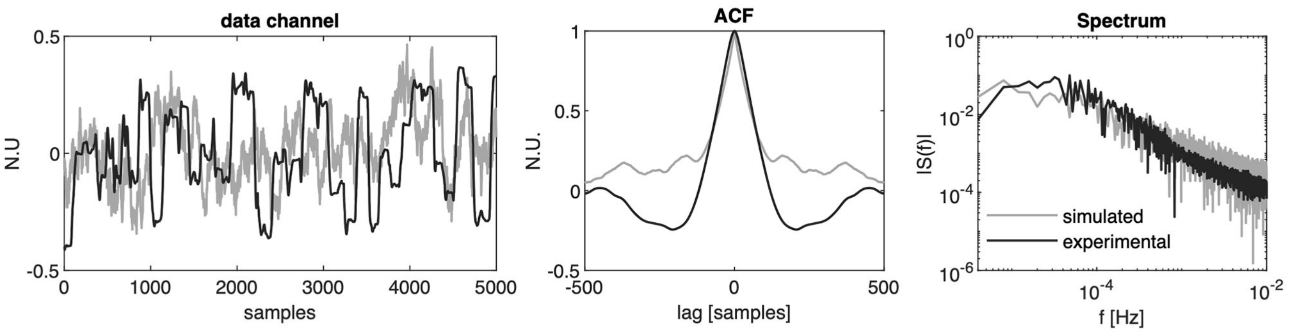

FIGURE 2 | Experimental vs. simulated data. From left to right: normalized orientation data from one channel of IMU recordings while the user controlled the position of a 2D cursor in a reaching task with a body-machine interface (black line) and simulated sensor data channel extracted from a distribution with the same mean and covariance matrix (gray line); autocorrelation function of the experimental and simulated signal cropped at a lag of 500 samples; single-sided amplitude spectrum of the experimental and simulated signal assuming a sample frequency of 50 Hz.

to remain constant. No constraint is imposed on the cumulative variance distributed along the remaining dimensions.

$$tr\left(\sum_{j=1}^{m}\lambda_{j,k}\right)=tr\left(\sum_{j=1}^{m}\lambda_{j,0}\right) \tag{15}$$

The second constraint imposes that the percentage of variance accounted for by the first m eigenvalues does not decrease compared to the initial condition.

$$\frac{\Lambda_k}{tr\left(\Lambda_k\right)} \geq \frac{\Lambda_0}{tr\left(\Lambda_0\right)} \tag{16}$$

A Model for an Adaptive Interface

In order to simulate interface adaptation, we refer to the algorithm initially proposed in De Santis et al. (2018). The goal of interface adaptation is to incrementally adjust the interface map to better resemble the distribution of the user's action while the user is controlling the interface. If we recall Equation (9), the optimal solution to the control problem in terms of reward maximization is given by $BV\,(BV)^T = I$. If the interface is static, this can be achieved only if the user learns to generate data points that lie in the potent space of the map. However, this process is likely to develop over a prolonged period of time as a result of the interaction of multiple learning mechanisms with task constraints (Rohde et al., 2019) and even then, the user may learn a solution far from the one with minimum norm.

A simple way to speed up the process is to steer the interface toward finding a better low-dimensional approximation of the user's input covariance. We can then reformulate Equation (11) to iteratively update the orthogonal components of the map to resemble the first eigenvectors of Σ_k:

$$\boldsymbol{b}_{k+1} = (1-\gamma)\,\boldsymbol{b}_k + \gamma\,\frac{\boldsymbol{q}_k\boldsymbol{q}_k^T}{\|\boldsymbol{b}_k\|}\boldsymbol{b}_k \tag{17}$$

TABLE 1 | Coadaptation.

Define: η, γ, K	
Initialize model parameters	$\Sigma_0 = \overline{\Sigma}$, $\mu_0 = \boldsymbol{0}$, $B_0 = [\boldsymbol{b}_{1,0}\|\boldsymbol{b}_{2,0}]$;
for k in [1, K], **do**:	
Draw an independent input:	$\boldsymbol{q}_k \sim \mathcal{N}\left(\boldsymbol{0}, \Sigma_k\right)$
Update the sample trajectory (Equation 13):	$\boldsymbol{s}_k = \alpha\boldsymbol{s}_k + \beta\boldsymbol{q}_k$
Project the data onto the map (Equation 1):	$p_k = B_k s_k$
Assign the reward (Equation 5):	$r_k = \frac{tr(\boldsymbol{p}_k\boldsymbol{p}_k^T)}{tr(\boldsymbol{s}_k\boldsymbol{s}_k)}$
Update user parameters (Equation 11):	$w_{k+1} \leftarrow (1-\eta r_k)\,\boldsymbol{w}_k + \eta r_k f(s_k, \boldsymbol{w}_k)$
Compute eigenvectors and eigenvalues:	$\boldsymbol{v}_{k+1} = \boldsymbol{w}_{k+1} / \|\boldsymbol{w}_{k+1}\|$; $\lambda_{k+1} = \|\boldsymbol{w}_{k+1}\|$;
Compute regularized variance (Equation 14):	$\hat{\Lambda}_{k+1} = diag(\|\boldsymbol{\lambda_k} + \boldsymbol{\lambda_C} + \boldsymbol{z}\|)$
Update the generative model (Equation 8):	$\Sigma_{k+1} = V_{k+1}\hat{\boldsymbol{\Lambda}}_{k+1}V_{k+1}$
Update map parameters (Equation 17):	$\boldsymbol{b}_{k+1} \leftarrow (1-\gamma)\,\boldsymbol{b}_k + \gamma f(\boldsymbol{s}_k, \boldsymbol{b}_k)$
end for	

where $\boldsymbol{b}$ is the first column vector of B. The expression can be easily generalized to multiple orthogonal components but, for brevity, we let the reader refer to Weng et al. (2003) for a detailed formulation. Equation (17) in its form assumes that $\boldsymbol{q_k}$ comes from a distribution with zero mean. In the following, we will assume without loss of generality that this condition is true.

A Model for User-Interface Coadaptation

In this section, we provide a mathematical modeling of a user coupled with an adaptive interface. In the context of the proposed framework, both the user and the interface aim at maximizing the transfer between a user-generated input $\boldsymbol{q_k}$ and its low dimensional counterpart $\boldsymbol{p_k}$. However, the user follows a strategy driven by reward maximization, while the map simply tries to approximate the covariance of the user's generative process. The algorithm for implementing user-interface coadaptation is summarized in **Table 1**.

The ability of the joint system to converge to a solution largely depends on the choice of the learning rate parameters for the user and the map, η and γ. Previous theoretical work suggested that imbalanced learning rates are more likely to converge to a stable equilibrium (Igual et al., 2019) and that interface learning rates that are too high quickly lead the joint system to instability and prevent the user from adapting (Hahne et al., 2015; Müller et al., 2017). Tuning the learning rate of the interface to find the ideal trade-off between speed and stability is often impractical especially when the learning rate of the user is unknown. The simulations proposed in the next sections aim to contribute some theoretical guidance for implementing interface adaptation and the consequences of parameters choices on the joint system convergence that find direct application to body-machine interfaces.

TABLE 2 | User learning.

Define: $B, K = 10k$	
for n in [1,10], **do:**	
for η in *list*, **do**:	
Initialize model parameters	$\Sigma_0 = \overline{\Sigma}$, $\boldsymbol{\mu}_0 = \boldsymbol{0}$, $B_0 = [\boldsymbol{b}_{1,0} \mid \boldsymbol{b}_{2,0}]$;
for k in [1, K], **do**:	
Draw an independent input:	$\boldsymbol{q}_k \sim \mathcal{N}(\boldsymbol{0}, \Sigma_k)$
Update the sample trajectory (Equation 13):	$\boldsymbol{s}_k = \alpha \boldsymbol{s}_k + \beta \boldsymbol{q}_k$
Project the data onto the map (Equation 1):	$p_k = B_k s_k$
Assign the reward (Equation 5):	$r_k = \frac{tr(\boldsymbol{p}_k \boldsymbol{p}_k^T)}{tr(\boldsymbol{s}_k \boldsymbol{s}_k)}$
Update user parameters (Equation 11):	$w_{k+1} \leftarrow (1 - \eta r_k)\, \boldsymbol{w}_k + \eta r_k f(s_k, \boldsymbol{w}_k)$
end for	
end for	
end for	

SIMULATION SCENARIOS

In this section we analyze two scenarios in order of complexity. We first examine the simulated user behavior in relation to the choice of the learning parameter when interacting with a stationary interface. We also verify that our model is sufficient to explain experimental data. We then propose simulations to characterize the behavior of the joint user-interface system for a range of possible learning parameters.

Simulating a User Learning a Stationary Interface

As previously mentioned, we assume that the user can be assimilated to a generative process with zero mean and a non-stationary covariance matrix Σ that generates a sequence of dependent samples through the ARMA model in Equation (13). The dimensionality of the input data and the interface have been chosen to match the ones in our previous experimental study, where 10 individuals learned to control a 2D cursor moving their upper limbs (De Santis and Mussa-Ivaldi, 2020). In the study, participants first performed 60 s of random arm movements and then a reaching task with the interface. Each participant interacted with a customized interface, initialized to the first two eigenvectors extracted applying principal component analysis to the dataset of random motions.

Consequently, here the dimension of the user input was set to eight and the dimension of the feedback to two, leaving the simulated user with 6 redundant dimensions. The interface map B is 2×8 rectangular matrix and was chosen identical to the map the participant interacted with during the experiment. The user model covariance matrix was instead initialized using the first 60 s of sensor data recorded when the same subject first performed the reaching task.

We ran multiple simulations with 20 different values of learning rate logarithmically spaced between 10^{-4} and 10^{-1} over a 40k samples horizon, which roughly correspond to an experimental session of 10–15 min. Since the trajectory of the simulated user is dependent on the random sequence of samples that are generated, each simulation was repeated 20 times with different random seeds. The variance of the additive random noise term in Equation (14) was chosen to be 10^{-4}.

The simulation steps are summarized in **Table 2**.

We then asked whether the model was able to fit the actual user distribution parameters recorded during the reaching task. We modified **Table 2** to take as input a sequence of 40k samples from the experimental data rather than asking the model to generate its own. As the assumption of the data having zero mean does not hold in this case, we simulated a non-centered user model. Since in this condition the reward associated to each sample is predefined, the model's behavior is deterministic. Accordingly, the model was simulated only once for each learning rate.

Simulating User–Interface Coadaptation

In this scenario, both the user and the interface parameters are allowed to change following the steps described in **Table 1**. In order to simulate a more realistic condition, we implemented the user as a generative process that outputs statistically dependent data according to Equation (13).

We simulated all the possible combinations for the learning rate of both the user and the interface considering 20 log spaced values between 10^{-4} and 10^{-1}. Hence, we trained a total of 400 models over 40,000 iterations 20 times, each using different random seeds.

The interface map and the virtual user's distribution parameters were once again initialized using participant #S8 as a reference, to allow comparing the results across the different scenarios.

Performance Metrics

We computed three metrics to assess the evolution of the user covariance manifold in relation to the interface map across samples. These metrics are commonly used to assess user learning in body-machine interfaces as well as other redundant control tasks (Ranganathan et al., 2014; Thorp et al., 2017; De Santis et al., 2018).

1. Planarity: quantifies the amount of variance that the simulated user distributes in two dimensions. If the user is effectively learning to maximize the reward over time (that is amount of data that project onto the potent space of the map) we expect the user to progressively reduce the probability of generating actions along the dimensions associated with a null feedback. Experimental data confirmed that body-machine interface users learn to increase planarity in a 2D task (Ranganathan et al., 2013, 2014; De Santis and Mussa-Ivaldi, 2020). Planarity varies between 0 and 1 and is computed at each iteration from the variance of the user generative model as follows:

$$\frac{\lambda_{1,k} + \lambda_{2,k}}{tr\,(\Sigma_k)}$$

2. Subspace Angle [deg]: is a measure of angular distance between subspaces and is used here to quantify how close the user distribution is to the interface map. Two maximally tangent (parallel) subspaces will have a Subspace Angle close to 0 deg, while 90 deg indicated that the two subspaces are orthogonal and share a minimal projection. It is computed as the angle between the hyperplane described by the map and the hyperplane described by the first two principal component of variance extracted from the user distribution at each iteration:

$$\cos^{-1}\left(\left| B_k^T \cdot \left[V_{1,k}|V_{2,k}\right] \right|\right) \cdot 180/\pi$$

3. VAF: Variance Accounted For by the interface map, varies from 0 to 100% and quantifies the percentage of user covariance that is transferred to the feedback though the interface map. This metrics effectively encodes the average reward associated with the current user distribution and can be considered a measure of control efficiency. It is computed every iteration as:

$$\frac{tr(B_k \Sigma_k)}{tr\,(\Sigma_k)} \cdot 100$$

4. Rate of convergence [samples]: quantifies the number of iterations needed for the user to improve performance by 63% while converging toward a stable solution either independently or jointly with an adaptive interface. It is computed over the values of Subspace Angle between the user and the interface over training as the time constant of the single exponential function that yields the best least square fit to the data.

In order to evaluate the proposed metrics over the experimental data, the parameters of the covariance matrix through time were estimated using a sliding window of 3,000 samples (60 s of data) over the recorded data sequence.

RESULTS

Simulating a User Learning a Stationary Interface

Here we consider the effect of the choice of the learning rate parameter on the ability of a simulated user to maximize the expected reward over time when interacting with a static map ($\gamma = 0$). We will first consider the plausibility of our simplified model of user learning by testing its ability to emulate the performance metrics extracted by the experimental data recorded from 10 actual users of our previous study (De Santis and Mussa-Ivaldi, 2020). Then we will analyze the results obtained after training an array of 20 user models with varying learning rates to interact with a static interface.

Emulating a Real User

The generative portion of the model has been replaced by a sequence of experimental data and we evaluated the ability of the model to fit the performance metrics computed from the users' data.

Figure 3 summarizes the performance of the user model trained on data from 10 individuals controlling a body-machine interface with the upper limbs. **Figure 3**, panel A compares the average performance of the model over the 10 experimental datasets in terms of Root Mean Squared Error (RMSE) on Planarity and Subspace Angle metrics computed on simulated and experimental distributions and the average reward computed over the dataset given the interface map.

The model that achieved the minimum average RMSE on both metrics was found for $\eta = 0.0013$ which corresponded to an average error on Planarity of 0.0639 ± 0.028 and 12.35 ± 7.72 deg on the Subspace Angle (mean ± standard deviation).

The evolution of Planarity and Subspace Angle across iteration for all the 10 participants considered is depicted in **Figure 3**, Panel B, where the solid black lines represent the metrics computed from experimental data, while the colored line the metrics computed from the model's distribution with $\eta = 0.0013$. From the figure, we can see that the behavior across participants varies greatly, both in terms of the evolution of the distribution metrics and the reward computed a-posteriori on the data. Nevertheless, the model allows to closely follow the course of Planarity and Subspace Angle in time.

Simulating a Virtual User

After having verified the plausibility of our model, we simulated a virtual user in a body-machine interface scenario using the algorithm outlined in **Table 2** while varying the fixed component of the learning rate, the parameter η. We compared the impact of assuming that the user learns though a sequence of independent vs. dependent data inputs. **Figure 4** summarizes the results of the simulations.

Panels A and D show how the expected reward changes across iterations as a function of the user distribution and the interface map. The results show that assuming data to be dependent does not affect the course of Planarity of the generative model covariance. However, this assumption greatly impacts the distance between the model distribution and the interface

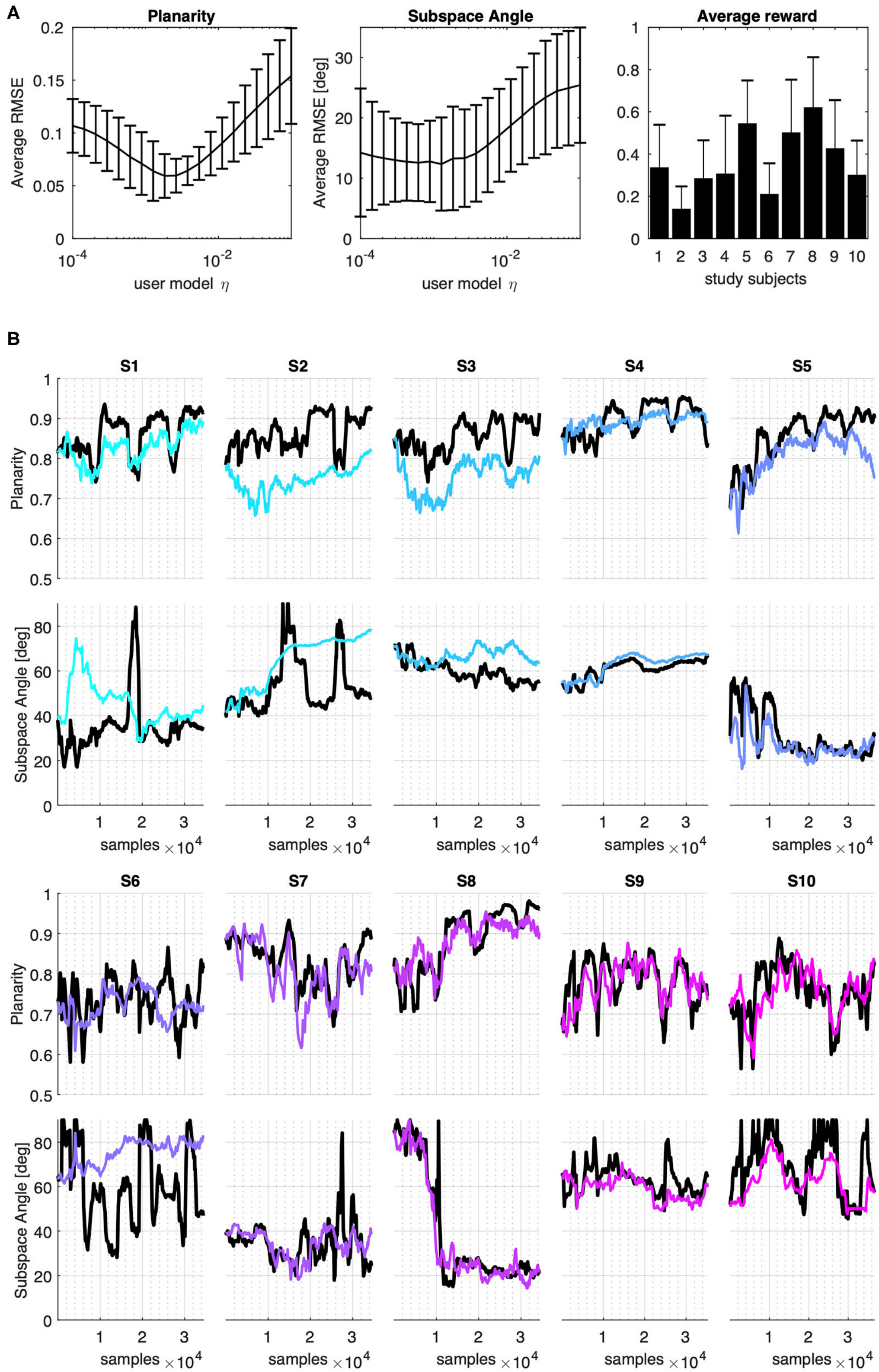

FIGURE 3 | Model prediction of experimental data. Planarity and Subspace Angle estimated from the data of 10 study participants from De Santis and Mussa-Ivaldi (2020) **(A)**: from left to right, average performance of the model vs. experimental datasets in terms of Root Mean Squared Error (RMSE) on Planarity and Subspace Angle metrics and the average reward computed over the dataset given the user interface map. **(B)** Model performance across iterations. Metrics computed on the experimental data are reported in black solid lines. Colored lines represent the values obtained from the data distribution generated iteratively by one out of 20 models with varying learning rates that have been trained with experimental data. The selected models in the figure have learning rate of 0.0013.

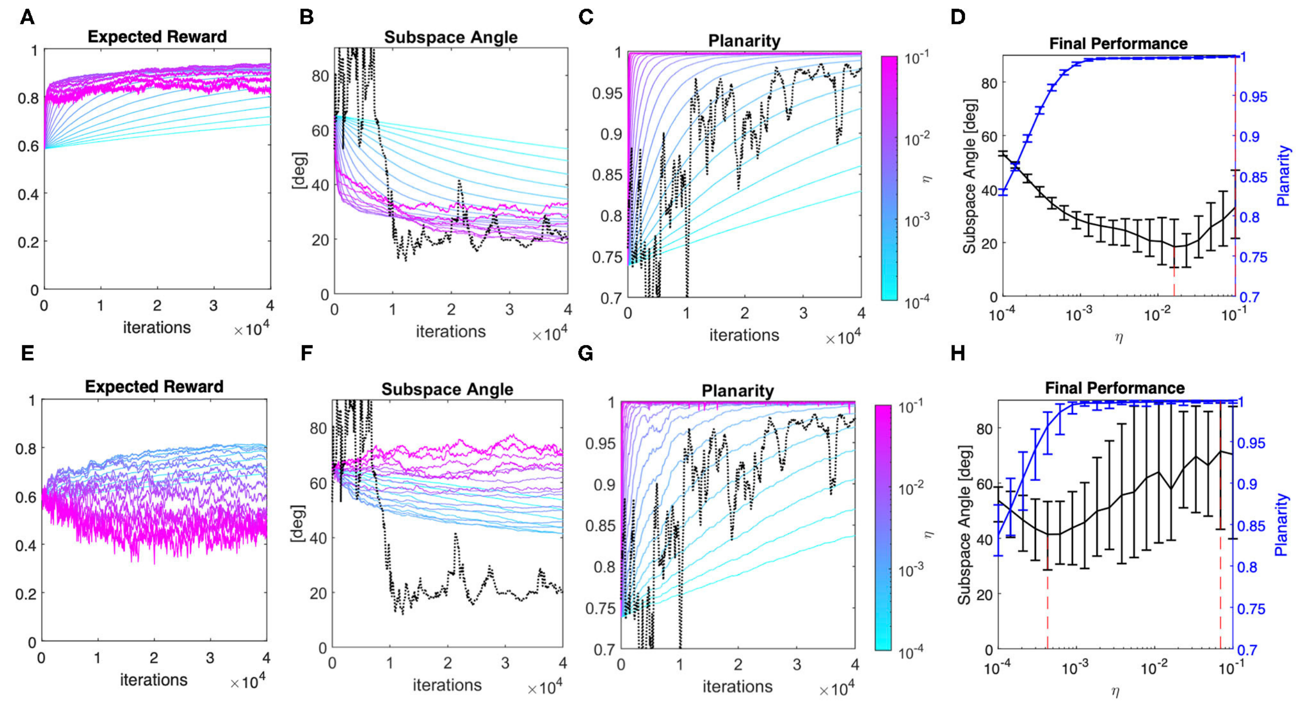

FIGURE 4 | User Model simulation: independent vs dependent data. Average expected reward, planarity, and subspace angle over 20 simulation runs of a model with varying learning rates generating a sequence of 40k independent (top row) or dependent (bottom row) data. Each model was simulated to evolve from the same initial condition as participant S8. **(A,E)** Expected reward computed over the generated sequences of independent and dependent data, respectively and averaged over the 20 simulation runs; **(B,F)** Subspace Angle between the 2D approximation of the simulated user's covariance and the interface map at each learning iteration for independent and dependent samples, respectively; **(C,G)** Planarity index computed from the simulated user's covariance matrix at each learning iteration for independent and dependent samples, respectively. The range of the learning rate parameter spanned an interval from to and the relative performance of the model is identified by a color that changes from light blue to pink for increasing learning rates, as indicated by the color bar. The dotted lines overlay the experimental metrics obtained from #S8, also reported in **Figure 3**; **(D,H)** summary of Planarity (blue line) vs. Subspace Angle (black line) obtained in the final 200 learning iterations at each learning rate in the case of independent and dependent samples, respectively. The solid lines represent the average value computed over the 20 simulation runs for each model, while the dispersion indicates the 95% confidence interval. The red dotted lines mark the best performing model for the two parameters considered.

map. As suggested by the difference in the values of Subspace Angle obtained in the case of independent (**Figure 4**, panel B) vs. dependent observations (**Figure 4**, panel E), random exploration leads to solutions that lie closer to the subspace identified by the interface map.

A first important observation is that the assumption that the data is independently distributed affects the relationship between the learning rate parameter and model convergence. From **Figure 4** (panels D and G) we notice that the range of values of the learning rate parameter that yield better final performance is reduced in the case of dependent data, with smaller learning rates leading to an overall better performance. In our simulations, the model that drew nearest to the subspace identified by the interface map was found for $\eta = 0.0162$ in the case of independent observations, and $\eta = 0.0004$ for dependent data sequences. Moreover, accounting for data dependency determined more than a 3-fold increase (3.2 ± 1.7) in the variability of the final solution across simulation runs (**Figure 4**, panels D vs. G).

This observation finds its counterpart in the experimental evidence that every user develops a unique solution to the interface control problem, as exemplified by **Figure 3**, Panel B. In fact, given a same model starting from the same initial condition, divergent results can be obtained for different data sequences. This can be seen comparing the results obtained for the two sequences of user's playback and simulated data in **Figures 3**, **4** and from **Supplementary Video 1**, that shows the complete evolution of VAF, Planarity, and Subspace Angle in each of the 20 simulation runs as the learning rate of the user increases from 10^{-4} to 10^{-1}.

In summary, these results suggests that (i) the particular solution an interface user may converge to depends strictly on the patterns of input covariance generated during learning and that (ii) it is virtually impossible to accurately predict the learning trajectory of an interface user unless the exact sequence of control actions is known.

Simulating User-Interface Coadaptation

This section summarizes the results obtained simulating a set of user-interface dyads with different combinations of the respective learning rate parameters η and γ. Here we assumed that the user generates a sequence of dependent inputs, and both the

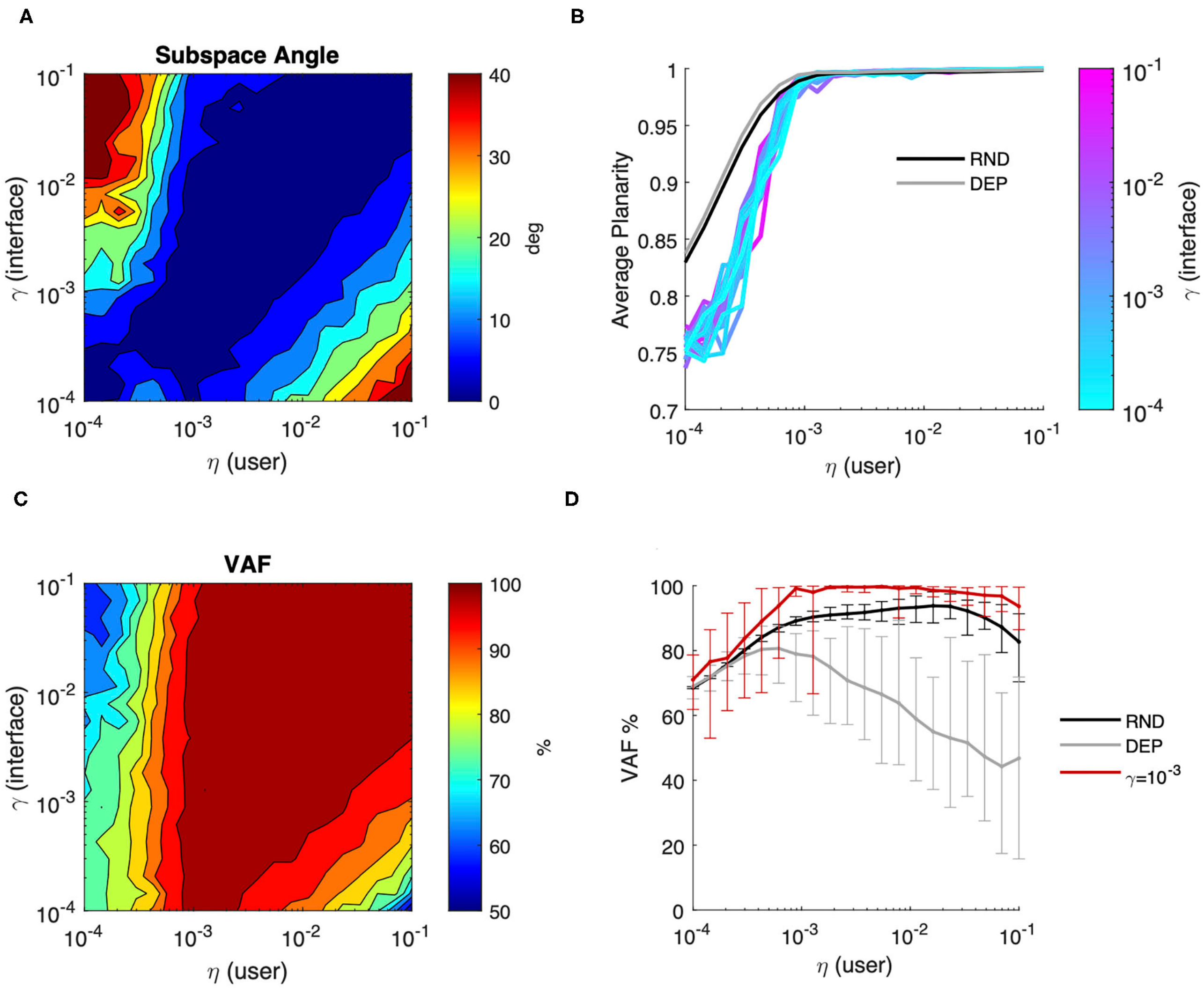

FIGURE 5 | User-interface joint performance after co-adaptation. Final performance computed as the average value over the final 200 iterations of joint learning across all combinations of user (η) and interface (γ) rates of adaptation; **(A)** average Subspace Angle between the maximum variance 2D approximation of the user's covariance and the interface map. Levels indicate steps of 5 degrees; **(B)** average Planarity (colored lines). The x-axis represents the learning rate of the user, while the color represents the interface adaptation rate. The gray and black lines represent the final Planarity obtained in the case of user learning with dependent and independent samples, respectively; **(C)** average Variance Accounted For by the interface map. Levels indicate steps of 5%; **(D)** comparison of the average percentage of variance accounted for by the interface for different degrees of user learning in the case of a static interface and independent samples (RND—black line) or dependent samples (DEP—gray line) and after interface coadaptation with $\gamma = 10^{-3}$ (red line). The error bars represent the 95% confidence interval over 20 simulation runs.

user and the interface adapt their parameters every iteration step. The interface's goal is to minimize information loss and the user's implicit objective is to maximize the expected reward over time through action reinforcement. Results obtained during co-adaptation are contrasted with simulation results of user learning with dependent and independent data sequences but without interface adaptation in terms of (i) final performance (**Figure 5**) and (ii) the evolution of the solution over time (**Figures 7**, **8**).

Figure 5 summarizes the final performance of the user model relative to the interface as a function of the learning rate of the two processes and provides a visual comparison between the performance achieved by user learning alone and by user-interface co-adaptation. As we can see from **Figure 5**—panel A, in the end of the simulation the user model and the adaptive interface learn to encode very similar subspaces for a broad combination of user/interface learning rates. In general, the best performance was achieved when the user and the interface adopted comparable learning rates ($\eta_i = \gamma_i$: 0.87 ± 2.0 deg), while the least favorable conditions occurred when a fast-adapting interface ($\gamma \geq 10^{-2}$) was combined with a very slow learner ($\eta < 10^{-3}$) and whenever a very fast learner was paired with a slow-adapting interface. Notably, co-adaptation

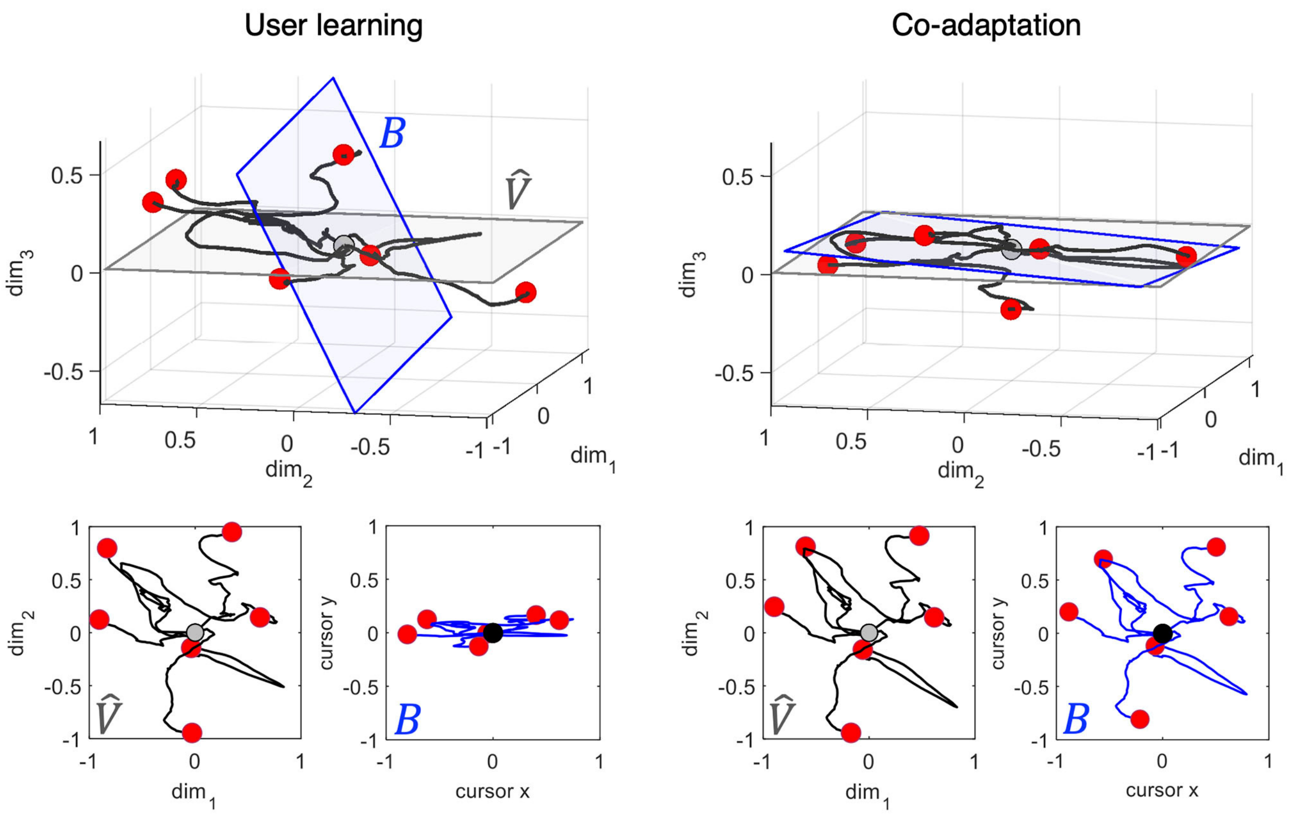

FIGURE 6 | Control efficiency after user learning vs. co-adaptation. Projection of six simulated smooth trajectories in the 8D space of the sensors into (top panels) the first three eigenvectors of the user model movement distribution, (bottom panels) the first two eigenvectors of the user model movement distribution and the corresponding 2D cursor movement at iteration 1000. The user model was trained with $\eta = 0.0013$ in both conditions, while the interface had $\gamma = 0$ in the user learning condition, and $\gamma = 0.0013$ during co-adaptation. The trajectories in body space are depicted in black, while the corresponding cursor trajectories are depicted in blue. All trajectories start from the origin. Red circles denote the end of a trajectory (the equivalent of a target point). The blue hyperplane B represents the subspace of the cursor coordinates defined by the interface map, the gray hyperplane represents the subspace spanned by the first two components of body movement variance ($\hat{V}$). The subspace angle between B and $\hat{V}$ was 69.12 deg in the User Learning condition and 21.79 deg in the Co-learning condition at iteration 1000.

yielded considerably smaller Subspace Angle on average (11.5 ± 12.6 deg) compared to a user learning through dependent data sequences for any combination of learning rates (≥40 deg on average, see **Figure 4**—panel G).

Contrarily to the distance between subspaces, Planarity of the user's generative model (**Figure 5**—panel B) was not dependent on the rate of model adaptation. Compared to the case of a user learning a static map, planarity during co-adaptation developed on average to a lesser extent only for very slow learning rates ($\eta < 0.0005$).

The global effect of co-adaptation on the control efficiency in terms of Variance Accounted for by the interface is summarized in **Figure 5**—panel C, while panel D compares the control efficiency during no map adaptation vs. $\gamma = 10^{-3}$. The figures show that even a relatively small degree of interface co-adaptation significantly improves the VAF compared to user's solo learning. More in general, we observe that co-adaptation yields a variance accounted for by interface map of 90% on average with the exception of user-interface dyads composed of very slow learners. This latter point should not be surprising, given that slow learners paired with a sufficiently slow-adapting interface can learn to accurately approximate the subspace spanned by the interface map, but are unable to sufficiently minimize variance in non-relevant dimensions, as shown by low levels of distribution Planarity.

Figure 6 provides an intuition of the impact of user-interface co-adaptation on control efficiency when controlling a 2D cursor through the body-machine interface. We simulated a set of six smooth trajectories in the 8D space of the sensors, that we call body trajectories. These trajectories were then mapped into 2D cursor trajectories by the interface map B. For the sake of visualization, we limit ourselves to consider the 3D subspace spanned by the first three components the body movement at a certain iteration k [the projection of the body movement along $(\mathbf{v}_{1,k}, \mathbf{v}_{2,k}, \mathbf{v}_{3,k})$]. This subspace is depicted in the top panels of **Figure 6**. The blue hyperplane B represents the subspace of the cursor coordinates defined by the interface map, the gray hyperplane represents the subspace spanned by the first two components of body movement variance ($\hat{V}$). The two planes correspond to B and $\hat{V}$ computed at $k = 1000$ from a model

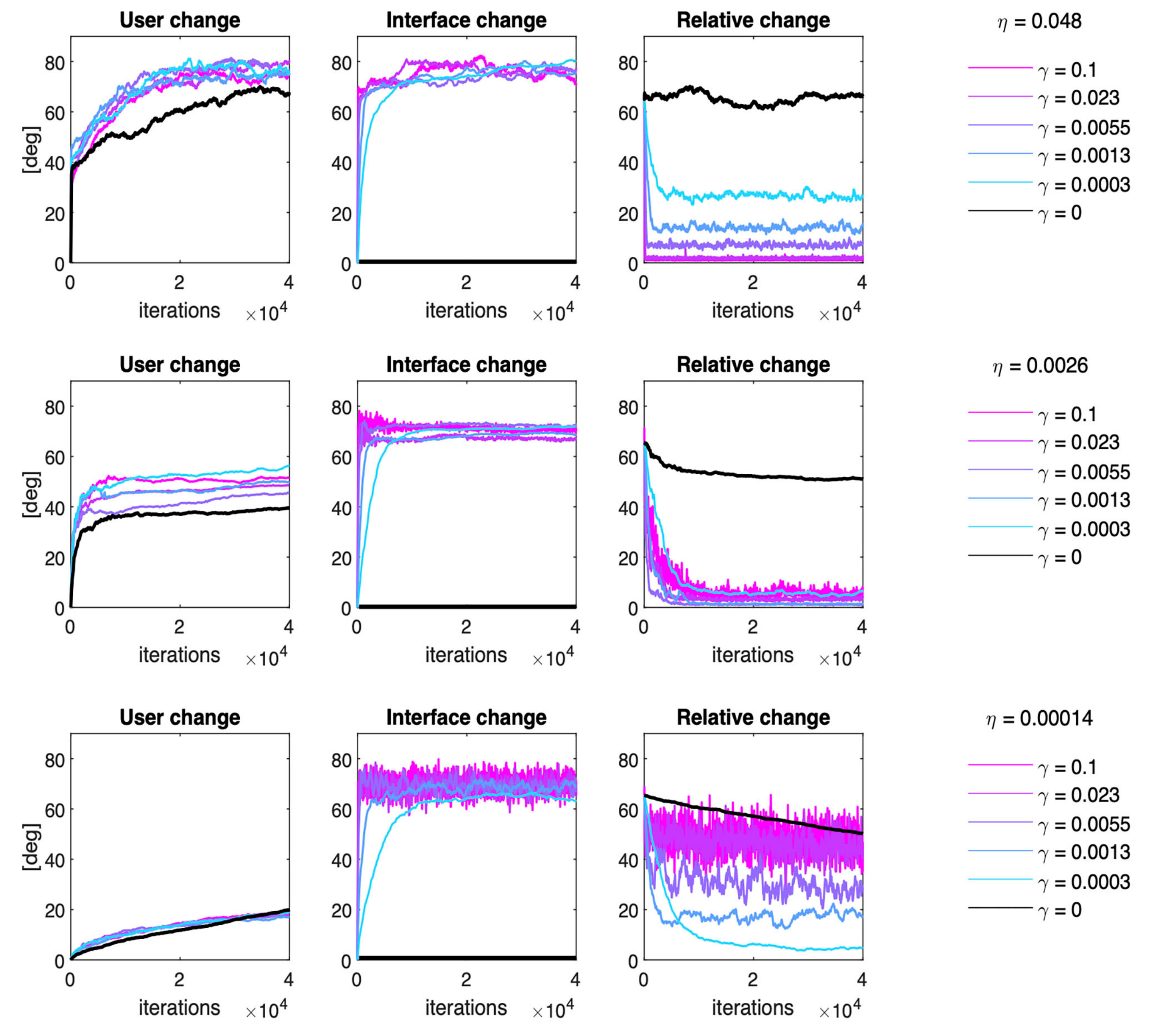

FIGURE 7 | Co-adaptation: examples of user and interface evolution though time. Effect of six different interface adaptation rates on the Subspace Angle of the simulated users relative to the initial condition (leftmost column), of the interface relative to the initial condition (middle columns) and the relative angle between the interface and the user at each training iteration (rightmost column). The effect of co-adaptation has been exemplified here for a slow-learning user ($\eta = 0.00014$, bottom row), a user with intermediate learning rate ($\eta = 0.0026$, middle row), and a fast-learning user ($\eta = 0.048$, top row).

of a user learning with $\eta = 0.0013$ vs. a model of user-interface co-adaptation with $\eta = \gamma = 0.0013$. The six body trajectories are shown in black starting from the center (gray circle) and ending each in a red circle. The bottom panels show the projection of the body trajectories on $\hat{V}$ (in gray) and on B (in blue). As previously noted, user-interface co-adaptation allows maximizing the amount of movement that projects into cursor displacements compared to user learning, yielding to a minimal distortion between the intended and perceived trajectory. The subspace angle between B and $\hat{V}$ was 69.12 deg in the User Learning condition and 21.79 deg in the Co-learning condition at iteration 1000. The figure shows how coadaptation can be advantageous from the standpoint of interface controllability already early in the traning.

Figure 7 provides a series of examples regarding the effect of co-adaptation on the average time course of the Subspace Angle between the user and the interface over training iterations. Three main points should be highlighted.

Firstly, interface co-adaptation does not eliminate the need for user learning. In fact, **Figure 7** (left column) shows that amount of change in the 2D subspace containing most variance of user input induced by learning is generally greater when the user interacts with an adaptive interface (colored lines), rather than a static interface (black line).

Secondly, user-interface co-adaptation yields better performance than user learning alone, as the relative distance tends to zero for suitable choices of interface adaptation rate (**Figure 6**, right column). In particular, adaptation rates that are too small tend to steer the system toward sub-optimal solutions (e.g., in the case of $\eta = 0.048$ and $\gamma = 0.0003$). Whereas adaptation rates that are too high induce not only suboptimal convergence, but also instability in the joint solution as the variability in the relative angular change grows proportionally with γ (e.g., in the case of $\eta = 0.00014$ and $\gamma > 0.0003$).

Lastly, the particular choice of γ seems to have a very marginal influence on the amount of change in the interface map compared to the initial condition (**Figure 7**, middle column). A two-way ANOVA considering the user and interfaces learning rates as independent factors over the 20 independent runs found that the amount of interface change is heavily dependent on the learning rate of the user [$F_{(19,\ 7600)} = 44.29$, $p << 0.001$], with greater change induced by faster-learning users (about 10 degrees more than slower users). The effect of the interface change is more marginal [$F_{(19,\ 7600)} = 2.14$, $p = 0.003$] mostly due to the high variability across repetitions, as a *post-hoc* test with Bonferroni correction only identified one significant comparison at the significance level of 0.01 ($\gamma = 0.0001$ *vs.* $\gamma = 0.0055$). No effect of the interaction between user and interface learning rates was found [$F_{(361,\ 7600)} = 1.05$, $p = 0.233$].

Finally, **Figure 8** summarizes the effect of co-adaptation on the speed of convergence of the user-interface dyad compared to a user interacting with static interface. Panel A highlights the combined effect of the user and the interface in determining the time constant for convergence to a negotiated solution in the co-adaptation scenario. Fastest convergence is achieved when the interface adapts as fast as the user does. Interestingly, the figure suggests that interface adaptation values in the interval $0.0006 < \gamma < 0.0026$ can yield to a reasonably fast convergence even in the case of very slow learners. Indeed, **Figure 8**—panel B clearly shows that interface adaptation allows reducing time to convergence compared to a static map condition consistently over the whole range of user learning rates.

Taken together, these systematic results provide an empirical evidence that co-adaptive interfaces can guide the user toward discovering more efficient solutions to the interface control problem.

DISCUSSION

This work introduced a mathematical framework for studying co-adaptation in body-machine interfaces that emphasizes the role of user's learning in shaping the interaction with an adaptive interface. The framework formulates co-adaptation in a task-independent and model-free way assuming that the user and the interface co-adapt toward maximizing control efficiency.

The generality of this novel framework can be exploited to simulate a variety of interaction scenarios, as knowledge of user intent or task goals is not required, it allows investigating the parameters leading to optimal co-adaptation dynamics and allows to empirically demonstrate the superiority of co-adaptation over user adaptation.

In the next sections, we will discuss the potential implications of our assumptions about user learning, what general recommendations for choosing the interface adaptation rate can be derived from our analysis, and finally how the framework could be generalized beyond the context of body-machine interfaces and what the possible limitations of the proposed formulation are.

What Can a Simple User Model Tell Us?

The starting point of our reasoning lies in the search for a suitable strategy in the context of learning in redundant environments (Newell and Vaillancourt, 2001; Ranganathan et al., 2013; Pacheco et al., 2019). It has been suggested that the earliest stages of learning a new skill are primarily reliant on mechanisms of exploration and reinforcement (Bernardi et al., 2015), whereas model-based learning requires a pre-existing internal representation of the environment the user is interacting with (Huang et al., 2011). When a first-time user is faced with the problem of controlling an external object through an interface, the need to attain task goals is blurred by the need to identify a suitable way to transfer intended commands to the object, in other words, to discover the causality of the interface as a "tool" (Maravita and Iriki, 2004).

Hence, we postulated a division of roles between the half of the user that aims at optimizing task performance and the half that aims to build a sensorimotor representation of the interface (Di Pino et al., 2014; Bernardi et al., 2015). Here we addressed how to model the second problem, reducing the first problem to its observable consequences. In particular, instead of modeling the process of generating reaching movements toward a target in the task space, we resolved to reproducing the observable traces of a reaching command—a trajectory of statistically dependent points. Then, we assumed that the problem of learning to interact with the interface successfully—that does not imply optimally or efficiently—could be solved by a model-free mechanism relying on reinforcement of successful actions through a process of trial and error (Huang et al., 2011; Sutton and Barto, 2018). The process results in the consolidation of memories through use-dependent plasticity (Krutky and Perreault, 2005; Diedrichsen et al., 2010). We are aware that this interpretation is fairly simplified, as multiple model-free and model-based mechanisms are likely contributing jointly to skill acquisition (Dingwell et al., 2002; Pierella et al., 2019). Nevertheless, we asked whether this simplified vision could be sufficient to reproduce features of skill learning expressed when interacting for the first time with a redundant tool in the form of a body-machine interface.

The results of our simulations suggest that this simplified model is indeed able to faithfully represent the emergence of a stable subspace of actions that result from the interaction with the interface. Interestingly, our model was also able to reproduce another feature of learning, that is the emergence of individual strategies as a function of the trajectory of actions generated during learning (Pacheco et al., 2019). When the model was trained on experimentally observed sequences of data, it

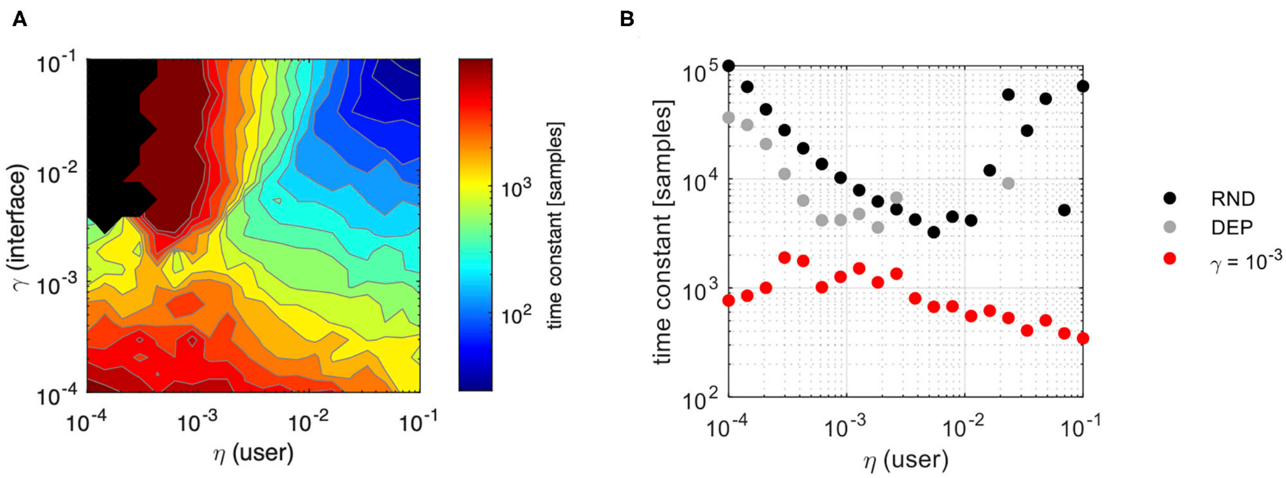

FIGURE 8 | Convergence analysis. Estimated convergence rate from exponential fitting of Subspace Angle values over iterations for different combinations of user and interface rates of adaptation; **(A)** estimated time constant to convergence for Subspace Angle during co-adaptation. Only values for which the goodness of fit $R^2 \geq 0.40$ have been included (black regions correspond to missing data); **(B)** comparison between the estimated time constants for different degrees of user learning in the case of a static interface and independent samples (RND—black line) or dependent samples (DEP—gray line) and after interface coadaptation with $\gamma = 10^{-3}$ (red line). Again, only values for which $R^2 \geq 0.40$ have been reported.

exhibited a similar trajectory as the individual the data was produced from. Variability in model solutions across multiple simulation runs was a direct consequence of assuming that the user explores the available action space through a sequence of dependent observations. Variability became irrelevant when the simulated user was given the possibility to sample the action space through independent observations. Moreover, learning with dependent action sequences made the model more likely to converge to sub-optimal solutions from the point of view of control efficiency, a tendency also observed in practice (De Santis and Mussa-Ivaldi, 2020). This result has important practical implications for the design and interpretation of studies involving sensorimotor learning, as it highlights how the simple choice of target locations in the workspace may implicitly bias the subject's behavior (Rohde et al., 2019).

How to Choose the Learning Rate for Optimal Co-adaptation?

Before answering, we should first ponder another question, that is "what should be considered optimal in co-adaptation?" For some, co-adaptation was successful if it could lead to improving control performance in a specific task (Orsborn et al., 2012; Hahne et al., 2015; Abu-Rmileh et al., 2019). For others, optimal co-adaptation was able to return performance to the baseline level after compensating for interface instabilities (Jarosiewicz et al., 2015; Kao et al., 2017). Here, we suggest that co-adaptation is optimal if it maximizes control efficiency. In this sense, the unsupervised paradigm for interface adaptation proposed here, was successfully applied in two studies, the first implementing a linear interface as described in this work (De Santis et al., 2018) and the second using a non-linear interface implemented through an autoencoder network (Rizzoglio et al., 2021). In the latter, co-adaptation led to both an increase in control efficiency and an improvement in performance during a reaching task.

Our simulations predict that for a same user (i.e., a model characterized by a certain learning rate and initial condition) co-adaptation leads to greater control efficiency than what the user would have otherwise attained and allows reaching a stable equilibrium faster. We found that, for a given user learning rate, interface efficiency could be maximized for a relatively broad range of interface adaptation rates. However, choosing an adaptation rate similar to the time scale of user learning would lead to the best performance, both in terms of steady state solution and in terms of stability. This result seems to disagree with that of Igual et al. (2019), where imbalanced learning rates between the adaptive myoelectric controller and the user were found more likely to drive convergence to a stable equilibrium in a reaching task. Simulation results within our framework also suggest that interface adaptation should be chosen conservatively small rather than too large. In fact, adaptation rates that are smaller than the user learning rate still lead to improvements in control efficiency at the cost of a slightly slower convergence and possibly to suboptimal solutions, while larger learning rates tend to introduce instability in the solution and inhibit joint adaptation, in agreement with the results of Hahne et al. (2015) and Müller et al. (2017). From the simulations carried out here, a value of interface adaptation rate close to 10^{-3} seems to be the recommended conservative choice. Indeed, this value is close to the empirical choice for the adaptation rate of the interface ($\eta = 0.002$) tested in De Santis et al. (2018), and the value of 0.005 identified as optimal in the tests performed in Hahne et al. (2015).

One point should be stressed. Interface co-adaptation is a viable way to optimize interface control, but it does not eliminate the need for user learning. Plug-and-play interfaces (Silversmith et al., 2020) are only applicable whenever a stable action subspace (or neural manifold) for a certain task has formed through repeated exposure to the interface.

Framework Generalizability and Limitations

One of the main features of the proposed framework is that it allows framing co-adaptation in a context that is task independent. However, we believe this should not hinder its application to instances when task goals and dynamics are well-known and/or can be modeled. In fact, the user generative model described here could be replaced with a model that select actions in a task-dependent or goal-oriented way. It could potentially be further expanded to account for the role of error-based and/or model-based mechanisms in determining the sequence of actions and corrections the user produces in response to the feedback from the interface and the task goals or constraints.

In this way, the framework could be exploited to study the effect of co-adaptation in the interaction between the user and the interface in specific tasks, as for instance during reaching, or in response to other design factors, such as the position and sequence of the reaching targets.

The other distinctive trait that increases the applicability of the framework is that interface adaptation in unsupervised, does not require any optimization routine, and can be run in real-time. The proposed interface is particularly well-suited for applications that make use of the statistics of the user's input to encode a lower dimensional space in which movement of the external device occurs, such as body-machine interfaces. However, supervised approaches are far more popular in brain computer interfaces where the decoder is trained to recognize motor intention. We believe that these two formulations are not incompatible, rather they can take advantage of each other's strengths. Stable decoders rely on the existence of consolidated patterns of brain activity, often referred to as neural manifolds (Gallego et al., 2017, 2020). Unsupervised adaptive approaches for subspace estimation in non-stationary situations could be applied to identify emergent patterns of brain activity concurrent to interface use upon which the decoder could be built. Degenhart and colleagues proposed a very similar concept to stabilize a brain-machine interface across days, with the difference that their approach relied on the existence of an already consolidated neural manifold (Degenhart et al., 2020).

One possible limitation to the proposed framework is that the analysis has been carried out for a user interacting with a linear interface, whose representational power may be limited when the input distribution presents considerable non-linearities (Portnova-Fahreeva et al., 2020). In a recent work (Rizzoglio et al., 2021) we proposed an implementation of a co-adaptive interface that makes use of an iteratively trained autoencoder network (Kramer, 1991) to perform unsupervised dimensionality reduction as opposed to standard principal components analysis. Hence, we believe the framework could be easily generalized to implement non-linear dimensionality reduction for manifold estimation and future work should investigate whether the conclusions drawn here still apply to non-linear interfaces.

A second limitation is that our approach does not allow considering the effects of interface adaptation on the explicit components of motor planning and on the engagement of model-based mechanisms in response to altered feedback. It is indeed possible that changes in the interface map introduce variability in the sensory feedback and further inconsistencies that negatively affect the performance in the task, triggering other mechanisms of adaptation (e.g., error-based). This phenomenon may be amplified whenever the learning rate imbalance triggers instability in the interface map. For an appropriate choice of learning rates, this effect is expected to rapidly disappear as soon as the system reaches an equilibrium.

Finally, as we have focused our investigation on the impact of co-adaptation on the convergence and stability of the system in the initial phases of learning, we have not specifically addressed the problem of stability over a long period of time. Nevertheless, the results from simulations foster the idea that the joint system reaches a point of equilibrium, suggesting that the solution could be stable over extended interaction despite the adaptive model having a constant learning rate. It is however possible that non-stationary adaptation rates for the interface may lead to further stability enhancement.

DATA AVAILABILITY STATEMENT

The data analyzed in this study is subject to the following licenses/restrictions: The code and the datasets generated and analyzed for this study are available from the corresponding author on reasonable request. Requests to access these datasets should be directed to Dalia De Santis, dalia.desantis@gmail.com.

AUTHOR CONTRIBUTIONS

DD conceived the work, formulated the model, carried out model simulations, data analysis and interpretation, drafted the manuscript, revised, and approved the submitted version.

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SUPPLEMENTARY MATERIAL

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Prosthetic Embodiment and Body Image Changes in Patients Undergoing Bionic Reconstruction Following Brachial Plexus Injury

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Brachial plexus injuries with multiple-root involvement lead to severe and long-lasting impairments in the functionality and appearance of the affected upper extremity. In cases, where biologic reconstruction of hand and arm function is not possible, bionic reconstruction may be considered as a viable clinical option. Bionic reconstruction, through a careful combination of surgical augmentation, amputation, and prosthetic substitution of the functionless hand, has been shown to achieve substantial improvements in function and quality of life. However, it is known that long-term distortions in the body image are present in patients with severe nerve injury as well as in prosthetic users regardless of the level of function. To date, the body image of patients who voluntarily opted for elective amputation and prosthetic reconstruction has not been investigated. Moreover, the degree of embodiment of the prosthesis in these patients is unknown. We have conducted a longitudinal study evaluating changes of body image using the patient-reported Body Image Questionnaire 20 (BIQ-20) and a structured questionnaire about prosthetic embodiment. Six patients have been included. At follow up 2.5–5 years after intervention, a majority of patients reported better BIQ-20 scores including a less negative body evaluation (5 out of 6 patients) and higher vital body dynamics (4 out of 6 patients). Moreover, patients described a strong to moderate prosthesis embodiment. Interestingly, whether patients reported performing bimanual tasks together with the prosthetic hand or not, did not influence their perception of the prosthesis as a body part. In general, this group of patients undergoing prosthetic substitution after brachial plexus injury shows noticeable inter-individual differences. This indicates that the replacement of human anatomy with technology is not a straight-forward process perceived in the same way by everyone opting for it.

Keywords: brachial plexus injury, bionic reconstruction, human-machine interfaces, upper limb amputation, prosthesis, body image, embodiment/bodily experience

INTRODUCTION

Global brachial plexus injuries or lower root avulsions have a devastating impact on upper extremity function and quality of life of affected patients (Carlstedt, 2008; Franzblau and Chung, 2015), who are predominantly young male adults (Seddighi et al., 2016). Due to the loss of neural connectivity of the hand and arm, also referred to as "inner amputation," both muscle function and sensibility of the affected skin are permanently impaired. In severe cases, this leads to a complete loss of hand function (Franzblau et al., 2015). Traditional surgical procedures, such as nerve grafting, nerve transfers, tendon transfers and arthrodesis, may fail to restore full function, sensation, and comfort with appearance of the affected extremity (Terzis and Papakonstantinou, 2000). Aside from functional impairments and pain caused by the injury, negative psychological consequences of brachial plexus lesions and upper extremity nerve damage have been widely reported (Franzblau et al., 2014; Franzblau and Chung, 2015; Miller et al., 2016). Post-traumatic stress disorder, depression and reduced social participation commonly occur (Bailey et al., 2009; Franzblau et al., 2014). While the reasons for these consequences are several, the changed visual appearance of the upper extremity seems to be a main factor eventually leading to reduced participation in and avoidance of social gatherings. Indeed, recent studies suggest that up to two third of all brachial plexus injury patients do not accept the appearance of their often motionless hand and arm, which can eventually become stiff, cold, and atrophic as shown in **Figure 1** (Carlstedt, 2008; Franzblau et al., 2014). This aesthetic dissatisfaction and the distorted body image affect social life, resulting in the reduced willingness to participate in social activities, especially if these include meeting new people (Mancuso et al., 2015; Verma et al., 2019). In the authors' experience the situation over time tends to gradually worsen, often leaving patients and their immediate social environment frustrated. For selected patients where the aesthetics of the functionless hand is a main concern, radiocarpal and finger joint arthrodeses are an option for improving function, appearance, and quality of life (Giuffre et al., 2012).

In cases of multiple root injury where above mentioned biological treatment options fail to provide sufficient improvement or are not feasible, the recently introduced concept of bionic reconstruction has expanded the treatment possibilities (Aszmann et al., 2015; Maldonado et al., 2016). In this procedure, the functionless hand is amputated and substituted with a myoelectric prosthesis. A psychological and functional assessment before amputation ensure that patients understand the consequences of the procedure, have the cognitive and emotional prerequisites for decision making, and only receive the intervention if a good prosthetic outcome can be expected (Hruby et al., 2018; Sturma et al., 2018). Prior to amputation, surgical augmentation of the residual limb may be necessary, in order to improve the position of the arm and provide sufficient EMG signals for myoelectric control (Aszmann et al., 2015). While improvements in patients' hand function, quality of life, and perceived disability have been observed (Aszmann et al., 2015; Hruby et al., 2017, 2019a), the long-term impact on body image is still unknown. Furthermore, outcomes in terms of prosthetic embodiment in this unique patient group have not been investigated. These insights into patients' perceptions treated with the novel approach of bionic reconstruction are particularly interesting, given that they have voluntarily opted for an amputation and a prosthetic fitting, which is not the case for the majority of prosthetic users. Understanding the impact of bionic reconstruction on body image perception will thereby offer valuable insights for all fields in medicine where human body function is replaced by technological means.

Therefore, the aim of this study was to investigate the body image of patients after a severe multilevel brachial plexus injury, and to report long-term outcomes after prosthetic fitting, with particular focus on the embodiment of the fitted device.

MATERIALS AND METHODS

Participants

For the purpose of this study, six patients who underwent bionic reconstruction were recruited between the years 2015 to 2018. General inclusion criteria to undergo bionic reconstruction can be found elsewhere (Hruby et al., 2018). Exclusion criteria included injuries or co-morbidities of the central nervous system (CNS), untreated psychological disorders, and patients who had obtained useful hand function after biological reconstruction or who had regained any useful sensory function of the hand. Patient characteristics can be found in **Table 1**. All patients involved in this study suffered a traumatic multi-level brachial plexus injury, meeting both of the following conditions: (1) damage to upper and lower brachial plexus roots with clinically evident impairment of shoulder, elbow and hand function as well as (2) avulsion of multiple roots confirmed via imaging and/or surgical exploration. The amputation level was determined by the presence of EMG signals in the forearm and sufficient elbow function. In patients where no elbow flexion against resistance could be achieved by surgical means or training, and where no EMG signals could be generated in the forearm, an amputation level above the elbow was chosen to allow prosthetic function (Hruby et al., 2019a).

During the mandatory pre-surgical assessment, all patients mentioned limited hand function as well as aesthetic dissatisfaction as current problems they wished to ease with bionic reconstruction, with function being the dominant motivator. Four of them (P2, P3, P4, P6) also named shoulder pain and/or deafferentation pain as a factor currently limiting their quality of life. Three of the patients (P1, P4, P5) described their lame limb as "hindering" in daily life, and P1 and P5 explicitly expressed that they would even consider an amputation without prosthetic replacement. Understanding the limitations of myoelectric prostheses (such as the lack of sensory feedback, no use in wet surroundings, and function not comparable with a heathy human hand) was a requirement for elective amputation. While P2–5 only expected a moderate functional gain from the prosthesis, P1 expected a clear improvement

FIGURE 1 | Lateral view of the hands of two different patients after a brachial plexus avulsion, showing different degrees of atrophy and intrinsic stiffness.

and P6 originally had some unrealistic expectations that were lowered in discussions with the medical team.

This study was approved by the ethics committee of the Medical University of Vienna, Austria and was carried out in accordance with the standards set by the Declaration of Helsinki (World Medical Association, 2013). All patients provided written informed consent to participate in this study.

Study Design and Procedure

All included patients underwent bionic hand reconstruction according to the latest best practices (Hruby et al., 2017; Sturma et al., 2018). For each of the study participants, previous attempts to restore biological hand function had failed. These patients approached our team with the wish to have their hand replaced with a prosthetic device, or were referred by their

TABLE 1 | Characteristics of included patients.

Patient ID	Type of brachial plexus injury	Gender	Time between injury and intervention (years)	Age group at intervention	Time between intervention and long-term follow-up (years)	Level of amputation
P1	Postganglionic injury of C5-6, avulsion of C7, C8-T1 unclear without any clinical function	Male	7	15–24	2.5	Transradial
P2	Avulsion of C5-T1	Male	8.5	55–64	3.5	Transhumeral
P3	Postganglionic injury of upper roots, avulsion of C8-T1	Male	9	35–44	4	Transradial
P4	Postganglionic injury of upper roots, avulsion of roots C8-T1	Male	14	45–54	4.5	Transradial
P5	Postganglionic injury of C5, avulsion of C6-T1	Male	5	55–64	5	Transradial
P6	Postganglionic injury of C5 without any clinical function, avulsion of C6-T1	Male	21.5	35–44	5	Glenohumeral

All patients were male and had a brachial plexus injury with multiple root involvement. The presence of elbow flexion against resistance and EMG signals on the forearm was a requirement for an amputation below the elbow. The level of the above-elbow amputations was decided based on the patient's preferences and physical findings such as shoulder stability.

physicians. After the first clinical assessment, an experienced therapist (AS) aimed at identifying two independent surface electromyographic (sEMG) signals on the functionless arm. These were meant to provide control inputs for the myoelectric prosthesis following the potential amputation. In patients where no sEMG signals could be detected, free muscle and nerve transfers were considered in order to create an additional neural interface for prosthetic control (Aszmann et al., 2015). Upon appropriate identification of signals, their selective control and stable presentation was trained using biofeedback techniques (Hruby et al., 2019b). If there was an unstable shoulder or weak elbow function in patients with EMG signals on the forearm, this was trained as well. Also, grasp function was trained with a prosthetic device mounted on a table and on the functionless arm. In addition to training, this allowed patients to experience realistic prosthetic function before committing to the amputation procedure. The final decision to undergo elective amputation was made after a psychological assessment conducted by an experienced psychologist (AP) (Hruby et al., 2018). Patients who were deemed suitable and agreed to participate in the study, were asked to fill out the Body Image Questionnaire (BIQ-20), as well as a questionnaire regarding their disability in daily live (Disabilities of Arm Shoulder and Hand, DASH). Post-operatively patients were fitted with a standard myoelectric prosthesis within the first 3 months, and received further prosthetic training. 2.5–5 years after the intervention, patients were asked to repeat the BIQ-20 and the DASH, as well as to answer selected questions described below regarding the embodiment of their prosthetic limb. The study procedure is outlined in **Figure 2**.

Assessment Instruments

The participants' body image was evaluated using the Body Image Questionnaire 20 (BIQ-20; originally published in German as "Fragebogen zum Körperbild - FBK-20") (Clement and Löwe, 1996). The BIQ-20 is a validated 20-item questionnaire designed to evaluate body awareness and possible body image disorders. It consists of two independent scales, negative body evaluation and vital body dynamics. The first includes possible negative associations one might have with their physical appearance and associated well-being (e.g., "There is something wrong with my looks/appearance"). The scale for vital body dynamics summarizes how physically strong and healthy individuals describe themselves (e.g., "I am physically capable of doing many things") (Löwe and Clement, 1996). An improvement in the body image is thereby seen with a higher score in the vital body dynamics scale and a lower score in the negative body evaluation scale.

Furthermore, at follow-up, participants were asked to report how often they had been wearing their prosthesis within the week prior to the assessment. Moreover, they were presented with six statements related to the embodiment of their prosthesis and were asked to indicate to which extent they can relate to them:

1. "I had the feeling that the prosthesis was part of my body."
2. "I felt the prosthesis only as a tool, and not as a part of my body."
3. "I did bimanual tasks with my intact arm/hand together with my prosthesis."
4. "I felt that I had full control over the prosthesis."
5. "I liked wearing the prosthesis."
6. "I felt that my prosthesis looked like a real part of the body."

For all questions, participants were asked to rate their level of agreement on a Likert-scale from 0 (never) to 10 (always).

In order to understand how participants perceived functional changes in daily life, the patient-reported Disabilities of Arm Shoulder and Hand (DASH) questionnaire was used before and after elective amputation as a secondary outcome (Gummesson and Ekdahl, 2003). Based on the answers to 30 questions, a score from 0 (no functional impairment) to 100 was obtained, with a minimal clinically important difference suggested at 10.83 points (Franchignoni et al., 2014). As patients rate the difficulties they have in daily life - independent from the hand they use for completing tasks - the DASH needs to be seen as a widely-used general assessment instrument for upper limb function rather than an instrument to purely measure prosthetic function.

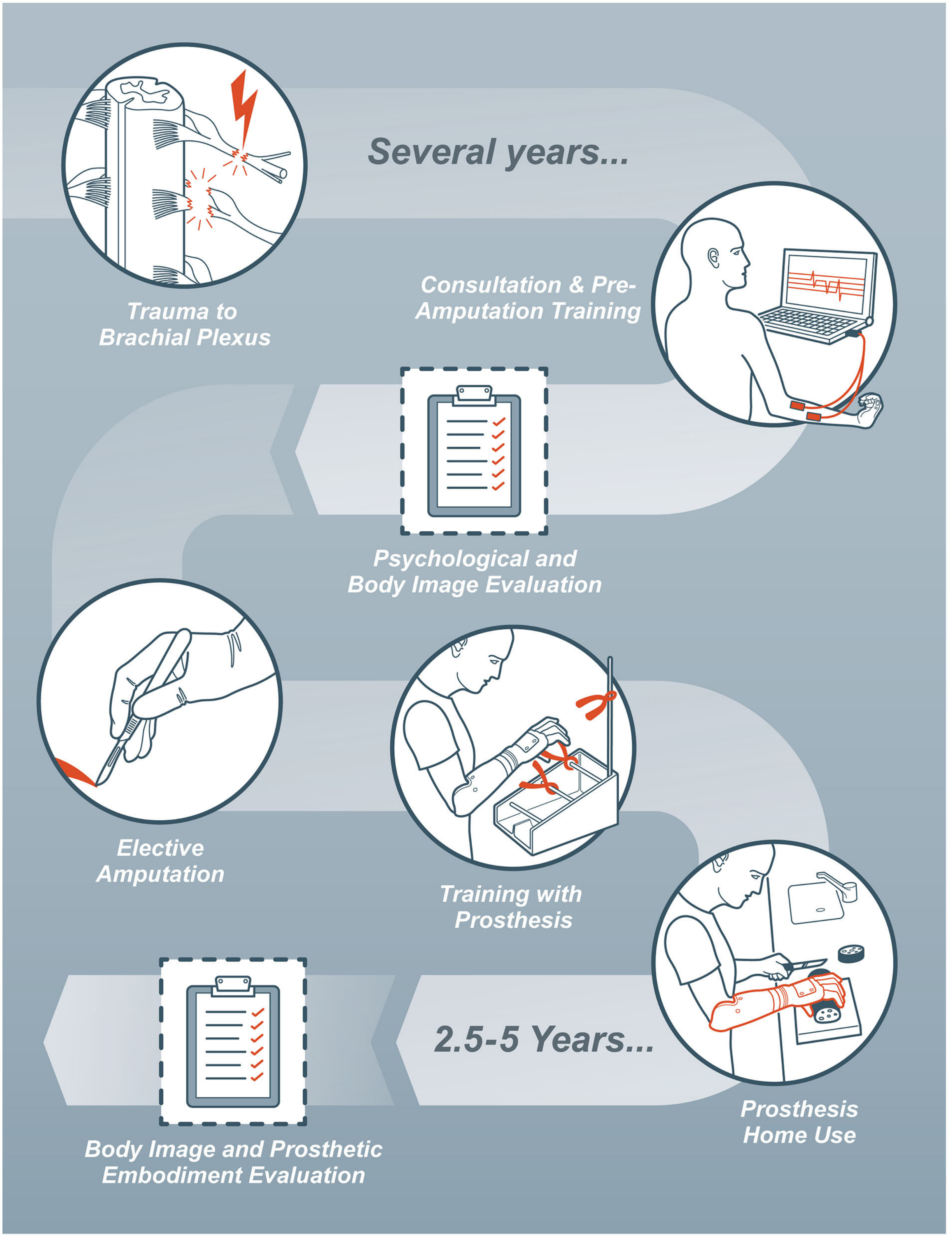

FIGURE 2 | Flowchart of the medical treatment process and assessments performed within this study.

TABLE 2 | DASH outcomes and BIQ-20 scores for negative body evaluation and vital body dynamics before and after elective amputation.

Patient ID	P 1	P 2	P 3	P 4	P 5	P 6
DASH score before the intervention	8.3	60	63.3	40.8	47.5	49.2
DASH score after the intervention	5	33.3	30.8	43.3	44.2	30
Negative body evaluation before the intervention	19	19	27*	42*	16	15
Negative body evaluation after the intervention	10	16	13	32*	18	12
Age-matched (Albani et al., 2006) mean value (SD) for negative body evaluation	18.3 (7.1)	19.1 (6.4)	19.0 (7.1)	19.0 (6.6)	19.1 (6.4)	19.0 (7.1)/ 19.0 (6.6)⌂
Vital body dynamics before the intervention	37	24*	35	33	26	43
Vital body dynamics after the intervention	40	28	27*	28	29	46
Age-matched (Albani et al., 2006) mean value (SD) for vital body dynamics	39.4 (6.7)	31.8 (7.3)	36.6 (6.8)	34.8 (7.0)	31.8 (7.3)	36.6 (6.8)/34.8 (7.0)⌂

Please consider that a lower score in the DASH questionnaire and BIQ-20 negative body evaluation is considered a better outcome, while the same is true for a higher value in the vital body dynamics score. An Asterik (*) indicates that the score is worse than the mean ± standard deviation (SD) of the age-matched norm. A blue background with white text in the scores after prosthetic fitting refers to an improvement compared to the assessment before amputation, while an orange background describes a higher value for negative body evaluation, or a lower value for vital body dynamics. ⌂P6 changed age group between baseline and follow up, with reference values for baseline and follow-up being reported.

Statistical Analysis

For all outcomes, explorative statistics were considered. Since the BIQ-20 delivers data on an ordinal scale, a Wilcoxon test with a significance level of $p < 0.05$ was used to assess differences between baseline and follow-up. Statistical analysis was performed using SPSS 26 (IBM, Armonk, NY, United States).

RESULTS

Body Image Questionnaire

The BIQ-20 scores for negative body evaluation and vital body dynamics pre- and post-bionic reconstruction are displayed in **Table 2**. The single item answers for every participant can be found in the **Supplementary Material**. As both parameters change with age, **Table 2** also presents the age-matched mean values for both scores as a reference. The values originate from a survey of a representative German sample population (n = 2,473) as described by Albani et al. (2006). The median value for negative body evaluation improved significantly ($p = 0.046$) from 19 (IQR 16.75–25) at baseline to 14.5 (IQR 12.25–17.5) at follow up with bionic reconstruction. No significant changes were found in vital body dynamics ($p = 0.916$), with a median value of 34 (IQR 27.75–36.5) before amputation and 28.5 (IQR 28–37.25) after prosthetic fitting.

Prosthetic Embodiment and Prosthesis Wearing Time

When asked about their prosthesis wearing time, three patients (P4, P5, and P6) reported to wear their prosthesis almost daily. One patient wore it every 2nd day (P3), one patient less than twice a week (P2), and one patient (P1) stated that he had not been wearing it within the last week. This patient clarified that he found it easier at work and home to use only his able hand in combination with the residual limb. Still, he enjoys wearing the prosthesis for social events.

The individual ratings of the patients regarding their prosthetic embodiment are displayed in **Figure 3**, and further summarized in the **Supplementary Material**. All patients partially or mostly agreed with the statement "I had the feeling that the prosthesis was part of my body" (IQR 5–6.75). Similar results were found for the statement "I felt I had full control over the prosthesis" (IQR 5–7.75). Big inter-individual differences were reported for the statements "I felt that the prosthesis looked like a part of the body" (IQR 3.25–8.5), "I liked wearing the prosthesis" (IQR 4.25–8.75), and "I felt the prosthesis only as a tool and not as a part of my body" (IQR 2–6.75). When asked whether they performed bimanual tasks with their able hand/arm together with their prosthesis, four of six patients rated this with "5," while the other two had lower ratings of 4 and 0 (IQR 4.25–5).

Disabilities of Arm Shoulder and Hand

DASH scores of all patients are reported in **Table 2**. The perceived hand and arm function improved in 5 of 6 participants, with a mean score of 44.9 ± 18.0 at baseline to 31.1 ± 13.0 at follow-up. This represents a clinically important difference (Franchignoni et al., 2014) overall, and a clinically important difference in 3 of 6 patients. The single item ratings for all patients can be found in the **Supplementary Material**.

DISCUSSION

Bionic reconstruction is a new technique to restore lost hand function in individuals with severe brachial plexus injuries. The procedure is only considered in patients, where no further improvement of upper limb function can be expected by conventional surgical means or rehabilitative measures (Aszmann et al., 2015). Time between injury and baseline assessment/amputation therefore ranged from 5 to 21.5 years. Thus, the baseline situation evaluated restrictions in body image and functional impairments in patients who have lived with a functionless upper extremity for several years or even decades. This leads to the assumption that they had sufficient time to adapt to the situation, resulting in a relatively stable baseline, which was not expected to change without further interventions. Similarly, at 2.5–5 year follow-up after bionic limb replacement we expected to identify long-lasting effects of bionic reconstruction on patients' body image, not influenced anymore by the initial excitement for the new prosthetic device.

While the evaluation of (prosthetic) hand function in these patients as reported elsewhere (Aszmann et al., 2015; Hruby et al., 2017, 2019a,b) was not an aim of this study,

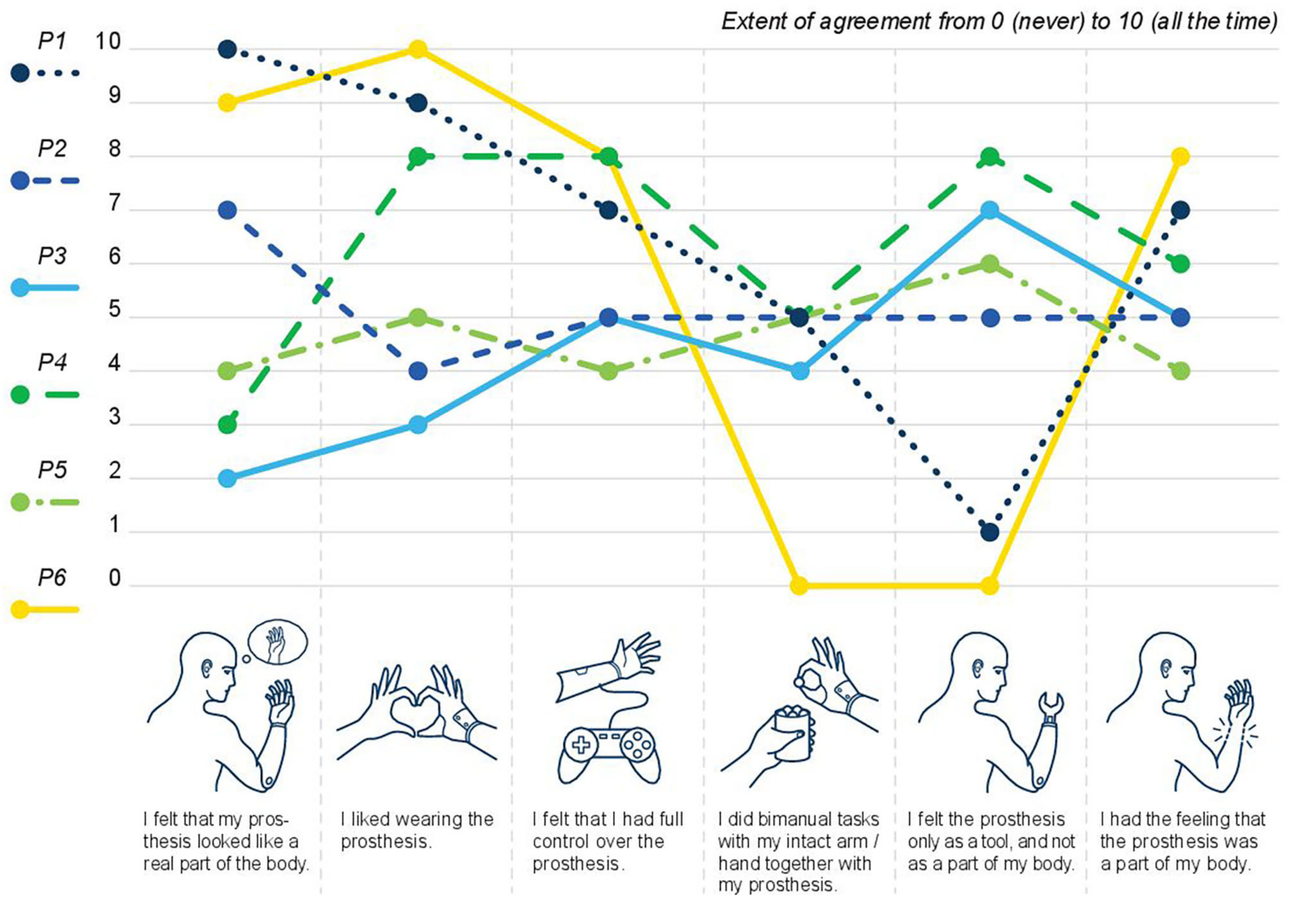

FIGURE 3 | Prosthetic embodiment after bionic reconstruction: the level of agreement from 0 (no agreement/never) to 10 (full agreement/always) is displayed per question and study participant.

the use of the DASH questionnaire allowed interpretation of body image changes related to hand function in daily life. Hereby, an overall improvement in perceived disability was observed, with five out of six participants reporting better DASH outcomes. Three of them had a clinically meaningful improvement, while no clinically relevant deterioration was reported. This led to the conclusion that perceived overall upper limb function improved with the prosthetic fitting or remained similar. Interestingly, the patient who showed a slightly worse DASH score at follow-up (mainly due to feeling slightly more disabled in some ADLs), also had a decline in *vital body dynamics* in the BIQ-20. In general, when comparing the single-item differences in the DASH score before and after amputation, an overall improvement in performing ADLs (as assessed in questions 1–21), with some inter-individual differences can be observed. DASH results for pain, stiffness and weakness in the remaining arm appear less uniform, with pain during activities even tending to increase after bionic reconstruction. This could be explained by remaining problems related to shoulder instability causing increased pain with the additional weight of the prosthesis and prolonged use of the arm.

In this regard, it is important to note that our study population still had mostly unchanged impairments regarding elbow and shoulder strength and range of motion after amputation. Also, an asymmetric body shape in the shoulder and upper arm area remained due to atrophic muscles still being present after elective amputation of the arm/hand and its bionic substitution. Therefore, the changes in body image observed in this study may primarily originate from the changed appearance of the hand – changing from a motionless atrophic appendix to a functional prosthetic limb. As summarized in **Table 2**, in five out of six patients *negative body evaluation* improved with bionic reconstruction, which was statistically significant. This means that it was easier for them to cope with their physical imperfections and that they had fewer negative associations with their body. The fact that modern prostheses resemble the appearance of a healthy hand more than an atrophic "plexus hand" (see **Figure 1**) might explain these results. Wearing a prosthesis might thereby reduce unwanted attention toward the appearance of the hand, which some of our patients described as bothersome and incriminating. Restoring cosmetic appearance has been described as an important factor for a positive body image and social comfort in amputees (Desteli et al., 2014). In line with this, a qualitative study in individuals with traumatic amputations has shown that having a prosthetic device helped them to minimize their sense of difference and was therefore perceived as very helpful in social situations (Saradjian et al., 2008). This social function of having a prosthesis was also verbalized by P1 who preferred not to use his prosthesis in daily life, but enjoyed wearing it at social gatherings. His otherwise limited use can be explained by the fact that the patient reported very little functional problems in daily life within the DASH questionnaire even before bionic reconstruction, resulting in a limited need for functional improvements with the prosthetic device. In line with this, five of six patients showed improvements or no changes with bionic reconstruction when asked whether their upper limb problems interfered with their social activities (question 22 in DASH). Three of them felt more capable or confident in relation to their upper limb impairment (question 30 in DASH), while the others had unchanged results.

In terms of prosthetic embodiment, major inter-individual differences were observed. For the statement "I felt the prosthesis only as a tool and not as a part of my body," two participants did not agree at all (rating of 0 and 1/10), while the others rated this statement with 5, 6, 7, and 8, respectively. As expected, ratings of each individual for the statement "I had the feeling that the prosthesis was part of my body" were inverted to these results, although intra-group differences were not articulated that explicitly. Notably, the two individuals (P1 and P6) who had the strongest perception that their prosthesis was not a mere tool, but rather a part of their body, also enjoyed wearing it and felt that it looked very real. They were feeling that they had good control over their prosthetic device. Additionally, these two individuals had the highest scores for vital body dynamics and the lowest scores for negative body evaluation. This is in line with previous research in lower limb amputees describing a negative relation between body image disturbance and prosthesis satisfaction (Murray and Fox, 2002). Also, the BIQ-20 outcome and the embodiment of the prosthesis did not seem to be determined by the amputation level in our cohort, given that P1 had a transradial amputation and P6 had a glenohumeral amputation. The two individuals who perceived their prosthesis as a tool rather than a hand (P3 and P4, both with a transradial amputation) described it as not looking real. Perceived control and how they liked wearing the prosthesis varied between these two individuals. When asked whether they performed bimanual tasks with their intact hand/arm together with their prosthesis, five of six patients rated this with "5" or "4," while P6 had a rating of "0." Here, it is contra-intuitive that this participant who strongly perceived his prosthesis as a body part does not seem to use it at all together with his healthy arm, which would be expected for a prosthesis being integrated in the body scheme. A speculative explanation for this might be that his pain increased after amputation when performing activities, which may be pain in the unstable shoulder. Together with the general high pain level and perception of the arm as stiff and weak (DASH questions 24–29), this might have prevented him from doing bimanual tasks.

When putting the motivations and expectations of patients before bionic reconstruction in context with the outcomes, an interesting finding is that the two individuals who had the highest expectations for prosthetic function (P1 and P6) had the best outcomes in the BIQ-20, as well as enjoyed wearing their prosthesis most and perceived it as a part of their body. This gives the impression of a self-fulfilling prophecy for these two, while making it unlikely that less embodiment of the prosthesis and less clear findings in the BIQ-20 in the other patients can be explained by their expectations not being met. In this regard, however, it needs to be noted that expectations management is part of our pre-surgical procedure, which ensures that every patient gets a realistic understanding of possibilities and limitations. Another interesting finding was that half of the patients perceived their "plexus arm" as bothersome and hindering in performing ADLs. Surprisingly, the two patients without any useful elbow function were not amongst them. While all patients aimed for improved function with a bionic prosthesis, it is possible that they would have also benefited from an amputation and fitting with a cosmetic device. Indeed, a retrospective study including nine patients with an elective amputation after pan-plexus injury who wore no or only a cosmetic prosthesis, still found satisfactory outcomes and reduced shoulder pain (Maldonado et al., 2016). Still, our study procedure included the aim for restoring active hand function, and is thus not suitable for the evaluation of possible benefits of amputation without a functional prosthetic fitting.

In summary, our findings regarding prosthetic embodiment indicate that each individual perceives their prosthesis in a unique way. This is also in line with a recent qualitative study that investigated prosthetic embodiment and psychosocial implications in three upper limb amputees with a bi-directional interface enabling feedback (Middleton and Ortiz-Catalan, 2020), who all described their prosthetic embodiment differently. Another recent study identified an improved prosthetic embodiment over time when using sensory feedback (Cuberovic et al., 2019). Therefore, it is hard to predict the possible impact of using a bi-directional interface for prosthetic control in our group of patients. Similarly, we are not able to state whether the reason for amputation (elective vs. traumatic amputation) changes the way a prosthesis is perceived regarding the body image of a person.

While this study is the first to give insights in the long-term body perception and prosthetic embodiment of people with bionic reconstruction after brachial plexus injury, the small sample size limits the scientific significance of our observations. The limited cohort size, however, results from the novelty of the approach and the very limited number of individuals receiving bionic reconstruction world-wide. Still, neither the sample size nor the study design allows definite conclusions on whether bionic reconstruction should be used for improving negative body evaluation in patients with brachial plexopathy.

Furthermore, given the highly elective nature of the procedure, the results cannot be generalized for the whole population of patients with severe brachial plexus injuries. Patients, who after careful deliberation opt for keeping their functionless and asensate hand, likely have completely different motivations compared to the population we studied. Reasons for not undergoing bionic reconstruction may include concerns regarding a changed appearance after amputation, or a less positive attitude regarding prosthetic devices. Future qualitative studies might be able to better describe the viewpoints and priorities of patients (Graczyk et al., 2019). Conducting interviews with patients undergoing bionic reconstruction or deciding against it, might further aid an in-depth understanding of beliefs, mental processes, expectations and body image concerns related to decision-making and how they influence outcomes. Expanding our understanding of this topic will be helpful to determine how individuals feel and cope with their anatomy being replaced by technological tools.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethikkommission der Medizinischen Universität Wien Borschkegasse 8b/E06 1090 Wien. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individuals for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

AS, LH, OA, and AP conceived and designed the study. AB, AS, LH, and CG performed the data acquisition. AB and AS analyzed the data. AS, IV, DF, and OP interpreted the data. AS, IV, LH, and CG had the main responsibility for writing the manuscript. All authors were involved in editing the manuscript and gave their final approval for publication.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnbot.2021.645261/full#supplementary-material

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Grasping Embodiment: Haptic Feedback for Artificial Limbs

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Upper-limb prostheses are subject to high rates of abandonment. Prosthesis abandonment is related to a reduced sense of embodiment, the sense of self-location, agency, and ownership that humans feel in relation to their bodies and body parts. If a prosthesis does not evoke a sense of embodiment, users are less likely to view them as useful and integrated with their bodies. Currently, visual feedback is the only option for most prosthesis users to account for their augmented activities. However, for activities of daily living, such as grasping actions, haptic feedback is critically important and may improve sense of embodiment. Therefore, we are investigating how converting natural haptic feedback from the prosthetic fingertips into vibrotactile feedback administered to another location on the body may allow participants to experience haptic feedback and if and how this experience affects embodiment. While we found no differences between our experimental manipulations of feedback type, we found evidence that embodiment was not negatively impacted when switching from natural feedback to proximal vibrotactile feedback. Proximal vibrotactile feedback should be further studied and considered when designing prostheses.

Keywords: sense of embodiment, upper-limb prostheses, prosthesis abandonment, vibrotactile feedback, rubber hand illusion paradigm

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INTRODUCTION

Despite decades of public and private research into the development of upper-limb prosthetics, a significant portion of individuals who are prescribed upper-limb prostheses become unwilling and subsequently opposed to wearing them—a problem known as prosthesis abandonment (Biddiss and Chau, 2007a). Even the most expensive category of prostheses, electric prostheses, was estimated in a large longitudinal study to have a rejection rate of 23% (Biddiss and Chau, 2007b), and by a more recent study to have a rejection rate off 18% (Resnik et al., 2020). One of the core issues resulting in prosthesis abandonment is a reduced sense of embodiment, i.e., the sense of self-location, agency, and ownership that humans feel in relation to their bodies and body parts (Murray, 2008). If a prosthesis does not evoke a sense of embodiment, the user is less likely to view it as useful and integrated with their body. Besides the risk of prosthesis abandonment, sense of embodiment is crucial for individuals with acquired limb loss and congenital limb deficiency, as lack of sense of prosthesis embodiment is also connected to higher levels of depression, activity reduction, and lower levels of social integration (Murray, 2004).

Reintroducing closed loop feedback modalities such as haptic feedback is a commonly cited method to improve the sense of embodiment and overall usability of prostheses

(Marasco et al., 2011; Saunders and Vijayakumar, 2011; Page et al., 2018). State-of-the-art neural prostheses using implanted peripheral nerve interfaces have made vast improvements in motor control and have begun to offer forms of haptic feedback through direct nerve stimulation (Cuberovic et al., 2019; Middleton and Ortiz-Catalan, 2020), but safety concerns have limited this feedback's strength and efficacy (Günter et al., 2019). Applying vibrotactile feedback to a residual area on a lost or congenially deficient limb that is coupled with pressure sensitive elements at key locations on a prosthesis may be a safe, cheap, and effective alternative to direct peripheral nerve stimulation in the restoration of haptic feedback in prosthetic devices. Our study contributes to the investigation of this idea by replicating a rubber hand illusion effect in immersive virtual reality to explore how applying proximal vibrotactile feedback affects the sense of embodiment of a virtual arm during grasping activities.

Sense of Embodiment and the Virtual Hand Illusion

Sense of embodiment refers to the sense of self-location, agency, and ownership that humans feel in relation to their bodies and body parts (Carruthers, 2008; Kilteni et al., 2012; Gouzien et al., 2017; Frohner et al., 2019). Interestingly, sense of embodiment has been shown to be elastic, and can be manipulated in an individual by altering the sensory information they have access to. Sense of embodiment can be rapidly and reliably induced with an artificial hand via the rubber hand illusion paradigm. The rubber hand illusion was first empirically investigated by Botvinick and Cohen (1998). Participants sat at a table that visually obscured their left hand but showed an artificial rubber hand in lieu of the obscured hand directly in front of the participant. To induce the original illusion, the rubber hand and the obscured hand are simultaneously brushed to couple visual and haptic feedback. This synchronous multimodal stimulation results in a reportedly strong sense of ownership of the rubber hand and a proprioceptive drift—a perceived change in location of one's real, but obscured, hand toward the location of the artificial hand—when asked to blindly point to the tip of one's own obscured finger with one's visible hand. Thus, for the rubber hand illusion to be successful, visual feedback of the rubber hand must be coupled with haptic feedback as perceived on the obscured real hand. This causes proprioceptive drift toward the location of what is seen: the artificial rubber hand. When the rubber hand illusion is in effect, the participant not only reports that the artificial hand feels like it is a part of them, but that it seems to replace their existing hand, indicating that their sense of embodiment has shifted to the artificial hand.

Interestingly, induction of the rubber hand illusion paradigm is not limited to a coupling of visual and haptic feedback. It can also be achieved by coupling visual feedback with proprioceptive information that results from movement of the obscured hand (Dummer et al., 2009; Kammers et al., 2009). Importantly, the strength of the illusion and its effect on sense of embodiment depends on the temporal synchrony of the visual feedback with another modality, such as haptic or proprioceptive feedback. If, for example, the participant taps their real fingers, the artificial hand must exhibit congruent movements simultaneously for the illusion to be induced (Arata et al., 2014).

Since the original experiment, the rubber hand illusion has been reproduced and modified in various scenarios, including replacing the real hand with artificial hands in virtual and augmented reality, or robotic hands (Suzuki et al., 2013; Aymerich-Franch et al., 2017; Huynh et al., 2019). However, all studies have consistently shown that besides visual information, at least one mode of synchronous sensory information must couple the artificial hand to the unseen hand.

Haptic Feedback

The human hand has one of the highest densities of mechanoreceptors in the body, and the sense of touch, or haptic feedback, is useful in many everyday tasks. Lack of haptic feedback is associated with a myriad of general problems, including inability to sense limb movement and position, major impairment in skilled performance, and abnormal and spontaneous movements (Johansson and Westling, 1987; Augurelle, 2002; Hager-Ross and Johansson, 2004). However, the majority of affordable and readily available prostheses, such as myoelectric and body powered prostheses, offer no replacement for haptic feedback when the prosthetic is physically contacted, requiring amputees to rely entirely on visual feedback. Neural prostheses are beginning to offer forms of haptic feedback through stimulation of reinnervated nerves. For the time being, however, signal strength and sustainability are both limited by safety concerns (Günter et al., 2019), resulting in users reporting an inability to sense degree of grasping pressure and no meaningful sense of "losing the grip of something" (Middleton and Ortiz-Catalan, 2020). Despite this limited degree of haptic feedback reintroduction, neural prosthesis users have reported an increase in their sense of embodiment of their prosthetic after switching from a non-neural to a neural prosthesis (Cuberovic et al., 2019; Middleton and Ortiz-Catalan, 2020).

As direct haptic feedback in neural prosthesis further develops, alternative methods to reintroducing haptic feedback should be considered. An important question with regards to establishing an effective non-direct form of haptic feedback for amputees is how to stimulate a sense of touch on a limb that has been removed. Given that prosthesis users do not have the possibility for local feedback (if not innervated) the purpose of this research was to determine if proximal feedback, i.e., feedback administered to a upper arm residual, would also allow for the induction of sense of embodiment. Therefore, we investigated how converting natural haptic feedback from the fingertips into vibrotactile feedback and administering this vibrotactile feedback to another location on the body may allow participants to experience haptic feedback without its natural delivery to their fingertips. To measure how these manipulations affect participants, we used a virtual hand illusion task to first assess if participants' sense of embodiment of a virtual hand changes after controlling a virtual hand that has been spatially shifted. Then, we investigate how converting natural haptic feedback from the prosthetic fingertips into vibrotactile feedback administered to another location on the body may allow participants to experience haptic feedback and if and how this experience affects embodiment. If sense of embodiment is not negatively impacted when switching from natural feedback to proximal vibrotactile feedback, proximal vibrotactile feedback should be further studied and considered when designing prostheses.

Vibrotactile and Proximal Feedback

Vibrotactile feedback is an excellent option for reenabling the haptic feedback of prosthetics (Pylatiuk et al., 2006; Chatterjee et al., 2008; Stepp and Matsuoka, 2012). Using vibration feedback has been demonstrated to have improvements over using vision alone as a feedback (Clemente et al., 2016; Rosenbaum-Chou et al., 2016; Yamada et al., 2016). Raveh et al. (2018) created a task where participants had a myoelectric-controlled hand attached to their right arm. The attached hand had pressure sensors that triggered vibrotactile feedback in motors attached to the participant's upper arm. When vibrotactile feedback was enabled and visual acuity was limited in a dark room during a Box and Blocks task, participants completed the task more quickly and with fewer errors than when the vibrotactile feedback was not enabled. In addition to functional improvement through vibrotactile feedback, D'Alonzo et al. (2015) found strong evidence that vibrotactile feedback promotes embodiment using the rubber hand illusion with amputee participants who had phantom sensations. The authors recruited participants who had phantom sensations of fingers that had drifted onto mechanoreceptors on their residual limb and mapped and applied vibrotactile stimulators to the finger-mapped areas. They found significant differences in questionnaire results, proprioceptive drifts, as well as skin conductance responses when vibrotactile feedback was given synchronously to the appropriate phantom sensation areas vs. asynchronous feedback to those areas. This is a promising example of vibrotactile stimulation facilitating strong embodiment of an alien limb, but it remains to be seen how strong sense of embodiment can be promoted when tactile receptive fields have not already migrated to specific areas on the residual limb.

Few rubber hand illusion related studies have investigated how manipulating the location of haptic feedback can affect the illusion. Riemer et al. (2014) found that stroking fingers on the obscured hand spatially incongruent with the fingers on the rubber hand eliminated the effects of the illusion. This suggests that changing the location of haptic feedback in the rubber hand illusion may result in decreased embodiment. However, there is evidence that stroking incongruent receptive fields on the back of the obscured hand during the rubber hand illusion does not significantly reduce embodiment unless it is also coupled with postural mismatch (Costantini and Haggard, 2007), which is an important example of changing location of haptic feedback without reducing embodiment.

Objectives and Hypotheses

To assess how different haptic feedback locations (local vs. proximal) and modalities (natural vs. vibrotactile) affect proprioceptive drift, we created a virtual rubber hand illusion task in which participants grasp an object in VR. Detailed hand tracking and virtual collision detection were used to activate small vibrotactile motors attached to participant's fingertips and upper arm to provide haptic feedback for the virtual hand at different body locations while keeping visual feedback for grasping constant.

The goal of this study was to replicate a rubber hand illusion effect in VR to explore how changing the site and modality of haptic feedback affects sense of embodiment. We used a virtual hand illusion task in VR in conjunction with five different haptic feedback conditions (Natural, Natural + Local Vibratory, Local Vibratory, Proximal Vibratory, and No Haptic Feedback) to evaluate the overall sense of embodiment associated with a virtual limb. Keeping visual feedback constant, we modulated both the type and location of haptic feedback. We hypothesized that measurements reflecting the strength of the sense of embodiment of the virtual arm would increase significantly, relative to the sense of embodiment of the virtual arm before each condition. We also expected measurements reflecting the strength of the sense of embodiment of the virtual arm to differ across types of feedback. More specifically, we expect feedback conditions involving the natural feedback from touch (Natural, Natural + Local Vibratory) to induce a stronger illusion than the three conditions that did not. Finally, we also expected measurements reflecting the strength of the sense of embodiment of the virtual arm to be the same or less when changing the feedback location from local to proximal.

MATERIALS AND METHODS

Participants

Participants were recruited through the UC Psychology Research Participation System (SONA Systems, Tallinn, Estonia). Participants were screened for right handedness and were asked to wear contacts rather than glasses to avoid discomfort from the head mounted display. In total, 30 participants were recruited of which 5 participants were excluded due to hardware or software malfunction. A total of 25 participants [14 females; mean age = 19.12 years, standard deviation (SD) = 1.30] were ultimately included in data analysis. To oblige the University of Cincinnati COVID-19 restrictions, researchers and participants wore masks at all times during the experiment; all surfaces and non-disposable equipment were regularly cleaned and disinfected before and after each participant. Headsets have been disinfected and put on a 48 h rotation before reuse. Furthermore, researchers always kept a 10ft minimal distance from participants, which required participants to don the experimental equipment by themselves following verbal instructions by the experimenter. This study is aligned with and covered by the University of Cincinnati Institutional Review Board Protocol #2012-2827. All participants read and signed an informed consent form before engaging in the experiment.

Apparatus

The experiment took place in an aligned virtual and physical environment with a participant in first person view sitting at a table (see **Figure 1**). A 5 cm^3 cube was available in the physical space and its dimensions were the same as the cube available on the virtual table. The VR environment was created in Unity 2020.1.7 (Unity Studios, San Francisco CA) and enacted with an

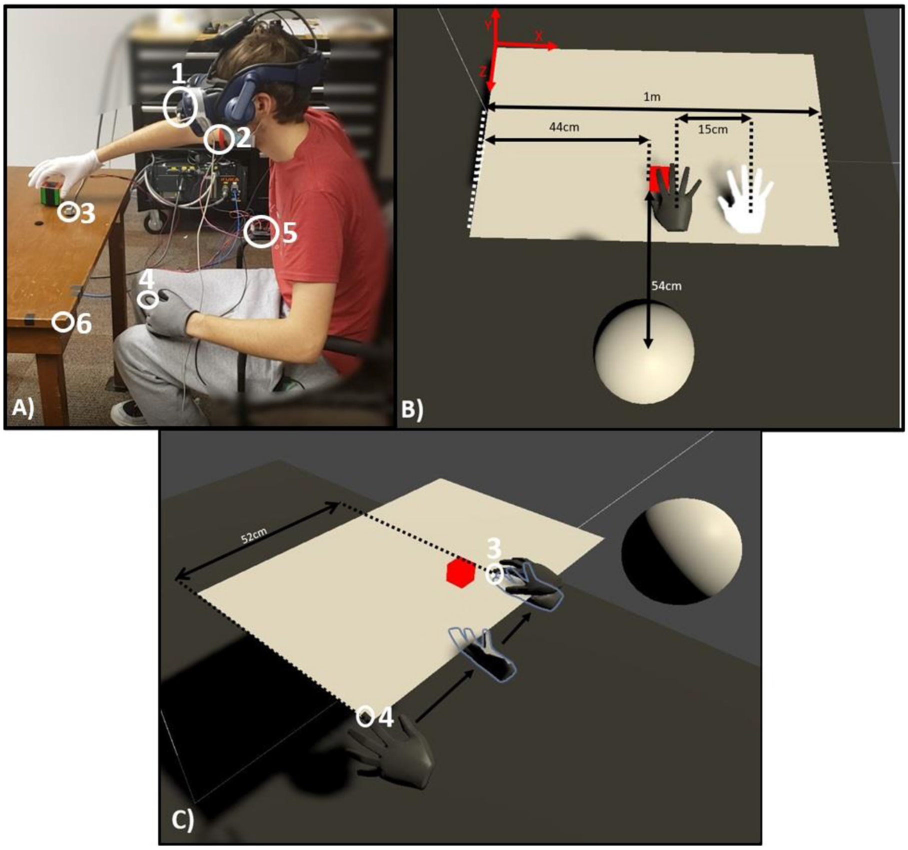

FIGURE 1 | Experimental setup. **(A)** A participant during the natural feedback condition. (A1) Leap Motion sensor; (A2) vibrostimulator armband; (A3) fixed Polhemus sensor; (A4) reference Polhemus sensor attached to tip of index finger; (A5) Arduino controlling vibration signals; (A6) table corner used to reset left finger at the start of each proprioceptive estimate. **(B)** A top-down depiction of what participants viewed in VR. The white hand represents the actual location of the participant's right hand while the dark hand is its visible position shifted 15 cm. **(C)** Over the shoulder depiction of a proprioceptive estimate. (C3) Fixed Polhemus sensor; (C4) reference Polhemus sensor attached to tip of index finger. Arrows show the reference sensor as it travels from the start of the proprioceptive estimate, to midway through the estimate, and at its final resting point when the participant declares they are satisfied with their estimate. During the estimate, the participant's headset is blacked out, so they are not viewing either hand in the virtual space.

HTC Vive Pro headset (HTC Corporation, Bellevue WA). A Leap Motion (San Francisco CA) hand tracking system was integrated with the VR environment. The Leap Motion tracking sensor was attached to the front of the headset. Two wired Polhemus Patriot (sampling rate 60 Hz, Alken Industries, Ronkonkoma NY) sensors were attached to the table and the participant's left index finger for proprioceptive drift assessment.

Vibrotactile stimulation has previously been used to successfully induce the virtual hand illusion (Kokkinara and Slater, 2014; Padilla-Castañeda et al., 2014). We therefore created a glove with one vibrotactile motor (Tatoko 10 mm × 3 mm Mini Vibration Motor DC 3V 12,000 rpm Flat Coin Button-Type) on the tip of the right index finger, and one on the tip of the right thumb. In addition, participants were asked to don an armband around their upper arm with one vibrotactile motor on their biceps and one on their triceps. The motors were driven by an Arduino Uno which were activated when the appropriate finger collided with the virtual cube in Unity.

Procedure

Participants were seated at the experiment table, where they read and signed a consent form. They were then given instructions on how to place the vibrotactile motors. First, they pulled the disposable armband over the center of the upper right arm. They adhered one vibrotactile motor to the center of the biceps, and a second motor 180 around the arm on the triceps. They then donned a pair of disposable gloves and adhered one vibrotactile motor to the tip of their right index finger, and a final motor to the top of their right thumb. Finally, they wore a reusable glove on top of the disposable glove on their left hand, which had one of the two Polhemus sensors (*reference sensor*) attached to its index fingertip.

After all upper limb equipment was correctly attached, participants were directed to the Polhemus sensor fixed to the table in front of them (*fixed sensor*). They were told that they had to repeatedly grasp the cube that was placed on the table in front of them and that during before and after each grasping task, they would need to place their right index finger on top of the sensor while their vision was obscured. Next, participants were asked to put on the Vive Pro headset.

Once the headset was turned on, participants found themselves in a VR space with a virtual table positioned in the exact location relative to the physical table in front of them (see **Figure 1**). The real cube was also secured on the right side of the table and was represented by a virtual cube in the same location in VR. The participant's right hand was tracked using the Leap motion sensor and made visible as a virtual hand. This pre-testing VR space was used to explain the details of the experiment before initiating data collection.

During each of the 5 conditions, the task was to grasp and release the virtual cube. A metronome clicking at 1 Hz per second was played through the Vive Pro earphones, and participants were instructed to repeatedly open and close their right hand in order to grasp the cube at a rate matching the metronome clicks for 2 min, resulting in 120 grasping motions per condition. Importantly, after the initial pre-testing space (where the virtual right hand was positioned in the same location as the real right hand), the virtual hand's position was shifted 15 cm to the left during all grasping phases (see **Figure 1B**). The 15 cm-shift is a distance that is considered within the optimal window to induce the rubber-hand illusion (Lloyd, 2007; Davies et al., 2013; Kalckert and Ehrsson, 2014).

The experiment consisted of 5 conditions in which the type of haptic feedback (natural, natural + local vibrotactile, local vibrotactile, proximal vibrotactile, and no tactile feedback) was manipulated. In all conditions besides "proximal vibrotactile" and "no tactile feedback," haptic feedback was administered locally to the fingertips. In the natural haptic feedback condition, a real cube was placed in the position of the virtual cube under the right hand to be grasped. In the natural + vibrotactile condition, the real cube was placed in the position of the virtual cube and the participant received haptic feedback through the vibration motors in the glove whenever the fingers reached and passed through the virtual cube. In the local vibrotactile condition, the participant received haptic feedback through the vibration motors in the glove whenever the fingers reached and passed through the virtual cube. The local vibrotactile feedback condition alone allowed us to investigate if local vibrotactile feedback was sufficient to drive the illusion. The natural feedback + local vibratory allowed us to further investigate if there were additional benefits or detriments from local vibratory feedback relative to natural feedback. In the proximal vibrotactile condition, the participant received haptic feedback through the vibration motors in the armband whenever the fingers reached and passed through the virtual cube. Finally, in the no haptic feedback condition, participants repeatedly grasped the virtual cube with no haptic feedback provided. Conditions were block-randomized within participants to decouple the effect of feedback type on embodiment from effects of repeated exposures across conditions.

At the start of each condition, participants were prompted to give an initial estimation of the perceived location of their right index finger (proprioceptive estimate). To this end, the Vive screen was blacked out, and participants were instructed to bring their left index finger with the reference sensor attached to the reset position, which was the left corner of the table (see **Figure 1C**). Then, they were instructed to bring their hand under the table and in one fluid motion place the reference sensor against the bottom of the table where they believed the tip of their right index finger, which was placed upon the fixed sensor. They verbally declared when they were confident with their estimate, and the researcher stopped and saved the recording of the two sensors positions. This proprioceptive estimate assessment was performed three times before each condition, and 3 times after each condition, resulting in three pre-grasping and three post-grasping estimate recordings.

After each condition's post-grasping proprioceptive estimates, participants were instructed to carefully remove the headset, and answer the virtual hand embodiment questionnaire. The questionnaire contained nine questions adapted from Longo et al. (2008) and Huynh et al. (2019) and was designed to assess the strength of the subjective experience of virtual hand embodiment (see **Table 1**). Answers to each question were collected using a seven-point scale ranging from strongly disagree to strongly agree. The questionnaires were given to participants on paper to help reset the effects of the illusion in between conditions, as participants re-adapted toward their natural felt location of their right hand by holding and using a pen.

DATA ANALYSIS AND RESULTS

Data Preparation

Each participant was recorded with three pre-grasping and three post-grasping estimates before and after each of the five feedback conditions, yielding 30 total recordings. The final 10 samples of both position time series in x-direction (see **Figure 1B** for a depiction of XYZ coordinate planes) were isolated and averaged in each recording, resulting in one Offset value per trial. The X coordinate of the reference sensor was subtracted from the X coordinate of the fixed sensor, resulting in the *Offset* value for each estimate assessment.

The Offset reflects the difference value on the X axis between the participant's right index finger and where they have placed their left index finger under the table (see **Figure 1C**). An Offset of 0 means they were able to perfectly line up their two index fingers with the table in between. A negative Offset means they placed their left index in the direction of the virtually shifted hand with respect to the fixed sensor, and a positive Offset means they placed their left index finger to the right of the fixed sensor (see **Figure 1A**). We define the *Proprioceptive Drift* as the difference between the pre-grasping offsets and the post-grasping Offsets.

The manipulation that was constant across all conditions was the shift imposed on the virtual location of the hand; the virtual hand was visually shifted 15 cm to the left with respect to the real hand (in the more traditional rubber hand illusion our real hand would be referred to as the "obscured" hand). As such, participants received visual feedback of their hand that was shifted 15 cm to their left, which in line with the rubber-hand illusion theory, should drive the illusion and by extension their proprioceptive reports toward the left. In other words, we expected post-grasping Offsets to be more negative (shifted more toward the virtual hand) than pre-grasping Offsets.

TABLE 1 | Questionnaire descriptive statistics.

	While grasping the cube…	Category	Mean of 7-point Likert scale	Standard error
1	…it seemed like I was looking directly at my own hand, rather than a virtual hand	Ownership	5.24	0.23
2	…it seemed like the virtual hand began to resemble my real hand	Ownership	5.87	0.20
3	…it seemed like the virtual hand belonged to me	Ownership	5.89	0.20
4	…it seemed like the virtual hand was my hand	Ownership	5.49	0.22
5	…it seemed like the virtual hand was part of my body	Ownership	5.47	0.18
6	…it seemed like my hand was in the position where the virtual hand was	Location	6.04	0.23
7	…it seemed like the virtual hand was in the position where my hand was	Location	6.20	0.19
8	…it seemed like I could have moved the virtual hand if I had wanted	Agency	6.27	0.20
9	…it seemed like I was in control of the virtual hand	Agency	6.40	0.18

Items adapted from Longo et al. (2008) and Huynh et al. (2019).

We therefore analyzed the Offset values for each participant to determine if Offset systematically varied as a function of the *Estimate Block* (Pre-grasping, Post-grasping), *Feedback Type* (Natural, Natural + Vibratory, Vibratory, No Haptic Feedback), and *Feedback Location* (Local, Proximal, No Haptic Feedback).

We performed a sensitivity analysis following the procedures described by Westfall et al. (2014), using the web-based app (Pangea) developed by the first author and available on his webpage (https://jakewestfall.shinyapps.io/pangea/). Results showed that considering our sample size ($n = 25$) and the number of estimate attempts per condition (3), the mixed-effect analysis we employed had 80% power to detect moderate effect sizes: Cohen's $d > 0.30$ for test condition effect and Cohen's $d > 0.35$ for test condition × feedback type and test condition × feedback location.

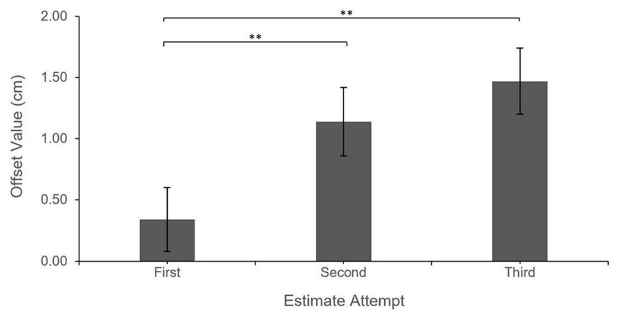

FIGURE 2 | Feedback type Offset by estimate attempt. Error bars reflect the standard error. ***$P < 0.001$; **$P < 0.01$.

Feedback Type

To determine if feedback type affects embodiment, we submitted the Offset values to a linear mixed model (LMM) analysis (R package: lmerTest) with *Estimate Block and Feedback Type* as fixed effects. Analyses of the descriptive statistics suggested an effect for the repeated measures taken on the Offset values; thus, we included *Estimate Attempt* (First, Second, Third) in the model as a control variable. To control for inter-individual variability, *Participant* was entered into the model as random effect. We excluded outlier data with a standardized residual distance <2.5 standard deviations from the average standardized error. Seven data points which comprised ∼1.2% of total number of data points were excluded.

The results revealed a significant main effect of Estimate Attempt on the Offset values, $F_{(2,540.95)} = 25.05$ $p < 0.0001$. Pair-wise comparisons with Tukey correction showed that Offsets were significantly greater (more shifted away from the virtual hand) for Second ($M = 1.14$ cm, $SE = 0.28$) and Third ($M = 1.47$ cm, $SE = 0.27$) estimates compared to First estimates ($M = 0.34$ cm, $SE = 0.26$), all ps < 0.001; there was no significant difference between Second and Third estimates, $p = 0.13$.

Additionally, after controlling for Estimate Attempt, there was a significant main effect of Estimate Block (Pre-grasping vs. Post-grasping), $F_{(1,540.96)} = 26.06$, $p < 0.0001$. Offset values were greater (more shifted away from the virtual hand) for the Pre-grasping estimates ($M = 1.33$ cm, $SE = 0.22$) when compared to those made Post-grasping ($M = 0.64$ cm, $SE = 0.22$), indicating a shift in the perceived position of the real hand toward the virtual hand; this effect occurred regardless of Feedback Type, i.e., all interaction effects were non-significant, all $p > 0.33$. See **Figures 2**, **3** for illustration of described effects.

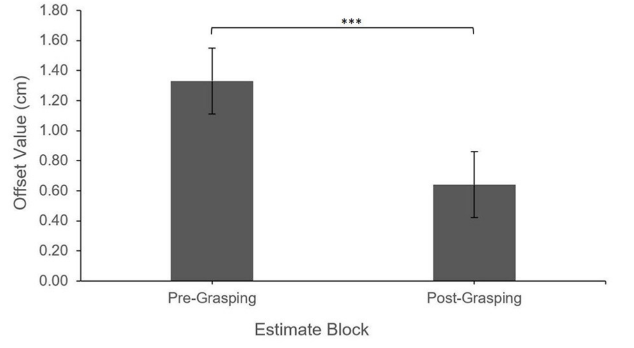

FIGURE 3 | Feedback type Offset by estimate block. Error bars reflect standard error. ***$P < 0.001$.

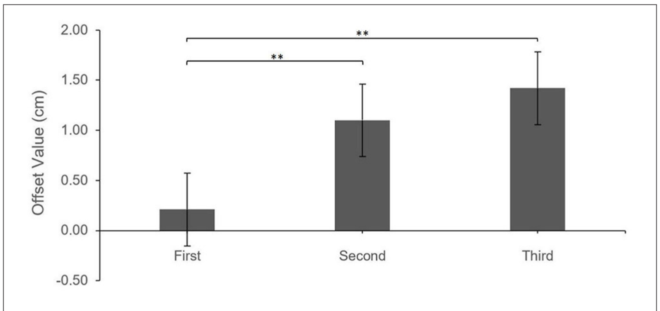

FIGURE 4 | Feedback location Offset by estimate attempt. Error bars reflect standard error. $^{***}P < 0.001$; $^{**}P < 0.01$.

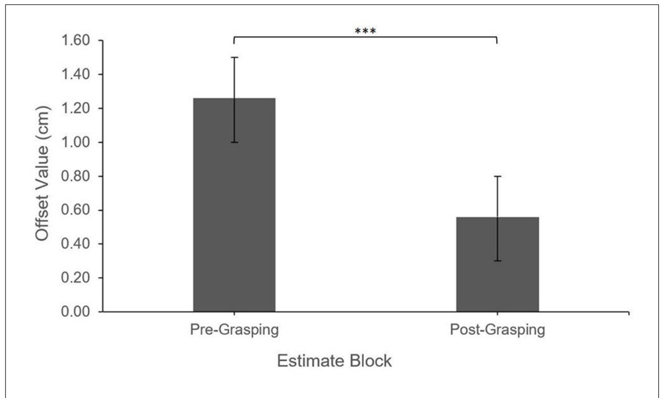

FIGURE 5 | Feedback location Offset by estimate block. Error bars reflect standard error. $^{***}P < 0.001$.

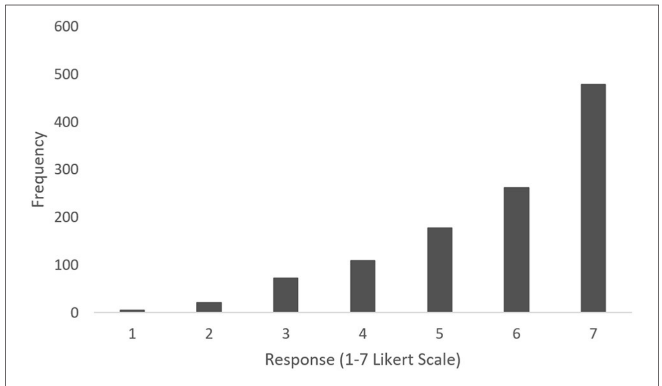

FIGURE 6 | Overall questionnaire response frequencies across all questions and conditions.

Feedback Location

To determine if the location of feedback moderates the effect of embodiment, we submitted the Offset values to a second linear mixed model (LMM) analysis (R package: lmerTest) with *Estimate Block* and *Feedback Location* as fixed effects. Again, analyses of the descriptive statistics suggested an effect for the repeated measures on the Offset values; thus, we included *Estimate Attempt* (First, Second, Third) in the model as a control variable. To control for inter-individual variability, *Participant* was entered into the model as random effect. We excluded outlier data with a standardized residual distance <2.5 standard deviations from the average standardized error. Twelve data points which comprised ∼2.9% of total number of data points were excluded.

The results revealed a significant main effect of Estimate Attempt on the Offset values, $F_{(2,390.80)} = 22.76, p < 0.0001$. Pair-wise comparisons with Tukey correction showed that Offsets were significantly greater (more shifted away from the virtual hand) for Second ($M = 1.10$ cm, $SE = 0.32$) and Third ($M = 1.42$ cm, $SE = 0.30$) estimates compared to First estimates ($M = 0.21$ cm, $SE = 0.30$), all $ps < 0.001$; there was no significant difference between Second and Third estimates, $p = 0.21$.

Additionally, after controlling for Estimate Attempt, there was a significant main effect of Estimate Block (Pre-grasping vs. Post-grasping), $F_{(1,390.91)} = 19.21$, $p < 0.0001$. Offset values were greater (more shifted away from the virtual hand) for the Pre-grasping estimates ($M = 1.26$ cm, $SE = 0.24$) when compared to those made Post-grasping ($M = 0.56$ cm, $SE = 0.26$), indicating a shift in the perceived position of the real hand toward the virtual hand; this effect occurred regardless of Feedback Location, i.e., all interaction effects were non-significant, all $p > 0.16$. See **Figures 4**, **5** for illustration of described effects.

Questionnaire Scores

Questionnaire scores were extremely skewed toward high scores (see **Figure 6**). A chi-square test of independence was performed to examine the relation between condition and question response. Question responses were formed by condensing Likert scores into Disagree (scores 1–3) Neutral (score 4), and Agree (scores 5–7). The relation between condition and question response was not significant, $X^2_{(8,N=1,125)} = 14.49, p < 0.05$.

Questionnaire scores were broken down into their established categories of Ownership, Perceived Location, and Agency (see **Table 1**). Pearson's product-moment correlations were run to compare questionnaire scores to Proprioceptive Drifts across the five feedback conditions. Questionnaire responses for Ownership did not correlate with Proprioceptive Drifts across conditions, $r_{(123)} = -0.26, p = 0.79$. Questionnaire responses for Perceived Location did not correlate with Proprioceptive Drifts across conditions, $r_{(123)} = 0.02$, $p = 0.84$. Questionnaire responses for Agency did not correlate with Proprioceptive Drifts across conditions, $r_{(123)} = -0.10, p = 0.92$.

DISCUSSION

While we plan to work with amputee populations with robotic hands in the future, VR serves as a useful tool to investigate the utility of various forms of feedback as well as the sense of embodiment. An eventual goal in prosthetics is to restore natural feelings to both control and feedback of the prosthesis. Working with non-amputees in VR allows use to directly compare natural forms of haptic feedback to potential alternatives. In the current experiment, we assessed if participants' sense of embodiment of a virtual hand changes after controlling a virtual hand that has been spatially shifted. We then investigated the impact of different feedback types and feedback locations on embodiment of a virtual hand. Participants repeatedly grasped a cube in VR, while the actual haptic feedback they received was manipulated. They either grasped only a virtual cube, grasped the cube in VR while simultaneously grasping the real cube, or received vibratory feedback on their fingertips or on their upper arm.

Analyzing Proprioceptive Drift derived from Estimate Offsets for both haptic Feedback Type and Feedback Location, we found a significant main effect for Estimate Block, indicating a significant proprioceptive drift toward the shifted virtual hand when comparing pre-grasping Offsets to post-grasping Offsets. However, the drift was equally present across all feedback conditions and feedback locations, with no difference between them. It is important to note that the present study is powered to detect moderate-sized effects. Thus, it is possible that we have missed small effects of feedback type and location that might exist. Results are conclusive in suggesting, however, that embodiment effects were observed regardless of the experimental condition. In general, the existence of a significant drift shows that the virtual hand illusion was successfully replicated in our VR environment. Furthermore, our results suggest that participants' proprioceptive feedback (through the grasping activity) coupled with the visual feedback was enough to facilitate the illusion and was not further affected by additional forms of feedback. This is in line with a recent similar study by Huynh et al. (2019) who found that synchronous motor feedback is sufficient to induce a rubber-hand illusion.

Besides this, Huynh et al. (2019) also showed that sense of embodiment is strengthened as more types of feedback are combined, even demonstrating that synchronous feedback in one modality appeared to compensate for asynchronous feedback in the other. We were surprised to find that combining feedback types in our study did not enhance the sense of embodiment of the virtual hand over the no haptic feedback condition, which resulted in a similar drift as the other four conditions. This seems to suggest that the visual feedback coupled with motor feedback from control of the virtual hand were sufficient to drive the effect of the illusion. As our aim for his study was not to explore the impact of motor feedback, but the impact of dislocated feedback, we will have to leave the exploration of this discrepancy (by for example including a no-motor condition) to future research.

Besides the presence of the proprioceptive drift effect, we also found a significant main effect for Estimate Attempt for both feedback type and location, indicating that proprioceptive estimates trended to the right (the opposite direction of the visual shift of the hand) as participants iterated through each set of three estimates. This may reflect the elasticity of the illusion, with the estimate immediately following the grasping phase resulting in the highest drift toward the virtual hand and a quick temporal decline of the effect afterwards.

In addition to the quantitative assessment of proprioceptive drift as an indicator of sense of embodiment, we also used a modified embodiment questionnaire to assess the subjective experience of participants. Answers in all categories were extremely skewed toward high scores, with all questions averaging at least five (Somewhat Agree) on the seven-point Likert scale. Questionnaire scores did not significantly differ across feedback condition. Like the proprioceptive estimate findings, these questionnaire response findings suggest that participants' proprioceptive feedback (through the grasping activity) coupled with the visual feedback was enough to facilitate the illusion and was not further affected by additional forms of feedback. The fact that the scores were extremely skewed toward the affirmation of embodiment might be due to the fact that in immersive environments, such as VR, the only available visual feedback is entirely provided by the simulation. Hence, we might have a natural tendency to trust the provided visual feedback, especially with respect to relative position without additional frames of reference. While our primary interest is improving the sense of embodiment of a virtual hand in order to extend these findings to improve prosthetics, we are also interested in how sense of embodiment of a virtual body can impact the quality of VR products and training programs. Vibrotactile feedback is already used within controllers of modern VR systems to signal different types of interactions. Further research on how types and locations of haptic feedback affect the embodiment and immersion of a virtual body will enable the enhancement of a myriad of VR tools and products.

When questionnaire scores were broken down into their established categories of Ownership, Perceived Location, and Agency and correlations were run between each category's questionnaire scores and proprioceptive drift values across feedback conditions, none of the three categories' scores correlated with proprioceptive drifts. The evident lack of correlation between questionnaire scores and proprioceptive drift measurements, which was already documented by Rohde et al. (2011), renders the fact that most rubber hand illusion research considers questionnaire responses and proprioceptive drift to be equally as valid assessments of embodiment, surprising. Together with the fact that we were able to show that even the illusion as expressed in drift assessment vanishes quickly, we overall may need to consider alternative paradigms if we want to gain a true assessment of prosthetic embodiment.

In this context, there may be limitations in applying our findings from VR to the improvement of real-world prosthetics. D'Alonzo et al. (2019) found that vibrotactile feedback can reliably induce a virtual hand illusion. However, they also found evidence suggesting that vibrotactile feedback applied in a VR setting induces a stronger illusion as compared to a vibrotactile feedback in a real rubber hand setting. This finding indicates that when moving from virtual environments to world applications real, vibrotactile feedback is less effective in impacting embodiment.

There are also limitations relating to several optimizations of the virtual hand illusion that were not implemented in our setup that may have enhanced the strength of the illusion and highlighted more differences between feedback conditions. Body continuity is a significant factor in the strength of the rubber hand illusion that was not implemented in our setup but may have increased the strength of the illusion (Perez-Marcos et al., 2012; Tieri et al., 2015). The level of realism and congruence in appearance can also impact the strength of the illusion, with gender (Schwind et al., 2017), race (Lira et al., 2017), and overall appearance (Pyasik et al., 2020) each impacting measurements of sense of embodiment when manipulated. We would have likely increased the strength of the illusion along with its impact on sense of embodiment if we had added a wrist and arm to the virtual hand, along with improving the realistic appearance of the hand and adjusting its gender and race for each participant. Nevertheless, we believe that despite the lack of differences found among the conditions in this study, we are encouraged by the proprioceptive drift driven by the experimental task. Furthermore, it is encouraging that converting local feedback to proximal does not reduce the effect of the illusion. Another option for future studies would be to incorporate an asynchronous feedback condition to determine if the proprioceptive drift observed in the present synchronous feedback conditions persists (or even increases) as has been observed in other studies (D'Alonzo et al., 2019).

CONCLUSION

In this study we investigated the feasibility of proximal vibrotactile feedback for inducing embodiment of a virtual hand. We showed that neither the location of feedback induction, nor the changed modality limited the induction of proprioceptive drift as a measure of induced embodiment of the virtual hand. These findings might have a large impact on the future of prosthetics and all wearable devices as adding proximal, vibrotactile feedback is less invasive and risky than neural connection while still providing closed loop feedback in grasping activities and subsequent sense of embodiment, which may in turn enhance prosthesis acceptance rates. Finally, proximal vibrotactile feedback is a low-cost solution and may be added to existing prosthetic systems by simply retrofitting (or creating new ones) using relatively simple technology.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by University of Cincinnati Institutional Review Board/Human Research Protection Program. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

CM, TL, KS, and PS contributed to conception and design of the study. CM collected data and wrote the first draft of the manuscript. RM contributed to experiment setup creation. CM, SC, and PS contributed to statistical analyses. SC and TL wrote sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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Interaction in Assistive Robotics: A Radical Constructivist Design Framework

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Despite decades of research, muscle-based control of assistive devices (myocontrol) is still unreliable; for instance upper-limb prostheses, each year more and more dexterous and human-like, still provide hardly enough functionality to justify their cost and the effort required to use them. In order to try and close this gap, we propose to shift the goal of myocontrol from guessing intended movements to *creating new circular reactions* in the constructivist sense defined by Piaget. To this aim, the myocontrol system must be able to acquire new knowledge and forget past one, and knowledge acquisition/forgetting must happen *on demand,* requested either by the user or by the system itself. We propose a unifying framework based upon Radical Constructivism for the design of such a myocontrol system, including its user interface and user-device interaction strategy.

Keywords: upper-limb prosthetics, myocontrol, machine learning, incremental learning, human-robot interaction, human-machine interfaces, radical constructivism, interaction design

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INTRODUCTION

According to the layman's definition, a Human-Machine Interface (HMI) is the hardware/software system enabling a user control a device (computer, robot, tool, etc.); it is the channel through which user-device *interaction* takes place (Castellini, 2016). Unsurprisingly, most HMIs rely on the assumption that the user can voluntarily and precisely control arms, hands and fingers—think, e.g., the handles of a wheelbarrow, the cockpit of an airplane, and the surface and operating system of a smartphone. However, this assumption fails when the device to be controlled is an assistive one. An upper-limb amputee using a prosthetic arm in daily life or a stroke survivor progressively getting in control of a rehab exoskeleton cannot properly use their limbs to control their machines—here a more flexible and smart kind of HMI is required (Beckerle et al., 2018), able to interpret the user's intent to move using bodily signals typically related to muscle activation (*myocontrol*, see, e.g., Castellini et al., 2014).

But myocontrol is still unreliable, notwithstanding three decades of intense research (Schweitzer et al., 2018). The human-friendliness and dexterity of upper-limb prostheses, for instance, increases every year, while their rejection rate remains high, largely due to poor myocontrol (Vujaklija et al., 2016). Better sensors, better physical interfaces and better machine-learning (ML) methods and models are the main avenues researchers are pursuing (Fougner et al., 2012; Jiang et al., 2012); still, without neglecting these issues, a fundamental ingredient the recipe lacks is a tight *coupling* between user and machine (Hahne et al., 2017; Beckerle et al., 2018). Coupling arises from reciprocal adaptation which in turn relies on "transparent" control of the device—the device should move according to the user's wishes without the user even consciously realizing it (Makin et al., 2017).

Here, a somewhat deeper psychological interpretation of the informal notion of transparent control (Fougner et al., 2012) is required. Musculoskeletal impairments, preventing motor commands from being correctly executed, lead to the disappearance of *circular reactions*—basic sensori-motor associations created during the infancy by interacting with the environment (Piaget, 1966; Evans, 1973; Sanchez and Loredo, 2007), significantly degrading the patient's quality of life. But they can also be restored/created anew by exploiting the plasticity of the neural circuitry which can be induced, e.g., in virtual reality (Yanagisawa et al., 2016), sometimes with consequences on the perception of pain. Myocontrol could possibly then be used to foster the restoration, or novel creation, of such circular reactions, to replace those destroyed by the patient's condition. Correct and reliable intent interpretation would then be a desirable side effect.

To this aim, the ideal assistive device reacts as dexterously and quickly as the musculoskeletal system itself (Botvinick and Cohen, 1998) while providing proper sensory feedback in real time; but this is just a necessary condition. The user must also be involved in a fruitful sensorimotor interaction with the device, *teaching* it how it should work (Nowak et al., 2018). We believe that a Radical-Constructivist (von Glasersfeld, 1995) framework can unify all these aspects and provide useful guidelines for the design of better ML systems, user interfaces and experimental protocols for myocontrolled assistive devices.

ON THE PURPOSE OF ASSISTIVE SYSTEMS

In mammals (actually, in all beings endowed with a nervous system) every single movement produces a "sensorial trace"—in the simplest setting, indeed a proprioceptive one. Simple, basic, stereotyped movements corresponding to similarly simple sensorial traces, for instance the act of flexing a wrist and the feeling of flexing it, become strongly *associated* to each other through repeated execution since birth, thanks to the plasticity of the nervous system. According to Piaget, such sensori-motor associations are the building blocks of one's own body control and even, possibly, of intelligence *tout court* (Piaget, 1966); the paradigm of enactive/embodied knowledge and learning points in the same direction (de Bruin et al., 2018).

Radical Constructivism

Piaget's theory of cognitive development contends that, in the 1st month after birth, an infant's activity is characterized by simple, genetically determined reflexes such as rooting and sucking; subsequently, till 4 months of age, the interest shifts to the body, trying to *reproduce* pleasant events—a rudimentary form of goal-directedness (Piaget, 1966). These cyclic behaviors had been called *circular reactions* by Baldwin (Baldwin, 1894) because a random action would generate a pleasant stimuli leading to the repetition of said action. Piaget further developed this idea by introducing the concepts of *assimilation, accommodation, organisation* and *action scheme,* which led him to further distinguish primary, secondary (4–12 months) and tertiary (12–18 months) circular reactions (Piaget, 1966).

In particular, an action scheme (von Glasersfeld, 1995) is a goal-directed extension to the traditional stimulus-response reflex model, consisting of (1) the recognition of a specific situation; (2) the execution of an action associated with that situation; and (3) the comparison of the new situation, obtained as a consequence of the action, to an expected (desired) result. The infant will first recognize a situation as an instance of something known (assimilation, Piaget, 1966; von Glasersfeld, 1995), then it will execute an activity associated with it, and lastly, it will try to assimilate the obtained result to its expectations. If this attempt fails, either the initial recognition will be modified, in order to prevent further triggering of the same action in the future, or a new scheme will be created, by modification of the expected result (accommodation).

The continual execution of action schemes, at first at random, then in a progressively coordinated fashion, leads to their self-organisation into more and more complex ones, effectively building up sensorimotor coordination in the infant. In order to form, use and organize action schemes, however, an infant needs a set of basic capabilities, namely (von Glasersfeld, 1995) to be able (a) to *remember* and *retrieve* past experiences; (b) to *compare* and *determine (dis)similarity* between them and the current situation; and (c) to *evaluate* experiences as interesting and/or beneficial, that is, to match them against a goal. The need for such a system-oriented perspective leads us to adopt a more operational kind of constructivism then Piaget's, *Radical Constructivism* (von Glasersfeld, 1995). RC is based upon six fundamental principles, derived more in detail from Piaget (1966), von Glasersfeld (1983, 1995), Varela et al. (1991), Kant (1998):

1. *[Experiential world]* Although all human beings share the same physical space, each one lives in a secluded experiential world, an inner universe constructed by interacting with the environment.
2. *[Objects]* The objects found in the experiential world *use* the environment but are not determined by/do not conform to it; rather, they are determined by/conform to the way the individual constructs them. This idea goes back to Immanuel Kant's *Copernican revolution* (Kant, 1998).
3. *[Functions]* Objects are constructed via a self-organizing system of *basic functions*: reflexes, circular reactions, assimilation, accommodation and organisation (Piaget, 1966).
4. *[Autopoiesis]* This self-organizing system is autopoietic (Varela et al., 1991): the outcomes of the construction extend and further develop the basic functions that constructed them.
5. *[Viability]* In the process of constructing the experiential world, *viable* objects are preferred—objects which better fulfill the goal for which they have been constructed (von Glasersfeld, 1983).
6. The *[environment]* then provides material for the construction of each individual's experiential world and puts to the test its viability.

Musculoskeletal Impairments From the RC Perspective

Primary and secondary circular reactions clearly encompass the above-mentioned intuitive notion of (simple, basic, stereotyped) "sensorimotor associations." They are subsequently hierarchically organized in action schemes thanks to assimilation, accommodation and organisation. Action schemes corresponding to more complex, high-level, goal-directed actions can be decomposed into finer-grained action schemes, and, in the end, into their constituent circular reactions (this idea already appears in, e.g., von Glasersfeld, 1995; Kumar et al., 2018). For instance, "reaching for and grasping a cup of tea" can be decomposed into simpler actions schemes, e.g., "focus on the cup," "stretch the arm," "pre-shape the hand," etc. Each such scheme can be decomposed in turn, till primary and secondary circular reactions are reached. Each time such an action scheme is executed, all lower-level action schemes and circular reactions it involves are executed in turn. This way, the organisation of the objects at the core of this action continually consolidates and adapts, increasing its own viability and tightening the coupling between the environment and the subject.

Seen from this perspective, acquired musculoskeletal impairments disrupt specific sets of primary and/or secondary circular reactions, and, consequently, all action schemes based upon them. As a consequence, the organization of these schemes gets gradually undone. A trans-radial amputation, for example, annihilates—among others—all secondary circular reactions related to the missing wrist, as well as all higher-level ones based upon them. Phantom-limb sensation and pain and maladaptive cortical reorganization (Flor and Birbaumer, 2000; Erlenwein et al., 2021) can probably be seen as consequences of such a disruption. In RC terms, the experiential world of those who suffer from a musculoskeletal impairment undergoes a dramatic reorganisation; objects which had been constructed during the patient's life as a healthy person disappear and new action schemes are constructed, which are necessarily much less viable then before. Following the previous example, trans-radial amputees shift the dominance to the remaining limb, adapt the gait to the altered weight of the body and perform manipulation tasks using compensation movements (Schweitzer et al., 2018)—these are only some of the new experiential objects they construct. An amputation significantly reduces the patient's quality of life; nevertheless, the new action schemes are the most viable *given the prosthetic system at the patient's disposal* and the autopoietic nature of the objects in the patient's experiential world.

Myocontrol as a Means to Fix a Broken Experiential World

A prosthetic system (the prosthetic device plus its myocontrol system) should then aim at bi-directionally connecting the patient to the device in such a tight way that novel primary and secondary circular reactions form, functionally replacing the missing ones and constituting the basis of new action schemes; this would translate to better feeling of immersion and embodiment, more trust in the prosthesis, better control and higher functionality in daily living. These ideas, moreover, apply to all assistive devices requiring fine control by a disabled user (exo-suits, exoskeleta for rehabilitation, active orthoses, virtual rehabilitation systems, etc.) via residual muscle activity—wherever myocontrol is involved.

We contend that the ideal assistive system should foster the re-organisation of the patient's experiential world, rather than detecting the patient's intent. For instance, it should enable an amputee flex and extend the wrist with such a short latency and high precision, that no *conscious* attempt to do it is felt; and it should provide such an apt and subtle substitute feeling for the flexion/extension of the wrist, that the association between the action and the feeling becomes intimate, indissoluble—indeed, a new primary circular reaction. Currently, no prosthetic device is able to provide such a swift motion, but virtual reality is a viable test-bed, for instance to ease neuropathic pain or as a prosthetic training environment (Ortiz-Catalán et al., 2014; Nissler et al., 2019). Such a claim is substantiated by numerous hints found in literature about the swiftness of self-powered prostheses and its fallout on prosthetic rejection, for instance relating the feeling of immersion and embodiment to short mechanical latency, its looks and the reliability of myocontrol (Farrell and Weir, 2007; Smith et al., 2011; Beckerle et al., 2018).

An RC myocontrol system is then a bidirectional interface (Beckerle et al., 2018) translating actions and feelings back and forth, fostering the construction of new circular reactions.

INTERACTION FOR ASSISTIVE ROBOTICS: A RC PERSPECTIVE

In the previous Section we have tried to provide the RC perspective on musculoskeletal impairments and the aim of RC myocontrol. We now sketch its characteristics and give an example of it.

Radical-Constructivist Myocontrol

Consider the six principles mentioned above, which RC-based myocontrol should adhere to. Its *experiential world* is the space of signals available to interact with the user, typically, bio-signals gathered from the user and environmental signals provided by the device and the physical environment. The *objects* in its experiential world, constructed in the course of time, are (a) signal patterns gathered from the user while trying to perform specific actions; and (b) a model associating signal patterns to said actions. *Assimilation* and *accommodation* correspond then to defining the patterns/actions associations in the model: a pattern can be associated to an existing action (assimilation), or associated to a new action or rejected (accommodation). Assimilation and accommodation are therefore *supervised* functions—the system needs to interact with one or more oracles to know the pattern/action association, e.g., the experimenter, the user or a decision procedure.

Finally, the *organisation* of the objects in the system's experiential world corresponds to the creation or adjustment of the above-mentioned model, determining its *viability*—the degree to which the predicted actions adhere to the patient's desires and needs. In a virtuous loop of data acquisition and reorganisation of the objects, the viability increases in time, possibly reaching a local optimum.

Operationally—consider again the three basic requirements of a constructivist system highlighted above—RC myocontrol must be able to

1. match a signal pattern to a previous one, estimating the confidence of the match;
2. store, delete, retrieve and forget signal patterns; and
3. decide to acquire new patterns and/or ask the user to provide new data, or delete past patterns.

Flexing a Virtual Wrist, in a Radically-Constructivist Sense

How would a typical RC myocontrol look like, in practice? We believe that it would consist of a *(supervised) incremental machine learning method, updated on-demand via carefully designed interaction with its oracles*. More in detail, basic requirements (1) and (2) are provided already by standard, supervised machine learning, where building a pattern/action model is enforced by minimizing a cost functional. Furthermore, *interactive* machine learning provides the ability to gather and assign new patterns/delete past ones and update the model given the new set of patterns. Item (3) can be enforced by querying the user and/or the experimenter/therapist by using, e.g., *measures of confidence* of a pattern match. An initial attempt can be seen in Nowak et al. (2018).

The interaction with a human oracle, however, seems more problematic; here, specific attention must be given to the interaction protocols and to the interface to the user and/or the experimenter, which must be readily, intuitively *interpretable,* allowing the user to form a suitable *mental model* of the device. The principles of Interaction Design (IxD, Norman, 2013), a branch of Design Science concerned with usability and friendliness of devices, could help. The main predicament of IxD is that objects should be designed such that they can be used in the right way only ("human errors are design errors"). In the case of myocontrol, there should be one way only to teach the device which patterns correspond to which signals, and to have it acquire and forget data (from this perspective most of IxD seems based upon constructivist principles).

Following up the previous example of the wrist flexion, we now sketch a possible RC wrist myocontrol system. The system's objects are two signal patterns, one for the resting state and one for the full wrist flexion, gathered in the course of time from a patient using surface electromyography (Merletti et al., 2011). A regression method has been used to build a proportional model of the wrist flexion, and a realistic virtual reality wrist closely and swiftly displays the estimated wrist flexion to the patient. Electro-cutaneous stimulators (see, e.g., González-Vargas et al., 2015) are used to convey a feeling of proportional intensity to the patent's forearm. Within the limits of the virtual world, the patient can walk and freely move the arm and forearm while flexing the wrist. Each time the wrist flexion does not reflect the patient's desire, for instance because of the limb-position effect (Campbell et al., 2020), the patient can act on either of two virtual buttons on the forearm, clearly labeled with a resting wrist and a fully flexed one. Pressing one of the buttons starts a further data gathering related to the action represented on the button itself; the model is instantaneously updated.

A further element of the user interface is sound feedback, issued whenever the confidence of the model estimation drops below a threshold; this feedback denotes the necessity for the patient to provide more data in an area of the input space where the uncertainty is high [this strategy already appears in Gigli et al. (2020)]. In the course of the time spent within the virtual world, we expect the objects in the experiential world of the myocontrol system, that is the signal patterns corresponding to the resting state/full flexion and the regression model, to increase their viability with respect to the environment, and a new hierarchy of circular reactions related to the flexion of the wrist to arise in the user's experiential world. As a side-effect, the enaction of the virtual wrist flexion becomes more and more accurate with respect to the patient's desire—this can easily be assessed by administering a TAC test (Simon et al., 2011) to the patient at specific intervals of time.

CONCLUDING REMARKS

The requirement that the user be at the centre of research in assistive robotics is nowadays relevant in literature and is clear from the growing number of research projects in which clinics and healthcare companies are involved. User-centred design should be employed at all stages, and this requires a deeper understanding of the neurological and psychological processes behind (re)learning new sensorimotor faculties. In this perspective article we have argued that Radical Constructivism offers such a theoretical and practical framework to conceive and design a human-centered approach to assistive robotics; in particular, that RC can be used to understand musculoskeletal impairments, shift the paradigm of myocontrol and set a new aim to it, and design in a principled way the HMI and the patient-device interaction.

A number of open issues remain, three of which seem particularly interesting at the time of writing. In the first place, interactive machine learning has been explored only marginally so far in myocontrol, the classical approach being the collection of data at the start of each control session (Castellini, 2016), therefore there is yet no comparison. The potential superiority of one approach with respect to the other will be proven only in the course of time and via testing on end-users. Secondly, we are aware of no neural correlates of circular reactions that can be detected with state-of-the-art brain imaging techniques (although, e.g., Virji-Babul et al., 2012 is a promising study going in this direction), so how to detect the creation and disappearance of novel circular reactions induced by RC myocontrol is still an open question. Lastly, a way of numerically determining the interpretability of an assistive system is a fascinating, although still unexplored, issue.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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frontiers in Neurorobotics

MINI REVIEW
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Feel-Good Requirements: Neurophysiological and Psychological Design Criteria of Affective Touch for (Assistive) Robots

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Previous research has shown the value of the sense of embodiment, i.e., being able to integrate objects into one's bodily self-representation, and its connection to (assistive) robotics. Especially, tactile interfaces seem essential to integrate assistive robots into one's body model. Beyond functional feedback, such as tactile force sensing, the human sense of touch comprises specialized nerves for affective signals, which transmit positive sensations during slow and low-force tactile stimulations. Since these signals are extremely relevant for body experience as well as social and emotional contacts but scarcely considered in recent assistive devices, this review provides a requirement analysis to consider affective touch in engineering design. By analyzing quantitative and qualitative information from engineering, cognitive psychology, and neuroscienctific research, requirements are gathered and structured. The resulting requirements comprise technical data such as desired motion or force/torque patterns and an evaluation of potential stimulation modalities as well as their relations to overall user experience, e.g., pleasantness and realism of the sensations. This review systematically considers the very specific characteristics of affective touch and the corresponding parts of the neural system to define design goals and criteria. Based on the analysis, design recommendations for interfaces mediating affective touch are derived. This includes a consideration of biological principles and human perception thresholds which are complemented by an analysis of technical possibilities. Finally, we outline which psychological factors can be satisfied by the mediation of affective touch to increase acceptance of assistive devices and outline demands for further research and development.

Keywords: affective touch, human-machine interfaces, tactile feedback, assistive robotics, design requirements

1. INTRODUCTION

Human-machine-interfaces and robots used for assistance, service or rehabilitation purposes currently exhibit very limited abilities to mediate subtle affective touch, i.e., tactile processing with a hedonic or motivational component (Morrison, 2016a), in humans (Beckerle et al., 2018). Conversely, they are not able to sense, process and understand such touch. In current robotics, tactile information is mostly used for precision grasps, which are mainly realized by intrinsic tactile sensing (Bicchi, 1990) with sensors placed within the structure of an end effector. Affective touch would require extrinsic tactile sensing via sensor arrays at the point of contact. In every application area where robots interact closely with humans, the ability to understand and use this level of tactile information can be advantageous (Beckerle et al., 2018). Interfaces mediating touch can profit from the ability to elicit affective feelings in their users, e.g., vivid haptic feedback can increase immersion in virtual or augmented reality applications (Hoffman, 1998; Ku et al., 2003). Moreover, psychological effects such as bodily illusions, where users get the impression that an artificial limb is their own one, benefit from such technologies (Crucianelli et al., 2013, 2018). It has been shown that affective information can enhance the rubber hand illusion and thus has the potential to create a more realistic experience of prostheses and other assistive devices (Crucianelli et al., 2013; van Stralen et al., 2014). Nevertheless, interfaces mediating affective information are scarcely researched and only few prototypic implementations exist (Bonanni et al., 2006; Huisman et al., 2013, 2016; Raisamo et al., 2013; Culbertson et al., 2018). Accordingly, further research is needed in order to improve and extend the capabilities of human-machine-interfaces and assistive robots with regard to affective tactile interactions.

For the purpose of designing appropriate technical devices, an understanding of the relevant neurobiological and psychological mechanisms in humans is required. Although current fundamental research of affective touch has not yet answered all open questions in those areas (Olausson et al., 2010), important progress has been made, which enables future technical development. This review summarizes key findings from neurobiological and psychological research to provide guidance for the design of future technical implementations. In section 2, we begin with a brief overview of known mechanoreceptors relevant to active touch, and then introduce the biological background of affective touch and its effects on psychological factors during human-machine interaction in section 3. Section 4 examines the previous implementations that aim for mediating affective sensations to offer design recommendations as section 5 concludes the review with a brief overview and discussion.

2. NEUROBIOLOGICAL BACKGROUND

In human glabrous and hairy skin, a large number of different sensory receptors are found in the dermis or epidermis. For example, nociceptors measure noxious mechanical or thermal events, and mechanoreceptors to measure tactile sensations. Different receptors and types of tactile fibers are known for the tactile innervation of glabrous and hairy skin. Some of them are common in both skin types, others differ and especially in hairy skin additional variations with respect to different parts of body were found (Vallbo et al., 1995). This goes along with differences in the function of glabrous and hairy skin. While hairy skin is more relevant for affective touch, which is the topic of this review, glabrous skin is more involved in discriminative touch, although, both types of skin are able to receive mediated touch as for example recently discussed in Corniani and Saal (2020). In order to transfer physiological findings to technical systems such as robots, sensing and feeling of the environment by receptors in the skin has been studied and characterized primarily with respect to the manipulation of objects (Johansson and Flanagan, 2009; Dahiya et al., 2010), i.e., active touch (Gibson, 1962). Hence, for defining design criteria for technical systems, myelinated Aβ afferents for discriminative touch, which are of higher density in glabrous skin, were in most cases considered (Corniani and Saal, 2020). In this review, we want to focus on affective or mediated touch and unmyelinated mechanoreceptors, which are highly related to affective touch, although it was recently suggested that both myelinated as well as unmyelinated fibers should be considered as rather interleaved than separated sources for different facets of tactile information (Marshall et al., 2019). For reasons of overview and differentiation, we first provide a brief overview of the sensory receptors in the human glabrous skin that are most relevant for tactile perception during object manipulation, i.e., that sense information for discriminative touch to be transferred by myelinated Aβ afferents, while briefly referring to differences between glabrous and hairy skin. Then, we focus on unmyelinated mechanoreceptors. Recently studied receptors which are hypothesized to play an important role in affective touch, i.e., C-tactile afferents, as well as brain processing of CT afferent signals are presented in more detail, to address the need for systematic reviews in this area (Corniani and Saal, 2020).

2.1. Mechanoreceptors for Discriminative Touch

For discriminative touch, four different types of myelinated Aβ afferents in different layers of the glabrous skin and with different distribution, morphology, and function (Vallbo and Johansson, 1984; Lederman and Browse, 1988) responding to mechanical pressure or distortion of the skin (Vallbo and Johansson, 1984) are mainly considered in design criteria for technical systems. In the following we give a brief overview on myelinated Aβ afferents of glabrous skin concentrating on their response characteristic and point out differences to hairy skin.

In glabrous skin, which is most relevant for the manipulation of objects, fast adapting (FA) tactile units responding to the transient phases of stimulation, i.e., responding only to changes in the signal, and slowly adapting (SA) units that are sensitive to static forces and show a sustained discharge can be differentiated (Vallbo and Johansson, 1984). These two main groups can further be differentiated, e.g., with respect to differences in responses to the stimulus pattern. For example, the SA sub-type SA1 units (Merkel corpuscle end-organs) are particularly sensitive to edge contours of objects (Johansson et al., 1982; Johansson and Vallbo, 1983). They show a higher response frequency during the beginning of contact and decreasing feedback over time (Johansson and Vallbo, 1983) while SA2 units (Ruffini corpuscle end-organ) are responding with a constant frequency during the contact phase (Vallbo and Johansson, 1984). Interestingly, SA2 units do not only respond to indentation but also to skin stretch with a directional property (Knibestöl and Vallbo, 1970; Johansson, 1976, 1978) and might therefore contribute to measure shearing forces (Vallbo and Johansson, 1984), e.g., caused by a tool slipping out of the hand. FA2 receptors (Pacinian corpuscle end-organs) respond particularly to rapid onset and offset of those (Johansson and Vallbo, 1983) and to high frequency vibrations (Johansson et al., 1982; Dahiya et al., 2010). In contrast, FA1 (Meissner corpuscle end-organ, Iggo and Muir, 1969) responds to rapidly occurring small changes in the indentation of the skin (Johansson and Vallbo, 1983), i.e., they respond as long as the stimulus is changing. FA1 receptors can only be found on glabrous skin unlike other aforementioned receptors that are also located on hairy skin (Vallbo et al., 1995). Rapidly adapting hair and field afferents replace F1 receptors in hairy skin (Vallbo et al., 1995) and might be more sensitive to higher frequencies (Corniani and Saal, 2020).

Aβ afferents in the glabrous skin can be differentiated with respect to the size of their receptive fields and location (Johansson, 1978; Vallbo and Johansson, 1984; Johansson and Flanagan, 2009; Dahiya et al., 2010). In Vallbo and Johansson (1984) a comprehensive overview is given: corresponding to the small, accurate receptive fields, FA1 and SA1 receptors are responsible for localizing contact stimuli on the skin surface and to detect details of the surface structure at the site of contact. FA1 and SA1 units show a non-uniform distribution. They accumulate in the skin of body parts that show high tactile resolution, such as finger tips. While FA1 units are located in the papillary (close to the skin surface) SA1 units can be found at the tip of the intermediate epidermal ridges. Hence, both units are located in the very upper part of the dermis. FA2 and SA2 units have large receptive field with obscure borders. While FA2 units are found in the subcutaneous tissue SA2 units are located in the dermis but lower than FA1 and SA1 units. Vallbo et al. (1995) shows that receptive fields of hair and field afferents in hairy skin are oval or irregular in shape without orientation and larger than those of SA1 and SA2 receptors.

2.2. C-Tactile Afferents

C-tactile (CT) afferents are unmyelinated, low-threshold, i.e., responding strongly to light stimuli (<5 mN), mechanoreceptive nerve fibers found in the hairy skin of humans (Vallbo et al., 1999; Ackerley and Watkins, 2018). They strongly respond to slow and light tactile stimuli (Nordin, 1990; Vallbo et al., 1999; Löken et al., 2009; Morrison et al., 2011). Such stimulation characteristics are typical for caressing or stroking with a soft material, which is why it was hypothesized that CT afferents play a major role in affective touch and its social components (Löken et al., 2009; Ackerley et al., 2014; Huisman et al., 2016). This is grounded on two main observations: activations in the insular cortex of the human brain for stimulation of CT afferents (Olausson et al., 2002) and reports on maximized pleasantness when stimuli match CT-optimal characteristics.

The first observation is established by findings of neurological investigations, which have revealed that especially the contralateral posterior insula was found to respond to stroking with a soft brush (Olausson et al., 2002; McGlone et al., 2012). As the insular cortex is involved in emotional processing (Olausson et al., 2002; Leibenluft et al., 2004; Craig, 2008, 2009; McGlone et al., 2012), a social function of these nerve fibers appears obvious. This is further supported by the findings of Morrison et al. (2011), where participants watched other persons' arms being stroked and similar reactions to these purely visual stimuli were measured in the posterior insula.

The other observation, reported by multiple studies (Morrison et al., 2011; Crucianelli et al., 2013, 2018; van Stralen et al., 2014; Culbertson et al., 2018), is the stimulation being rated most pleasant by the participants when characteristics of the stimulation, e.g., stroking speed, complied with CT-optimal values. Therefore, it seems evident that CT afferents play a significant role in affective and social touch.

2.2.1. Response Characteristic

The signal propagation speed of CT impulses was found to be around 0.9 m/s (Vallbo et al., 1999). With a sustained indentation, the firing rate with high-frequency impulses at initial contact attenuates within 4–5 s (Vallbo et al., 1999; Ackerley and Watkins, 2018), which indicates intermediate adaptation characteristics compared to the slowly and rapidly adapting myelinated mechanoreceptors (Olausson et al., 2010). In some CT afferents, the firing rate remain increased with irregular recurring short interspike intervals separated by much longer intervals for 30 s after an initial adaptation phase of 12 s, and then, peaked and gradually decreased with more regular firing for 40 s until cessation, which is known as delayed acceleration (Vallbo et al., 1999). Furthermore, CT fibers are prone to fatigue, i.e., the first response to a stimulus is much stronger than to a following and identical one, which can even lead to unexcitability (Nordin, 1990). After releasing skin contact, after-discharges were observed, which can last several seconds (Nordin, 1990).

2.2.2. Morphology and Location

In the human body, C-tactile fibers can be found in hairy skin areas (Vallbo et al., 1999; Liu et al., 2007; Löken et al., 2009) as well as the facial area (Nordin, 1990) and glabrous hand skin (Watkins et al., 2021). Besides, forearm has often been the focus area of research conducted with regard to CT afferents due to ease of access (Vallbo et al., 1999; Wessberg et al., 2003; Löken et al., 2009; Morrison et al., 2011; Crucianelli et al., 2018; Culbertson et al., 2018).

Although there is a lack of an accurate method to estimate the distribution density of CT afferents, they were encountered as often as Aβ-afferents in previous microneurography experiences (Olausson et al., 2010). Recently, Watkins et al. (2021) suggested that CT innervation of hairy arm skin is approximately 7 times higher than that of the glabrous hand skin.

The receptive field of CT afferents was found to be circular to oval in shape without a preferred orientation (Wessberg et al., 2003). There are 1–9 responsive hot-spots distributed non-uniformly over an area from 1 to 35 mm^2 (Wessberg et al., 2003).

We believe that considering only biological background in design of robotic devices would lead to deficient products. Therefore, these findings should be blended with the psychological requirements of humans experiencing affective touch.

3. REQUIREMENT ANALYSIS

Prioritizing design requirements should depend on the application field of human-machine interfaces. Since assistive devices and prosthetics have to operate in close contact with a human, aspects of physical and cognitive human-robot interaction, and especially, psychological factors have attracted the attention of researchers (Beckerle et al., 2018). Although modalities, applications, and benefits of tactile information as a channel of communication have been a hot topic in the haptics community (Che et al., 2018; Reed et al., 2019; Ozioko et al., 2020), here we focus on the social aspects of touch as they can improve the experience of humans while interacting with devices. For the design and implementation of human-machine interfaces aiming at eliciting affective sensations, it appears promising to optimize them with regard to the particular characteristics of human C-tactile mechanoreception. As explained in the previous section, in addition to myelinated fibers, CT fibers allow humans to perceive soft and gentle stroking usually as a positive affective experience (Olausson et al., 2002). The relaxing and pleasant effects of affective touch in human-human interactions (Ditzen et al., 2008) and even human-animal interactions (Vormbrock and Grossberg, 1988) inspires the research in human-machine interaction (Eckstein et al., 2020). The technical requirements of affective touch with its effects on psychological factors are investigated in this section by extending the previous study presented by Beckerle et al. (2018).

3.1. Psychological Factors

Although various psychological factors affect the quality of haptic interaction, we focus on embodiment, pleasantness, and continuity as previous studies frequently related these factors to affective and social touch.

3.1.1. Embodiment

Many assistive devices and systems that serve the functional substitution, such as exoskeletons and prosthetics, are designed to either support users in toilsome tasks or overcome dysfunctionalities. In either case, ensuring the harmony between acts of devices, and intentions or demands of users should be a primary goal for designers (Beckerle et al., 2017a,b). Therefore, the feeling of embodiment is a crucial psychological factor that can benefit from affective and social touch during interaction (Beckerle et al., 2018). To enable full-scale embodiment of robotic devices, bidirectional human-machine interfaces are expected to intensify dexterous control and thereby, improve user acceptance (Beckerle et al., 2019).

The potential of embodiment in robotics has led several researchers to conduct human-in-the-loop tests to evaluate embodiment (Caspar et al., 2014; Romano et al., 2015; Fröhner et al., 2018; Huynh et al., 2019; Penner et al., 2019). Motivated by the rubber hand illusion paradigm, recent studies investigate bodily self-experience and device embodiment in human-in-the-loop experiments by using either robotic hand (Caspar et al., 2014; Romano et al., 2015; Huynh et al., 2019) or robotic leg (Penner et al., 2019) as the artificial limb. Moreover, Fröhner et al. (2018) investigated how virtual limbs affect embodiment in a virtual reality environment.

Unlike the aforementioned and many other works with a psychological point of view, Crucianelli et al. (2013, 2018) incorporated the concept of affective touch to the rubber hand illusion experiment by designing an interface which is one of the few technically oriented studies considering affective aspects. They showed that slow, gentle stimuli enhance not only embodiment, but also its subfactors ownership, agency, and location. Yet, Carey et al. (2021) claimed that affective touch does not enhance subjective embodiment within the whole-body illusion but is rather body-part specific.

3.1.2. Pleasantness

Pleasantness of touch can be regarded as another important modulator during social interactions (Morrison et al., 2009) and stress management (Ditzen et al., 2007; Morrison, 2016b). Therefore, psychological research puts increased emphasis on pleasant touch (Löken et al., 2009; van Stralen et al., 2014; Huisman et al., 2016; Culbertson et al., 2018). Accordingly, considering pleasantness in interface design eliciting affection appears very promising to improve user experience (van Stralen et al., 2014). Affective touch should not be confused with pleasant touch as affective touch can result in unpleasantness when stimulation characteristics are ill-adjusted. Besides stimulation characteristics, perception of (affective) touch is influenced by external factors, such as emotional expressions (Ravaja et al., 2017), olfactory environment (Croy et al., 2016) and even emotional state (Kelley and Schmeichel, 2014) and personality (Koole et al., 2014) of subjects.

3.1.3. Continuity

Continuity of stimuli is an additional and relatively simple factor regarding technical implementation. While continuity is self-fulfilling in the case of continuous stimuli, such as brushing with sinusoidal motion, it can still be characterized by delay and pulse width in the case of discrete stimulation. Nevertheless, continuity should not be considered as a physical but a psychological factor since it affects the realism and pleasantness of the stimulation (Culbertson et al., 2018). Culbertson et al. (2018) stated delay and pulse width can be adjusted to maximize continuity and pleasantness.

3.2. Stimulation Parameters

After discussing psychological effects of affective touch, we review specific stimulation parameters which are required to mediate affective touch through human-machine interfaces from both neurophysiological and psychological perspective.

3.2.1. Neurophysiological Requirements

C-tactile afferents respond highly to slow, low-pressure and soft tactile stimuli, which are similar to caressing motions (Nordin, 1990; Morrison et al., 2011; Crucianelli et al., 2018) with impulse rates in 50–100 imp/s (Vallbo et al., 1999). Since high impulse rates of CT afferents correlate positively to pleasantness (Löken et al., 2009; Ackerley et al., 2014), a range of 1–10 cm/s, with peaks at 1, 3, and 10 cm/s, is considered to be CT-optimal as the neuronal firing rate is the highest within this range (Löken et al., 2009). The relationship between the neuronal firing rate and stimulation velocity resembles an inverted parabola (Löken et al., 2009; Ackerley et al., 2014). A preference of 3 cm/s over 30 cm/s of the posterior insula was also verified using functional magnetic resonance imaging (Morrison et al., 2011). Furthermore, CT afferents are not activated by tactile stimulation at high velocities (Crucianelli et al., 2018). However, recent results indicate that they respond to vibratory stimuli in a restricted frequency range with different stimulation patterns (Wiklund Fernström et al., 2002). While CT afferents are defined as low-threshold mechanoreceptors by their activation to touch at 5 mN or less (Vallbo et al., 1999), they respond to stronger indentation forces as 0.1–0.5 N (Nordin, 1990) and 0.2–0.4 N (Löken et al., 2009). Moreover, a range of 1 N–2 N was reported to be both perceptible and comfortable on the arm (Culbertson et al., 2018). Air puffs evoke no response in CT fibers (Ackerley et al., 2014). CT fibers are not able to discriminate between pin-prick and smooth-probe stimuli as they have similar responses to both (Vallbo et al., 1999). In terms of thermal sensitivity, CT fibers show weak responses for innocuous cooling unlike heating or even noxious heat (Nordin, 1990). However, it is noteworthy that only a small subset of high-threshold CT fibers react vigorously to noxious heating (Nordin, 1990). The highest firing frequencies of C-tactile nerves occur at temperatures near skin-temperature (Ackerley et al., 2014). Besides, Ackerley et al. (2018) showed that warm touch decreases firing of CT afferents while cool touch results in lower firing rates but afterdischarge spiking.

3.2.2. Psychological Requirements

Table 1 can be inspected to design human-machine interfaces considering affective touch. The table presents extracted parameters to guide interface design aiming at eliciting embodiment, pleasantness, and continuity with affective touch. The firing rate correlates positively to the perceived pleasantness ratings of the participants and, thus, a more pleasant experience (Löken et al., 2009). Apparently, 3 cm/s was tested and verified to be the most pleasant (Löken et al., 2009; Crucianelli et al., 2013, 2018; Ackerley et al., 2014; van Stralen et al., 2014). Beyond the previously mentioned velocity range of 1–10 cm/s, Culbertson et al. (2018) reported that a velocity of 13.5 cm/s was "interestingly" the slowest speed that was perceived as pleasant. It should be kept in mind that Culbertson et al. (2018) designed their interface to evaluate linear lateral motion on an arm by applying only normal forces for sequential indentation with an array of voice coils. They stated that slower speed stroking causes unpleasant and creepy feelings, which explains this "interesting" result by Culbertson et al. (2018). The discrete nature of the work also explains why researchers did not consider continuity as a factor, and pulse width and delay as parameters since they applied stimuli with continuous motion of a stimulator, except Culbertson et al. (2018). Embodiment and pleasantness are maximized during the rubber hand illusion when the stimulus is synchronous rather than asynchronous (Crucianelli et al., 2013, 2018; van Stralen et al., 2014). Additionally, pleasantness and continuity feelings are improved with vibration as long as vibration applied has low intensity (Huisman et al., 2016; Culbertson et al., 2018). Finally, softer materials make the touch more pleasant according to van Stralen et al. (2014).

TABLE 1 | Optimal parameters of stimulation to maximize psychological factors mentioned in section 3.1.

	Embodiment	Pleasantness	Continuity
Essick et al. (1999)	-	Velocity: 5 cm/s Material hardness: soft (velvet, cotton)	-
Löken et al. (2009)	-	Velocity: 1, 3, 10 cm/s	-
Crucianelli et al. (2013)	Velocity: 3 cm/s Synchronicity: synchronous	Velocity: 3 cm/s	-
van Stralen et al. (2014)	Velocity: 9 cm/s	Velocity: 3 cm/s Synchronicity: synchronous Material hardness: soft (brush)	-
Huisman et al. (2016)	-	Velocity: 6.41 cm/s Vibration: low intensity (Amplitude: 0.9 g, Frequency: 140 Hz)	-
Crucianelli et al. (2018)	Velocity: 9 cm/s	Velocity: 3 cm/s Synchronicity: synchronous	-
Culbertson et al. (2018)	-	Velocity: 13.5 cm/s Vibration: low amplitude Delay: low (12.5%) Pulse width: long (800 ms)	Vibration: low amplitude Delay: low (12.5%) Pulse width: long (800 ms)

The table presents the key findings of related research with a focus on psychological factors.

4. DESIGN RECOMMENDATIONS

From the detailed requirement analysis provided above, design specifications can be inferred to select and dimension components, e.g., actuators and sensors to meet the neurophysiological and psychological requirements. Besides the stimulation parameters mentioned there, a design should also align the haptic resolution of actuators and sensors with the physiological features of human sense of touch (Kern and Hatzfeld, 2014). Since haptic devices can be based on tactile stimulation, tactile sensing, or a combination of both principles as in telemanipulation, resolution of both actuators and sensors is expected to match physiological features of humans. While actuators should be as accurate as human perception can resolve, sensors should be as sensitive as human skin so that bidirectional haptic information can be transmitted (Kern and Hatzfeld, 2014).

While resolution requirements apply to any haptic system, they strongly depend on the location of stimulation on the human body and, thus, vary with the respective mechanoreceptor population, skin properties, and spatial acuity (Dahiya et al., 2010). So far, there is limited knowledge and research about interfaces to excite CT afferents. One of the first attempts of a haptic interface directly addressing social touch was "Tactile Sleeve for Social Touch" by Huisman et al. (2013). They designed a sleeve consisting of an input layer with force-sensing resistors and an output layer with vibration motors in the shape of a 4 by 3 grid. Sensors were designed to detect forces around 0.4 N, while vibration stimulation was controlled to proportionally code the applied force. A similar interface with cylindrical vibration motors instead of coin-type ones was used to investigate how velocity and intensity of vibrotactile stimuli affect pleasantness (Huisman et al., 2016). Another example of vibrotactile stimulation is presented by Raisamo et al. (2013) as they tested three stimulation patterns to determine their effect on pleasantness and continuity: saltation, modulation, and hybrid. Saltation provides separate pulses, modulation uses dynamic transition of amplitude between the actuators, and hybrid combines separate pulses of saltation to modulation. The modulation method was rated more continuous and pleasant, and stimuli rated as more continuous were also rated more pleasant and more relaxing (Raisamo et al., 2013). The aforementioned studies showed positive effects of low intensity vibrotactile stimuli as we stated in **Table 1**. Essick et al. (2010) implemented a rotary tactile stimulator to investigate textured-surface stimuli along different body site with controlled force and velocity. Instead of designing an interface based on continuous stimuli, Culbertson et al. (2018) presented a novel approach by lining up an array of voice coil actuators in a sleeve to mimic linear lateral motion like a caress. Actuators consistently applied 1–2 N of normal force while effects of delay and pulse width during sequential excitation on pleasantness and continuity were evaluated positively.

Although vibrotactile stimulation is not the only way to elicit pleasant sensations, it is frequently preferred in previous designs possibly due to ease of use and control of vibration motors. We believe that there is a lack of sophisticated designs that aim CT fiber excitation based upon requirements explained in this review, especially velocity and force requirements. Although the aforementioned designs apply, in addition to normal forces, lateral forces via vibration motors or voice coil arrays, we think that measuring and controlling shear forces can significantly improve performance of interfaces as highlighted by Beckerle et al. (2018). An array or even a matrix of linear actuators with position control of indentation can also be composed to investigate effects of stimulation patterns and indentation length on affective touch. A similar approach has been validated for a haptic interface using shape memory alloys (Hamdan et al., 2019; Muthukumarana et al., 2020) and can be adapted for affective touch. The research can be extended by modeling the impedance characteristics of human skin. Variable stiffness actuators can be investigated to implement an interface based on stiffness or impedance measurement rather than normal forces if current designs can be dimensionally minimized. Alternatively, twisted and coiled polymer actuators on a silicon skin present promising results for soft haptic interaction (Chossat et al., 2019). Along with mechanical enhancements, the response of CT fibers to thermal stimulation is still undiscovered as experiments to date have been performed at ambient temperature. Based on findings regarding responses of C-tactile afferents to thermal stimuli (Nordin, 1990; Ackerley et al., 2014, 2018), it would be benign to consider effects of different temperatures of touch in interface design by adapting mechanical and thermal stimulators, such as pneumatic haptic display (Lee et al., 2021).

5. CONCLUSION

Slow and gentle stimulation of human skin with high CT fiber population, such as hairy areas of the forearm, results in affective experiences going beyond tactile information transfer. Human-machine interfaces exciting CT afferents can be used to elicit affective reactions and thereby enhance embodiment of assistive devices. Beyond embodiment, increasing pleasantness and realism of interactions by mediating social touch can boost the acceptance levels and performance of assistive devices. Yet, this requires designers to optimize actuators and sensors with respect to the specific stimulation parameters of CT afferents which are compiled and structured in this review. In addition, one should note that different understandings of affective touch, i.e., pleasant touch and social touch, might change the design perspective.

Current shortcomings and possible improvements comprise the inclusion of lateral forces since affective touch is usually achieved by caressing or stroking hairy skin. However, there is not enough data from measurements for numerical analysis of lateral force requirements of affective touch: measuring shear forces can change the perspective of designers during actuator selection to create stronger emotional responses. Moreover, all interfaces designed so far are only suitable for laboratory use. Wearable interfaces for tests in daily life application appear commercially interesting, but also bear an exceptional potential to fundamentally investigate the effectuality of multisensory affective touch effects and interfaces in the field where multisensory stimuli exist unlike the laboratory environment.

AUTHOR CONTRIBUTIONS

MC, DN, EK, and PB conceptualized the article and coordinated its development. DN and MC analyzed the requirements. All authors provided perspectives and references as well as discussed and revised the manuscript.

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Identifying Interaction Patterns of Tangible Co-Adaptations in Human-Robot Team Behaviors

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As robots become more ubiquitous, they will increasingly need to behave as our team partners and smoothly adapt to the (adaptive) human team behaviors to establish successful patterns of collaboration over time. A substantial amount of adaptations present themselves through subtle and unconscious interactions, which are difficult to observe. Our research aims to bring about *awareness of co-adaptation* that enables team learning. This paper presents an experimental paradigm that uses a physical human-robot collaborative task environment to explore emergent human-robot co-adaptions and derive the interaction patterns (i.e., the targeted awareness of co-adaptation). The paradigm provides a tangible human-robot interaction (i.e., a leash) that facilitates the expression of unconscious adaptations, such as "leading" (e.g., pulling the leash) and "following" (e.g., letting go of the leash) in a search-and-navigation task. The task was executed by 18 participants, after which we systematically annotated videos of their behavior. We discovered that their interactions could be described by four types of adaptive interactions: stable situations, sudden adaptations, gradual adaptations and active negotiations. From these types of interactions we have created a language of interaction patterns that can be used to describe tacit co-adaptation in human-robot collaborative contexts. This language can be used to enable communication between collaborating humans and robots in future studies, to let them share what they learned and support them in becoming aware of their implicit adaptations.

Keywords: human-robot collaboration, human-robot team, co-adaptation, embodiment, interaction patterns, emergent interactions

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INTRODUCTION

With AI being increasingly used in social robotics (Breazeal et al., 2016), there is a growing number of possible applications in which artificially intelligent robots need to interact and collaborate with humans in the physical space. Creating AI for the physical world comes with many challenges, one of which is ensuring that a robot does not only execute its own task, but instead behaves as a team partner, to enable human and robot to become one well-functioning unit of collaboration. One of the mechanisms that can be used to enable this, is a process of co-adaptation, where both human and robot, through (physical) interaction, adapt their behavior to develop successful patterns of collaboration over time (Chauncey et al., 2017).

To define what we mean by co-adaptation, we can think of how humans adapt their behavior in a reciprocal manner when they collaborate with other humans: the kind of adaptive interactions they use to achieve a fruitful collaboration. It is known that a human team's ability to adapt to new circumstances is vital for its performance, and team members tend to rapidly develop updated interaction patterns that fit with new situations (Burke et al., 2006; Uitdewilligen et al., 2013). Humans have the ability to intuitively interpret body language of their team members and to send signals when initiating adaptations (Sacheli et al., 2013). This kind of non-verbal interaction is not obvious when a team member is a robot. While we migh1t be able to interact with a robot using language, collaborative interactions are generally multimodal and contain many subtle and implicit non-verbal interaction cues that help us to create tacit knowledge. The focus of this paper is on these non-verbal interactions, and specifically those that are connected to physical contact.

Two classic examples of non-verbal interactions for co-adaptation in a human-non-human collaborative context can be found in human-animal interaction:

(1) The interaction between a horse and its rider (Flemisch et al., 2008);
(2) The interaction between a guide dog and a blind person (Lagerstedt and Thill, 2020).

When a human rides a horse, they start off as two separate entities with their own goals. As they interact for a longer period of time, they gradually start to better understand the other, adapting their interaction concurrently, until they become one joint system acting toward a common goal through subtle and implicit interactions. Another example is the interaction between blind people and their guide dogs: blind people truly need to trust and follow the choices of the guide dog, whereas in horse riding, the human makes most of the decisions. When guide dogs and blind people learn to navigate together, the human needs to learn to assess when to adapt its behavior to follow the dog, and when to give the dog directions about their route. The dog must learn to understand what the human is and isn't comfortable with and adapt its behavior to that. All this learning and adapting takes place through subtle physical interactions.

Mechanisms of adaptation have been studied in intelligent agents, more specifically in the field of multi-agent systems [e.g. (Foerster et al., 2016; Iqbal and Sha, 2019)]. Research addresses learning algorithms, such as different types of Reinforcement Learning, and investigates their effects on agent performance or team performance. Little to no attention is paid to the interactions that the agents engage in, which bring about the adaptations [except for some examples such as (Baker et al., 2020)]. Even when mechanisms of adaptation are studied in human-robot interaction contexts such as in Nikolaidis et al. (2017a), the effects on performance are studied. We believe that research should also address the interactions that bring about successful adaptation, to come closer to the fluency and naturalness of the above-mentioned human-animal examples.

There is a need for further study of the specific interactions and interaction patterns that bring about co-adaptation when humans and robots collaborate. A deeper insight in these interactions and patterns can help researchers and designers to study and create more natural and fluent human-robot collaborations that take the limitations and affordances of the physical world into account. In addition, such insights can support the collaborating human and robot to become more aware of their implicit adaptations and communicate about them, to further improve their collaboration. In Section "Co-Adaptation in Human-Robot Teams," we define co-adaptation in a human-robot collaboration context, and we explain the relevance of embodiment in this process in Section "Research Challenge." We describe an experimental paradigm that we designed and implemented to conduct an empirical study into co-adaptation and how it emerges from interactions. This human-robot team task was presented to human participants, after which we analyzed the team behavior in terms of interactions and interaction patterns. The resulting interaction pattern vocabulary and language provides a thorough analysis of co-adaptive interactions surrounding leadership roles in human-robot teams.

CO-ADAPTATION IN HUMAN-ROBOT TEAMS

Co-Adaptation - A Definition

In human-only teams, the term 'team adaptation' is used to describe the changes that occur in team behavior and performance. More specifically, (Burke et al., 2006) define team adaptation as "a change in team performance, in response to a salient cue or cue stream, that leads to a functional outcome for the entire team". They describe that it "is manifested in the innovation of new or modification of existing structures, capacities, and/or behavioral or cognitive goal-directed actions" (p. 1190). On top of that, it is argued that an important aspect in this is that the team members update their mental models according to changes in the task situation (Uitdewilligen et al., 2013).

We use the term *co-adaptation* instead of team adaptation, as we study the adaptive interactions at the level of the individual actors: team adaptation is a result of adaptative behavior exhibited by the individual team members. Also, co-adaptation is used more often in the context of (physical) human-robot interaction. We define co-adaptation in human-robot teams as follows:

> *A process in which at least two parties change their behavior and/or mental models concurrently as a consequence to changes in task or team situation while collaborating with each other.*

This concurrent changing of behavior and/or mental models is relevant for the team, as smooth collaboration requires partners to adapt to each other over time. Since humans are adaptive creatures by nature, and artificially intelligent systems are becoming more and more adaptive, there is an opportunity to study how they adapt together as they collaborate.

Co-adaptation is a process which generally takes place over a short period of time, e.g., over the course of several seconds or minutes; this timespan is generally considered in the study of co-adaptive behaviors (e.g., in Nikolaidis et al. (2017a), see also Section "Related Work"). It is not necessarily a deliberate process: adaptation happens as a consequence of interactions and an implicit or explicit drive to improve performance or experience. The resulting behaviors or mental models in both adapting partners do not necessarily persist over time and contexts, as new contexts and influences may cause the co-adaptation to continue. We used the above definition to describe co-adaptation as a design pattern in **Table 1** [according to the template specified in van Diggelen et al. (2019)]. This table provides a detailed explanation of the possible positive and negative effects of co-adaptation, as well as an overview of the kind of contexts in which it is relevant to develop or apply co-adaptation.

Related Work

In the sections below, we discuss related work on co-adaptation in human-robot or human-AI collaborative contexts, as we are studying interactions that bring about co-adaptation. Since we are specifically interested in analyzing and categorizing interactions and interaction patterns, we also looked at literature on interaction taxonomies within collaborative contexts. There is a body of research on dynamic role switching in human-robot collaboration, which has many similarities with how we described co-adaptation in terms of interactions. However, the existing literature [e.g. (Evrard and Kheddar, 2009; Mörtl et al., 2012; Li et al., 2015)] focuses on computational approaches to enable a robot to dynamically switch roles in an attempt to optimize performance of a human-robot team. While the existing studies evaluate the impact of the robot strategies on human factors, they do not study the natural interactions between the human and robot that arise as a consequence of the necessity for role switching. Therefore, we do not go into further depth on these papers.

Co-Adaptation

Most work on human-agent co-adaptation focuses on making the agent adaptive to the human, using information on different properties of the human [e.g. (Yamada and Yamaguchi, 2002; Buschmeier and Kopp, 2013; Gao et al., 2017; Ehrlich and Cheng, 2018)]. There have been studies that investigated how a human adapts in situations when collaborating with an intelligent agent, using the team's performance to determine the impact of co-adaptive collaborations (e.g. (Mohammad and Nishida, 2008; Youssef et al., 2014; Nikolaidis et al., 2017a,b). In addition to determining the effects of co-adaptation on performance, it is also necessary to study the kind of interactions that emerge throughout the co-adaptation process and support team members in the process of developing a fluent collaboration. A better understanding of these processes will help to initiate and maintain co-adaptation in human-agent teams.

(Xu et al., 2012) have outlined requirements for co-adaptation to occur in human-robot teams. First, they argue that in order to achieve a common purpose, both agents need to be prepared to adapt their behavior to their partner, should actively and dynamically estimate the partner's intention, and develop options of how to adapt their own behavior in response. Another requirement is that the agents need to be able to receive and appreciate feedback or reward from the other, to express their internal state to their partner in a comprehensible manner, and to establish with their partner a common protocol for interaction.

TABLE 1 | Proposed Design Pattern for Co-adaptation.

Proposed Design Pattern for Co-Adaptation	
Behavior patterns	Team members engage in collaboratively solving a task. While they do this, they observe each other's actions and adapt their behavior in an attempt to make the collaboration more fluent and effective.
Potential positive effect	The performance on the collaborative task increases. Both partners will be able to work more efficiently, as there is less idle time, fewer mistakes and more understanding between the partners
Potential negative effect	In the process of adapting, there is a risk of making mistakes. In addition, it takes time to adapt to a working strategy, which might have negative effects on the immediate performance.
Use when	Team partners need to collaborate but don't know the best strategy to complete the task. At the same time, the task and capabilities of the team members contain many implicit aspects that are hard to explicitly communicate or make agreements about.
Example	A human and a robot arm have to collaboratively assemble a product. There are different parts that either of them can assemble, and some parts need to be jointly assembled; e.g., the robot needs to hold up a heavy part while the human adjusts the bottom. If the human has to constantly provide the robot with instructions, this will slow them down, so it is useful to let the robot move autonomously and to synchronize their actions. When they start collaborating, the human might not trust the robot enough to adjust the bottom of a part that the robot holds up, in fear of being crushed underneath the part. The robot might see the hesitation and move the part upside down, such that the human can reach the object more easily. In turn, the human will have to adjust their workflow to do their task, but the fact that the robot adapted might increase the trust and understanding between the partners, which can in turn improve future team performance. While adapting, however, the human might make the mistake of trusting the robot too much, and think they can climb on top of the heavy part whereas the robot is unable to hold that weight. The co-adaptive process, if done too quickly or inconsiderate, therefore has the risk of making mistakes that hamper immediate performance.
Design rationale	A process of mutual adaptation helps to establish and maintain common ground, one of the main aspects of necessary for enabling collaboration between humans and machines (Klein et al., 2004; Sciutti et al., 2018). This might also be called mutual understanding, meaning that both parties are able to predict and/or explain each other's actions, leading to trust and eventually smooth collaboration (Azevedo et al., 2017). In human-only teams, co-adaptation leads to team adaptation (Burke et al., 2006), which has shown to be an essential aspect of successful teams.
Type	Collective

Third, the authors outline several inducing conditions, derived from experimental work, that can be used to ensure a mutually adaptive process will start, for example that both agents should be able to take initiative.

We formulated our own requirements for a task environment that would fit with our research goals of studying co-adaptive interactions, which include the mixed-initiative requirement as well as the requirements for dynamic and adaptive behavior (which we connected to an improvement in team performance). Moreover, we added two requirements that relate to the presence of a common ground (general common ground as well as interaction symmetry). Common ground is considered to be necessary for any collaboration (Klein et al., 2004), while interaction symmetry is often used to provide the possibility for imitation, which can create initial common ground [e.g. in Sasagawa et al. (2020)]. A full description of these requirements is given in **Table 2**.

Interaction Taxonomies

The literature reports two important existing studies into interaction taxonomies that describe interactions in collaborative tasks. One of those papers describes a top-down approach of describing different types of interactive behaviors based on game theory (Jarrassé et al., 2012); the other describes a bottom-up approach where interaction behaviors were identified from empirical observations (Madan et al., 2015). Both taxonomies were validated on their applicability by successfully classifying behaviors in different HRI scenarios. Although useful to describe collaborative behavior, the top-down approach [as used in Jarrassé et al. (2012)] resulted in a taxonomy that describes interaction at a high level of abstraction (distinguishing for example between competitive versus collaborative behavior). Such a taxonomy can be used to describe the overall behavior in a task, but it does not provide insights into (atomic) interactions that drive adaptation. The taxonomy presented in the other paper (Madan et al., 2015) presents interactions at various levels of detail, where the highest level of detail describes categories of interactions (i.e., *harmonious*, *conflicting* or *neutral*). The lower level interactions are more closely related to what we are interested in. They describe interaction patterns such as *harmonious translation*, *persistent conflict* and *passive agreement*. These interaction patterns focus on interactions related to collaborative object manipulation and were observed in a specific controlled task environment. This leaves room to study interactions in other contexts, to investigate a wider range of possible interaction patterns. Moreover, they do not provide information on how the different interaction patterns relate to each other; how they follow each other or how one pattern leads to a specific other pattern. We believe that the relations between interaction patterns are especially important when looking at adaptation. In our study, we take a bottom-up approach to identifying interaction patterns, which is similar to the work of Madan et al. (2015). This means that we do not predefine or design interactions, but that we set up a task that allows participants to behave as naturally as possible, and treat the data collection and analysis as an ethnographic study. Since such an approach requires us to have as little assumptions about behavior which will be observed as possible, we do not use the existing taxonomies when identifying interaction patterns. In our analysis, we focus specifically on adaptive interactions, as well as on how the different observed behaviors relate to each other. We will reflect on how our findings overlap or differ to the existing work in Section " Relation to Existing Interaction Taxonomies," to understand how they might complement or complete each other.

TABLE 2 | Task requirements for a collaborative, co-adaptive task environment.

Task requirements	
Mixed Initiative	Both parties can take the initiative for an interaction at any point in time [see (Xu et al., 2012)]
Interaction symmetry	Interaction modalities should have a certain level of symmetry, meaning that there is at least some overlap in the way the two parties can interact with the other, to enable imitation. Interaction symmetry thereby contributes to the common ground.
Performance improvement	By adapting their individual behavior, team members can support an improvement in team performance.
Collaborative advantage	It must be easier to be successful at the task when collaborating, as opposed to doing it on your own
Common ground	There must be a common ground between the collaborating partners. In our case this comes from the physical nature of the task

RESEARCH CHALLENGE

The goal of this study is to empirically investigate the interactions between humans and robots that underly their co-adaptation when jointly performing a task. A challenge is that the adaptive intentions and outcomes of interactions are often not directly clear and observable. Partners may themselves not be aware that their behavior is an adaptation to the developments, and may be a response to subtle cues, possibly processed unconsciously. In order to nevertheless investigate how such important processes take place in a human-robot team, the approach of observing and analyzing embodied human-robot team behavior was taken. Expressivity and intentionality of behavior plays a large role in embodied interaction (Herrera and Barakova, 2020). It is believed that in such a setting the subtle and perhaps unconsciously executed adaptations will be expressed by means of physical, embodied interactions, hence being accessible for observation and analysis.

The literature on using embodied intelligence when studying human-robot interaction shows two main lines of research:

- A line of research that focuses on human cognition: investigating how computers or robotic interfaces can be used to understand and extend human cognition and behavior. An example of this is extending human cognition through prostheses or sensory substitution [e.g., as in Kaczmarek et al. (1991); Bach-y-Rita and Kercel (2003); Nagel et al. (2005)].
- A line of research that focuses on using embodiment to create more intelligent computers (or machines or robots).

> The robot's intelligence is 'grounded' by a body with which it can interact with its environment [for example as described in Duffy and Joue (2000); Kiela et al. (2016)].

Our research approach is not directed at the intelligence of one particular partner of the team, but at the intelligence emerging from the interaction of partners. In the first described line of research (extending human cognition, e.g., using prosthetics), one of the main aims is to create a unity between the human and the added technology, such that for the human the artificial parts feels as though it is part of themselves. We research the unity of human and technology jointly forming a *team*, with both having a certain level of autonomy, and sharing a common goal. This approach distinguishes between cognition on an individual level (per agent) and collective cognition, at the team level. In our work, we focus on the team as a dyad formed by one human and one robot.

It is believed that studying embodied human-robot interaction, while they collaboratively perform a task, is an approach that can help us to discover and understand how a team adapts to the dynamics of the context, and how this adaptation emerges from the interactions between the team members.

FIGURE 1 | The field on which the task was executed. Participants moved from the goal on the left to the goal on the right (where the robot is stationed).

FIGURE 2 | Two participants interaction with the robot showing a situation with a stretched leash and thus in a leading role (top) and situation with a loose leash and thus a following role (bottom).

MATERIALS AND METHODS

Task Environment: Search-and-Navigation

We have developed a task in which a human and a robot jointly navigate through a space while searching for objects to collect additional points. The conditions and interdependencies described in **Table 2** were implemented in this task.

The team of human and robot are given the task of navigating between two points in space. The team's assignment is to reach the goal location with as many points as possible. They start with 60 points, and lose a point each second until they reach the goal location. Virtual objects were hidden in the task area: some close to the shortest route to the goal location; others further to the side. Picking up a virtual object yields the team 10 points. These scores were chosen after trying out the task several times, such that solely focusing on the goal would yield approximately the same score as solely focusing on the objects, while combining the capabilities of both team members could potentially result in a higher score than either of the extreme strategies, ensuring a trade-off between the two. The partners have complementary capabilities: only the robot knows where the objects are; only the human can oversee the route and distance to the goal (see **Figure 1** for an image of the field used). A sound cue is given when an object is picked up.

Design of Human-Robot Interaction

We designed and implemented a remotely controlled robot with a leash (**Figure 2**). An ambiguous form was selected for the robot, without anthropomorphic features. This was chosen on purpose, to allow humans interacting with it to focus on the interaction, not on its form.

The leash was designed to be the only direct communication channel between the robot and a participant, to ensure specific evaluation of the interaction through the leash without too much noise of other interaction modalities. On top of that, the leash interaction allows for subtle and implicit interactions as both the participant and the robot can pull the leash more or less. The robot was explicitly made to be quite large and heavy, to allow it to pull the participant in a direction as well.

For our study, the robot was remotely controlled by a human operator (i.e. the experimenter). It is usually preferable that

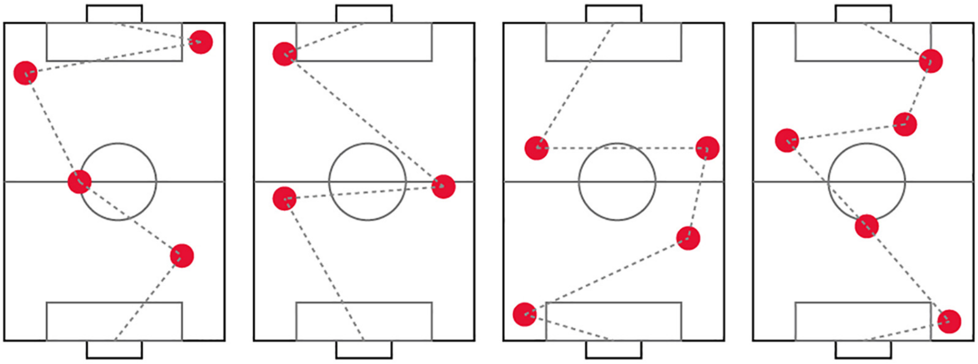

FIGURE 3 | The four predefined maps with the locations of the objects (red circles), including a line indicating the default route of the robot. The bottom of the field is the starting point.

the operator is hidden from the participant, however, due to technical limitations this was not possible. The human operator was therefore on the field together with the participant and the robot during the experiment. A small pilot with two participants showed that participants only payed attention to the human operator in the first few seconds of the experiment, after which they directed their attention to the robot only. Therefore, and for practical reasons, we decided that it did not pose a problem for our study goals that the human operator was visible. The human operator controlled the robot according to a set of pre-defined rules: to direct the robot to the closest virtual object (following a default route as much as possible, as specified in **Figure 3**) if the leash was held loose by the participant (the operator, in contrast to the participant, knew the locations of all hidden virtual objects). If the participant kept a tight leash, the operator directed the robot to give in and to move toward the participant until the leash was no longer stretched. A detailed description of these rules is provided in **Table 3**. The human operator made decisions based on visual cues: they carefully watched the leash to see whether it was stretched. Human response time to visual cues is known to be on average 0.25 s, therefore, we can assume that the robot responded to participant behavior with a delay of 0.25 s.

The task and robot were designed such that both partners had their own knowledge, enabling them to initiate actions that their partner cannot initiate. The knowledge of both partners was relevant for the task, making collaboration beneficial and enabling the partners to learn how to use their knowledge in the best possible way. All communication and coordination between the human and the robot took place through the leash, which ensured that interactions are physically grounded, and allowed for subtle and implicit interactions.

Experiment Setup and Initial Results

The experimental paradigm described above was previously used to study leadership shifts and its influence on subjective Collaboration Fluency in human-robot teams. This section will explain the experimental protocol used as well as results obtained in that study. For the current study, we have re-analyzed the data obtained in the original study to research specifically what interactions and interaction patterns bring about co-adaptation in such a task. In Section "Analyzing Behavior to Uncover Interaction Patterns" and "Data Analysis: Extracting Interaction Patterns" we will describe in detail how that analysis was done.

Experimental Protocol

Participants were told that they had to perform a collaborative task together with an intelligent robot, while holding the leash of the robot. They were presented with the described task and human-controlled robot, and were given instructions about how they could score points.

Before the start of the experiment, the participants were given the possibility to walk from one end of the field to the other with the robot. This was done to give participants an indication of the speed of the robot. After that, the first round started. The task was performed four rounds per participant. The locations of the virtual objects were different for every round. Four predefined maps with specified locations of the virtual objects were created for the human operator (**Figure 3**). Each of these maps were used for each participant during one of the rounds. The order of the maps was randomized for each participant to make sure that

TABLE 3 | The protocol used by the human operator to control the behavior of the robot.

Situation	Resulting Robot Behavior
The leash is stretched	Follow the human in the direction that the leash is pulled in
The leash is loose AND the human-robot team is on the predefined route	Follow the predefined route
The leash is loose AND the human-robot team is not on the predefined route AND there are virtual objects that have not been picked up	Move toward the nearest virtual object that has not yet been picked up
The leash is loose AND the human-robot team is not on the predefined route AND all virtual objects have been picked up	Move toward the goal

the observed behavior would not be influenced by the specific maps. After each round, participants were asked three interview questions:

(1) Can you explain the behavior of the robot?
(2) What was your strategy for completing the task?
(3) How did you experience the collaboration?

An overview of the answers given to these questions was given in van Zoelen et al. (2020). For the analyses described in the following sections, the answers to these interview questions were used to support the researchers in interpreting participant behavior.

Participants

A total of 18 people participated in the experiment (9 male, 9 female), consisting of students from different programs within Eindhoven University of Technology, with an average age of 23 (SD = 3.9). The participants were told that the person with the highest number of points on a single run would receive a gift voucher of €10 to motivate them to perform to the best of their abilities. Before the start of the experiment, participants gave their consent after carefully reading the consent form that explained all details of the experiment except for the focus of the research (evolving leadership shifts) and the specific behavior of the robot. After the experiment, they were debriefed on the exact purpose of the experiment.

Data Analysis: Coding Process

While performing the task, a camera placed in a corner of the field recorded the behavior of the participants. These videos were thoroughly analyzed through a process based on Grounded Theory (Charmaz, 2014), using different stages of open coding, closed coding, and categorizing. All videos were coded using an open coding process at first, to get a view on the different kinds of behavior present among participants as well as on events that triggered participants to switch between a more leading and a more following role. Using the results from the open coding, a coding scheme for closed coding was developed that contained codes describing task events, robot movement, participant movement, leash activity and the participant's location relative to the robot. Each code was characterized as a leading, following or neutral behavior (see **Table 4**).

TABLE 4 | The coding scheme that was developed to analyze the behavior of participants and the robot in the experiment.

Code Category	Code
Task events	Task is running
	Object sound
Robot movement	Standing still
	Moving toward object in goal direction
	Moving toward object away from goal
	Moving toward object across field
	Moving with participant
	Moving in goal direction
Participant movement	Standing still/waiting
	Moving around robot
	Moving in goal direction*
	Moving in robot direction
	Moving across field*
Leash activity	Loose
	Stretched*
	Pulled in direction*
	Loosening/stretching
Participant location relative to robot	Behind
	In front of*
	Next to

*Codes marked with a * were considered leading behavior by the participant. The presence of these codes was taken as an indication for leading behavior in all further analyses.*

All videos were then coded again using a closed coding process using The Observer XT (Noldus, 2019). This was done in an iterative manner, where each video was watched and coded again for each code category as specified in **Table 4**. Codes of different categories therefore could exist in parallel (e.g., codes for leash activity and codes for participant movement), while codes within a category (e.g., 'loose' and 'stretched') could not exist in parallel. An exception were the 'task event' codes; these were used to record how long it took participants to finish the task and to be able to see whether behavior lined up with task events. This left us with an overview of whether the participant was in a leading, following or neutral position across the three variables of leash activity, participant movement and participant location at each moment during the task. Combined with the visualization tool in The Observer XT, this enabled us to visually analyze the (development of) different behaviors across rounds simultaneously as well as to quantify the amount of leading behaviors present in each run. Intercoder reliability for the duration of sequences with another coder for 5.6% of the data (videos of 4 runs) was found to be 97.55%.

Previous Results

The task environment presented above has previously been described in van Zoelen et al. (2020). The main findings focused on three aspects:

- Interactions that trigger people to reconsider leadership roles;
- How leader/follower behavior changes over time;
- The interplay between subjective Collaboration Fluency and shifting leader/follower roles.

As the current paper builds upon and greatly extends the results presented in the previously published work, we will summarize these findings in the sections below.

Switch Triggers

An open coding process revealed six types of situations that typically triggered participants to reconsider whether they should behave in a more leading or following way. The first of those situations is at the start of the task, where participants express their initial idea about the role they should take on. The other five triggers are the following:

(1) Sound indicating a virtual object;
(2) A leash pull by the robot;

(3) The robot deviating from the route that leads to the final goal without clear leash pull;
(4) Getting close to the goal;
(5) The robot standing still.

Of these five triggers, numbers 1 and 2 are explicitly visible and clear moments in time, while numbers 3 and 4 are more implicit, slowly emerge and are harder to observe. Number 5 is a special case, as the robot standing still was sometimes clearly linked to the collection of a virtual object, but sometimes emerged more implicitly from the interactions in the task. Besides grouping them in explicit versus implicit triggers, they can also be grouped into task feedback (1 and 4) and partner feedback (2 and 3).

Leading Behavior Development

Apart from direct triggers for reconsidering leadership roles, we looked at how the level of leadership that participants expressed developed over the four different rounds in which the task was executed. Three different dimensions of behavior (leash activity, participant location relative to the robot, participant movement) were looked at separately. We found that for all these dimensions, six types of leadership behavior development could be observed, namely:

- Mostly following (a);
- Start off following, leading in the middle, following at the end (b);
- Start off following, increase of leading over time (c);
- Start off leading, increase of following over time (d);
- Start off leading, following in the middle, leading at the end (e);
- Mostly leading (f).

We categorized each dimension of behavior (leash activity, participant movement and participant location) into one of those types of leadership behavior development for each participant. This resulted in a very wide distribution of behavior, showing that participants engaged in highly personal ways of dealing with leadership roles and shifts in the context of the task. While many participants could be categorized in the same type of behavior for at least two of the dimensions (meaning that participants themselves behaved relatively consistently), the pattern of combined dimensions was unique for almost every participant. For a distribution of participants across the behavior development types, see **Table 5**. To understand how these types of behavior relate to task performance, we created a boxplot of the task performance related to each category of behavior development, using the categorization based on leash activity (**Figure 4**). Given the small number of participants, it is impossible to draw any hard conclusions from this (especially about category (a) and (b), as only one participant was categorized in either of those). Realistically, only (d) and (f) provide relevant information since both these categories contain 6 participants; it is interesting to see that in this case, the category that is more balanced (d) indeed scores better than the category in which participants were strongly leading all the time (f).

TABLE 5 | An overview of the distribution of participants across all six behavior development types for each behavior dimension (leash activity, participant location and participant movement).

	Leash activity	Participant location relative to robot	Participant Movement
Mostly following (a)	4 (n = 1)	4, 15 (n = 2)	15, 11 (n = 2)
Start off following, leading in the middle, following at the end (b)	13 (n = 1)	13 (n = 1)	18, 13 (n = 2)
Start off following, increase of leading over time (c)	14, 1 (n = 2)	7, 14, 10 (n = 3)	2, 12, 14, 1, 10 (n = 5)
Start off leading, increase of following over time (d)	3, 16, 7, 18, 15, 11 (n = 6)	3, 18 (n = 2)	8, 6, 3, 16, 7, 4 (n = 6)
Start off leading, following in the middle, leading at the end (e)	5, 12 (n = 2)	5, 12, 16, 1 (n = 4)	5 (n = 1)
Mostly leading (f)	9, 17, 2, 8, 6, 10 (n = 6)	9, 17, 2, 8, 6, 11 (n = 6)	9, 17 (n = 2)

Each number represents a participant.

Subjective Collaboration Fluency and Leadership Roles

Besides behavioral data, subjective Collaboration Fluency was also measured after each round of performing the task using a questionnaire, based on (Hoffman, 2019). We found that the score on this questionnaire increases significantly over time. This effect was visible within three runs of performing the task. This means that regardless of how people behave, the way in which participants interacted with the robot enabled them to develop a more fluent collaboration over time.

We also found that there was a weak (but significant) negative correlation between the Collaboration Fluency score and the amount of leading behavior people expressed through the leash and movement. This means that when participants were less willing to follow the robot, they also regarded the robot as less cooperative.

Analyzing Behavior to Uncover Interaction Patterns

The fact that participants were able to develop a fluent collaboration with the robot, while still showing a wide variety of behaviors, prompted us to have a closer look at the specific adaptive behaviors and interactions that emerged in this task. In the following sections, we will explain in more detail how we approached this further analysis as well as the results.

Data Analysis: Extracting Interaction Patterns

Using visualizations of the video coding, we studied the videos in more detail, paying specific attention to moments at which adaptations took place (moments at which the codes switched from a leading to a following code for example). We described the specific interactions that we observed at such moments, as well as the interactions of what happened in between those moments.

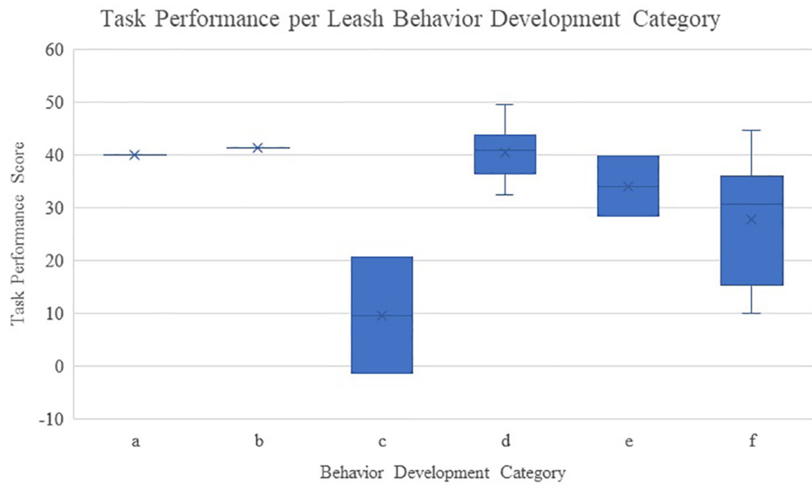

FIGURE 4 | An overview of the task performance of participants per category. For each participant, the average score of the four rounds was calculated. The categorization is based on which category participants were in when looking at their leash activity only: (a) mostly following, (b) start off following, leading in the middle, following at the end, (c) start off following, increase of leading over time, (d) start off leading, increase of following over time, (e) start off leading, following in the middle, leading at the end, (f) mostly leading.

In this process, we tried to focus on the smallest relevant unit of interaction (we will refer to these as unit interactions later in the paper). If it was unclear what a participant was doing at a specific instance, we looked at transcriptions of the interview questions to be able to reliably interpret the intention behind their actions.

The resulting list of interactions was categorized by manually clustering them, after which we described all these different interactions using more general concepts. This process can again be seen as another iteration of open coding: we carefully read each observed interaction and created a code (or sometimes a few codes) to describe the interaction. Within this process we tried to use similar words as much as possible, to keep the list of codes as short as possible. With this process, we aimed to make the interactions less dependent on the specific context of the task executed in the experiment, and more generally applicable. Such more generally applicable interactions are usually called patterns in literature (van Diggelen et al., 2019), and are often used as reference for designing human-technology interactions across different contexts. Important to note here is that patterns are not completely generalizable; they are part of a category of concepts that are called 'intermediate-level knowledge'(Höök and Löwgren, 2012). They are more abstracted than a single instance, but are not as generalizable as a theory. Their value comes specifically from the fact that they are relatively close to an actual context and task, while being applicable to a range of task and contexts. We will call the more generalized versions of the observed interactions *interaction patterns*. Besides a specification of these interaction patterns themselves, we have tried to combine them into sequences to create larger interaction patterns. Also, we have specified how certain interaction patterns related to others. The combination of the set of interaction patterns (the interaction vocabulary) and the details on how they can be combined and relate to each other will be referred to as the *pattern language*.

RESULTS: INTERACTION PATTERNS

Below, we will describe in detail the outcomes of the analysis of the interactions and interaction patterns. As mentioned above, we will describe exactly what interactions were extracted from the video data, how they were categorized and generalized into interaction patterns and how they can be combined into larger sequences.

Observed Interactions

By analyzing the videos of the collaboration between the human participants and the robot, a list of 34 types of interactions could be distinguished. They are the unit interactions: the smallest relevant co-adaptive interactions than can be described within the context of the experiment. These interactions were categorized in four types:

- Stable situations (10 interactions): interactions observed *in-between* adaptations, such as the interaction of the human leading and the interaction of the robot leading.
- Sudden adaptations (17 interactions): interactions in which the human and/or robot adapted their leader or follower role, therefore starting a transition from one stable situation to another. The adaptation happens in a single moment, over a short period of time, often in response to an event in the task or partner.
- Gradual adaptations (5 interactions): interactions in which the human and/or robot adapted their leader or follower role, therefore starting a transition from one stable situation to another. The adaptation happens gradually over a longer period of time, often in response to a newly hypothesized or discovered property of the partner's behavior.

- Active negotiations (2 interactions): interactions in which there was a sequence of several short adaptations that eventually also lead to a transition between stable situations.

The full list of these observed interactions and their categorization can be found in **Appendix A**, but some examples are the following:

- Stable situations: 'Human speeds forward dragging the robot along', or 'robot is in the lead but human actively runs around robot taking into account the route'.
- Sudden adaptations: 'Human changes direction, thereby loosening the leash, setting the robot free', or 'human pulls the leash and moves to the goal when getting close to the goal'.
- Gradual adaptations: 'Gradually the robot leads more'.
- Active negotiations: 'Alternating pulling the robot in a specific direction, waiting for the robot to go, then following the robot'.

The behavior of all participants in the experiment can be described as sequences of these unit interactions, thereby generating larger and higher level interactions.

Interaction Patterns for Adaptive Leader-Follower Behavior

The above described interactions are specifically related to the experimental task. In order to be able to apply them to other contexts, it is necessary to describe them in more general terms. Therefore, we formulated them into general interaction patterns that can appear in any human-robot collaboration where leader-follower dynamics are relevant. **Appendix A** shows how the observed interactions were described with interaction patterns. Important to note here is that some of the more complex interactions were described using two or three interaction patterns, while some interaction patterns were also used to describe more than one observed interaction. **Table 6** presents a list of the resulting more generalized interaction patterns, including their category and a short description.

The relatively long list of sudden adaptations contains a diversity of interaction patterns. Some of them are triggers for adaptation (e.g., 'unexpected action by a team member'), while others are outcomes (e.g., 'team member stops with what they're doing, waits'). After a closer look at the list we believe that four components can be distinguished within these sudden adaptations:

- External trigger: an event outside of the partner (e.g., in the task, environment or other partner) triggers an adaptation to a new stable situation;
- Internal trigger: an event inside of the partner (e.g., a specific expectation or change of mind) triggers an adaptation to a new stable situation;
- Outcome: a specific action that is preceded by an internal or external trigger, that will gradually develop into a new stable situation afterward;

TABLE 6 | The interaction patterns identified from the behavioral data, including a description of what they entail.

Category	Concept	Description
Stable situation	Human following	Human lets the robot do its task
	Human actively on top of things, actively supervising	Human is constantly in touch with the robot
	Active observation by human	Human is actively observing what the robot is doing
	Human leading	Human leads the robot
	Human executing the robot's task	Human executes the task of the robot
	Proactive following by human	Human actively predicts and observes what the robot will do, following their course of action
	Human dragging the robot along while doing all the work, the robot is a burden	Human ignores the robot as much as possible while focusing on completing the task
	Human focuses on their own task, but leaving time for the robot to catch up	Human executes their own task while leaving space for the robot to follow them in that course of action
Sudden adaptation	Unexpected action by a robot team member	The robot does something the human did not expect, possibly triggering a leadership shift
	Human waiting for the robot to finish their task	The human waits for the robot to finish their task, and decides on a leadership role after that
	Human trying to finish the robot's task when the robot is done	When the robot has finished their task, the human takes over the task to see if it can be improved upon
	Partner-interfering mistake	The robot makes a mistake that directly and strongly interferes with the human's course of action
	Human losing contact with the robot due to focus on own task	The human focuses very much on their own task, therefore lose contact with the robot
	Being close to finishing the task	The team is very close to finishing the task, which possibly triggers a leadership shift
	Human actively making up for the robot's limitations	The human foresees a limitation of the robot will hinder their performance, therefore undertakes action to avoid that
	Task achievement	A task achievement is reached, possibly triggering a leadership shift
	Human urging the robot to be more active, 'come on'	The robot is relatively passive, causing the human to actively urge the robot to be more active
	Human stops with what they're doing, waits	The human suddenly stops with what they are doing to wait, after which a new leadership role is chosen
	Repeating previous behavior patterns	The human recognizes a situation similar to an earlier situation, and repeats the behavior previously executed

(Continued)

TABLE 6 | Continued

Category	Concept	Description
	Human recognizing the autonomy of the robot	The human recognizes the autonomous capabilities of the robot, possibly triggering a leadership shift
	Quick response to leadership shifts due to continuous connection	Due to continuous contact between the team members, a leadership shift initiated by one team member is quickly and smoothly followed by the other
	Robot becomes active after being inactive	After a period of waiting of being inactive, the robot suddenly becomes active again, possibly triggering a leadership shift
Gradual adaptation	Human gradually letting the robot do more	The human gradually lets the robot do more over time
	Human learning to predict the robot's behavior	Over time, the human gradually gains insight into the robot's behavior, thereby enabling them to better predict their behavior
	Human trying to regain control in different ways until eventually taking the lead	Over time, the human attempts to take the lead and regain control in different ways, to eventually find a way to keep taking the lead
Active negotiation	Human executing leading in short intervals	The human takes the lead several times in short intervals, observing what the robot does in the following intervals, to actively search for and negotiate a new stable situation

TABLE 7 | The interaction patterns that fall in the category of sudden adaptations described in more detail.

Interaction Pattern	Type of sudden adaptation
Unexpected action by a robot team member	External trigger
Human waiting for the robot to finish their task	In-between-situation, preceded by trigger of the other partner working on a specific subtask, succeeded by a new stable situation
Human trying to finish the robot's task when the robot is done	External trigger and outcome
Partner-interfering mistake	External trigger
Human losing contact with the robot due to focus on own task	Internal trigger and outcome
Being close to finishing the task	External trigger, followed by any outcome
Human actively making up for the robot's limitations	Internal trigger (expectations) and outcome
Task achievement	External trigger
Human urging the robot to be more active, 'come on'	Outcome, preceded by trigger of the other being inactive
Human stops with what they're doing, waits	Outcome, preceded by any trigger
Repeating previous behavior patterns	Outcome, preceded by internal trigger
Human recognizing the autonomy of the robot	In-between-situation, preceded by external trigger (behavior of the other), succeeded by a new stable situation
Quick response to leadership shifts due to continuous connection	In-between-situation, preceded by any trigger, succeeded by a new stable situation
Robot becomes active after being inactive	Outcome and internal trigger

- In-between-situation: a specific action that is preceded by an internal or external trigger, that serves as a new trigger for adapting to a new stable situation afterward.

To understand how combinations of these components constitute an interaction pattern, each interaction pattern has been described using the above components in **Table 7**.

Using the extended description of the interaction patterns, we can create sequences of them to describe and analyze behavior that participants showed in the experiment. Examples of those are shown in **Figure 5**. The sequences shown in the figure all represent behavior that participants showed at a specific point in the task. For example, the top sequence is behavior shown by participant 14 in round 2. They were following the robot to pick up the object (stable situation, following). At some point, they were approaching the goal (the robot was also moving toward the goal), which triggered the participant to try to take over the robot's task by further exploring the field for objects (sudden adaptation, being close to finishing the task and trying to finish the other's task when the other is done). To urge the robot to follow, the participant pulled the leash in short intervals, but as the robot had already collected all objects, it would continue to move to the goal when the leash was loose (active negotiation, executing leading in short intervals). This resulted in the participant giving in and they again followed the robot (stable situation, following). Another interesting example is the sequence from participant 5, shown in round 4. The participant was focused on reaching the goal (stable situation, leading), when the robot drove over the participant's feet in an attempt to move with the participant (sudden adaptation, partner-interfering mistake). This caused the participant to immediately take over the robot's task by exploring the field for objects themselves (stable situation, taking over the other's task).

From these examples, it can be seen that sometimes different stable situations can exist at the same time to form more complex behavior. Also, different adaptations can happen after each other before a new stable situation is reached. This usually happens when a sudden adaptation is described as an outcome or an in-between-situation. Using sequences of interaction patterns of varying lengths, we can look at the dynamics of co-adaptation at different levels of complexity. This allows us to analyze the effect that small, short-term adaptations have on the overall development of leader-follower roles, but also to dissect large sequences of observed behavior into small units. An explanatory overview of how the observations translate into sequences of interaction patterns is given in a video in **Supplementary Material Appendix B**.

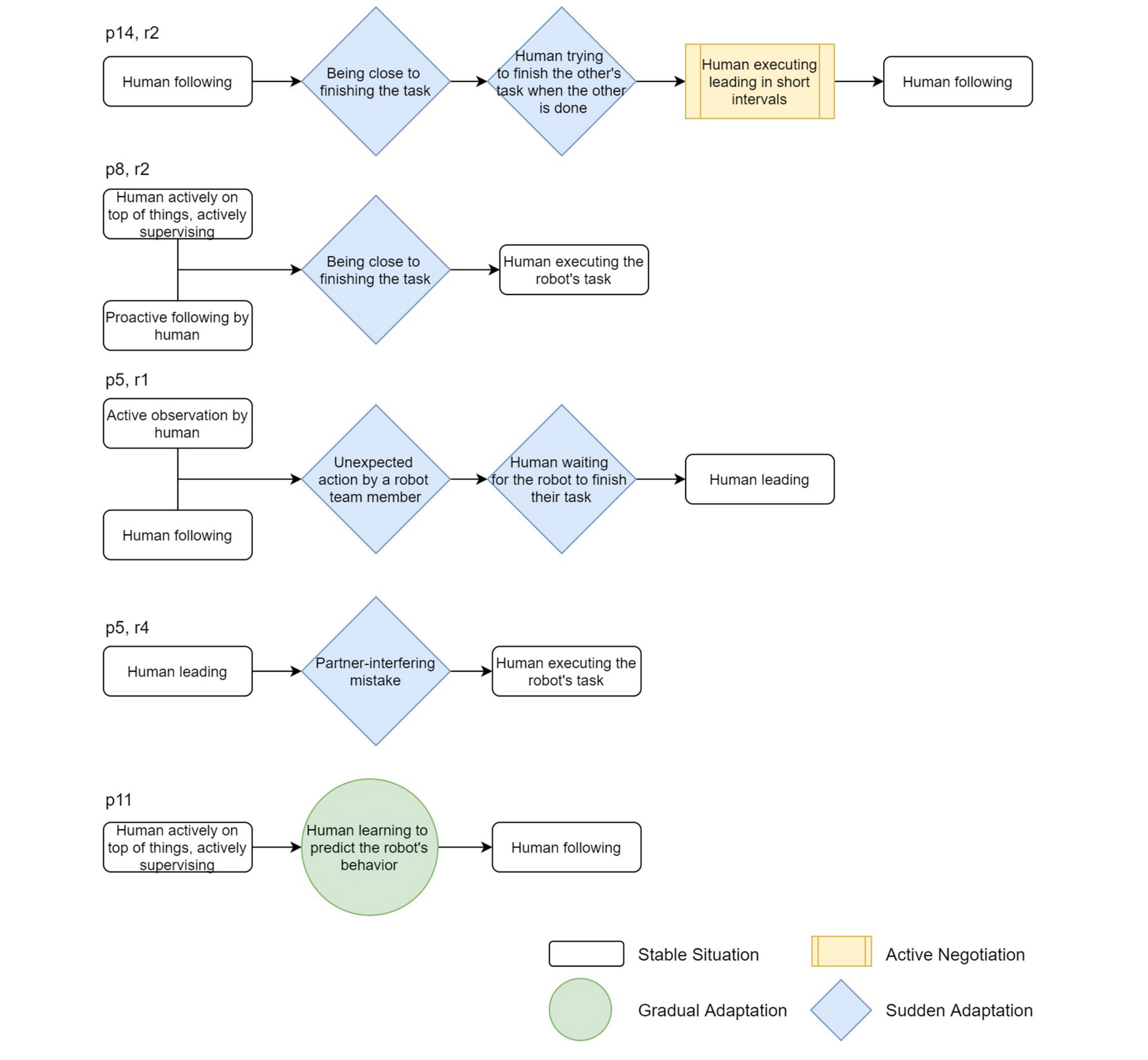

FIGURE 5 | Several example sequences of interaction patterns as they appeared in the experiment.

CONCLUSION AND DISCUSSION

We have studied the process of co-adaptation within the context of human-robot collaboration. We focused on the adaptations that emerge within the team as a result of interactions around dynamic leadership roles and complementary capabilities. An embodied approach was taken to study subtle and unconscious interactions that manifest themselves in observable physical behavior. We believe that the design of our experiment provides a different way of looking at HRI; one imposes little assumptions about interactions on the design, and that allows for natural interactions based on affordances. In the sections below, we will go into more detail on how the different aspects of our results can be of use for future HRI research and design.

Interaction Patterns and Team Design Patterns

We have extracted a list of interaction patterns from observed human-robot team behavior. The idea of describing human-robot or human-agent team behavior with patterns has been explored before, such as in van Diggelen et al. (2019); van Diggelen and Johnson (2019); van der Waa et al. (2020), under the name 'Team Design Patterns.' In existing research, it is described how these patterns can be useful for designers of human-robot teams, as well as for the actual team members to recognize what activities they are engaged in. These existing *pattern languages* are generally created in a top-down approach. While (van Diggelen et al., 2019) mention that Team Design Patterns can *emerge* from interactions between the human(s) and agent(s) in the team, the pattern languages described in van Diggelen and Johnson (2019); van der Waa et al. (2020) are still designed by the authors of the paper, although the design process is not described in detail. We deliberately use a different name to describe the patterns in our pattern language (interaction patterns instead of team design patterns), because our interaction patterns have not been designed. Rather, they were extracted from existing observations, while they emerged naturally from the context of the human-robot team task. While the Team Design Patterns are very useful, we believe that it is important to also study interactions in human-robot teams in a bottom-up manner, to represent the processes that occur naturally within teams when members collaborate in the real world. The embodied approach of our study enabled us to generate a new interaction pattern language that is based completely on empirical data. It describes the interaction patterns as an emergent feature, while we attempted to keep our own projections of human-only team interactions out of the analysis. Therefore, they can be used as a library of existing natural interactions when designing human-robot interactions; they provide pointers for what natural and fluent co-adaptive HRI can look like.

The approach of studying embodied interactions in a natural setting, and the development of a language to interpret the observed interactions, enabled us to identify the interaction patterns that underly the co-adaptation processes taking place within a team. The interaction patterns can be used in other contexts, other tasks, and other teams, due to our efforts to describe them in a way that is as context-independent as possible. This positions our work as an addition to the work of other researchers (van Diggelen and Johnson, 2019; van der Waa et al., 2020) who study team behavior at a higher level of abstraction, that is more focused on team composition and task division. In the design of and research into human-robot or human-agent teams, both types of pattern languages can be used in different stages of the process. The high-level pattern languages can be used for deciding on team composition and general collaborative interactions, while the elements in the lower level pattern language we describe can serve as pointers for designing the specific detailed interactions between the team members that elicit or support effective team behavior.

Interaction Pattern Language

The interaction patterns that we have described show that leader-follower dynamics can be described using the concepts of *stable situations, sudden adaptations, gradual adaptations,* and *active negotiations*. They give us a better understanding of the subtleties in leader-follower dynamics: very often it is not so much a matter of leading *or* following, but a bit of both: leadership roles constantly shift, and very often leadership is divided across the team members. The complete pattern language, consisting of interaction patterns as the vocabulary and the connections between them as grammar, provides a framework for analyzing co-adaptive interactions in human-robot collaborations, also in contexts different from the one used in our experiment. Using our pattern language to describe interactions can make it easier to understand why specific role divisions emerge and what can be done to change them.

Moreover, the pattern language can be used by collaborating humans and robots for when they want to communicate about the interactions they are engaged in. The different concepts described by the pattern language can for example be used in a knowledge base for the robot (e.g., in the form of an ontology). This can support the team members in becoming aware of their current leadership roles and possible developments in those roles, to give them more agency in making strategic decisions about the collaboration.

Relation to Existing Interaction Taxonomies

Our pattern language shows similarities to the interaction taxonomy described in Madan et al. (2015). More specifically, their description of *harmonious interactions* is similar to what we consider *stable situations*, while their description of *conflicting interactions* has overlap with our *sudden adaptations* and *active negotiations*. Our pattern language therefore partly confirms, but also extends their interaction taxonomy. We provide a more detailed description and categorization of their *conflicting interactions*, by expressing the difference between *sudden adaptations* and *active negotiations*, and by also adding *gradual adaptations*. Related to this, we feel that the term *adaptation* is more encompassing than *conflict,* as not all adaptive interactions within these categories come from a directly observable conflict. Moreover, we provide a detailed and task-independent description of the different types of *sudden adaptations*. The extensions originate from the fact that we explicitly focused on interactions that drive co-adaptation, rather than collaborative interaction in general. Moreover, through our extended description of *sudden adaptations,* we provide information on how different interaction patterns relate to each other (i.e. the 'grammar' of our pattern language), where in the work of Madan et al. (2015) only the taxonomy is provided (i.e. the 'vocabulary'). Our interaction patterns are also more detailed than those presented in the existing literature. They are described in such a way that they can also be used to design interactions, rather than to just analyze them.

In terms of the lower level interaction patterns, both the work of Madan et al. (2015) and our work are to some extent related to the task used to obtain them. Their interaction patterns were generated in the context of collaborative object manipulation, while ours were generated within a collaborative navigation context. We, however, explicitly formulated the interaction patterns in such a way that they are generally applicable outside of this initial context. To understand the extent of their generalizability, further evaluation in other task contexts will be useful.

Limitations

While the list of interaction patterns is quite extensive, it is probably not complete. The specific task context that we used in our experiment of course limits the kind of interactions possible. Also, while the analysis of the data was done in a systematic manner, it is bounded by the frame of reference of the researcher. In order to obtain evidence for the relevance of the proposed language, it is important to attempt to apply the analysis of interaction patterns used here to other tasks. That will provide more insights into the extent of the generalizability of the pattern language, as well as into necessary extensions or adjustments.

Furthermore, there are a few limitations forthcoming from the manner in which the task in the experiment was executed. We claim to study human-robot teamwork, butin our experiment a human operator controlled the robot following pre-configured rules. It may be that the robot behaved different from how a real robot would behave. Moreover, the participants were aware of the fact that the robot was controlled by a human operator, and even though a pilot study showed us that participants did not pay much attention to the operator, it may have still influenced the interactions that emerged. The task was also defined with a relatively low level of agency of the robot, causing the robot to initiate few adaptive behaviors. It is likely that participants noticed this, therefore it might have influenced their initiative to take or delegate leadership. Moreover, we studied a human-robot team in the form of a dyad, whereas the dynamics of team interactions can be very different for other (larger) team compositions. This again stresses the importance of testing the results of the present study in other tasks and contexts and, if possible, with real robots and different team compositions. Outcomes of such studies will help to elaborate and refine the interaction pattern language, eventually enabling a better understanding of co-adaptation in human-robot teams. This, in turn, will support the design of adaptive human-robot teams that are able to operate successfully in the complexity of the real world.

Final Conclusion

By observing embodied interactions within a human-robot team, we have extracted an interaction pattern language that can be used to describe co-adaptive behavior. This pattern language consists of a list of interaction patterns (the vocabulary) that together make up the different elements of co-adaptation. The interaction patterns can be categorized into stable situations, sudden adaptations, gradual adaptations and active negotiations. Furthermore, the sudden adaptations are built up of external triggers, internal triggers, outcomes and in-between-situations. These categorizations and concepts can be used to link different interaction patterns together, to make sequences of co-adaptive behavior. They can therefore be seen as the grammar of our pattern language.

In future studies, we will use the pattern language to analyze co-adaptive behavior in different tasks and contexts. We will analyze how the presence of certain interaction patterns influences team behavior and performance, to validate how useful the different patterns are in creating successful human-robot teams that make use of fluent co-adaptations.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

ETHICS STATEMENT

The study involving human participants was reviewed and approved by the Ethical Review Board of the Industrial Design Department at Eindhoven University of Technology (reference: ERB2019ID7). The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

EZ did the main research design, experimentation and analysis, as well as most of the writing. The experiment design and execution was done under supervision of MR, while the data analysis was done under supervision of KB and MN. EB, MR, KB, and MN all reviewed and edited the manuscript at different stages of the process. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2021.645545/full#supplementary-material

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frontiers in Neurorobotics

ORIGINAL RESEARCH
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Exploring the Embodiment of a Virtual Hand in a Spatially Augmented Respiratory Biofeedback Setting

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Enhancing the embodiment of artificial limbs—the individuals' feeling that a virtual or robotic limb is integrated in their own body scheme—is an impactful strategy for improving prosthetic technology acceptance and human-machine interaction. Most studies so far focused on visuo-tactile strategies to empower the embodiment processes. However, novel approaches could emerge from self-regulation techniques able to change the psychophysiological conditions of an individual. Accordingly, this pilot study investigates the effects of a self-regulated breathing exercise on the processes of body ownership underlying the embodiment of a virtual right hand within a Spatially Augmented Respiratory Biofeedback (SARB) setting. This investigation also aims at evaluating the feasibility of the breathing exercise enabled by a low-cost SARB implementation designed for upcoming remote studies (a need emerged during the COVID-19 pandemic). Twenty-two subjects without impairments, and two transradial prosthesis users for a preparatory test, were asked (in each condition of a within-group design) to maintain a normal (about 14 breaths/min) or slow (about 6 breaths/min) respiratory rate to keep a static virtual right hand "visible" on a screen. Meanwhile, a computer-generated sphere moved from left to right toward the virtual hand during each trial (1 min) of 16. If the participant's breathing rate was within the target (slow or normal) range, a visuo-tactile event was triggered by the sphere passing under the virtual hand (the subjects observed it shaking while they perceived a vibratory feedback generated by a smartphone). Our results—mainly based on questionnaire scores and proprioceptive drift—highlight that the slow breathing condition induced higher embodiment than the normal one. This preliminary study reveals the feasibility and potential of a novel psychophysiological training strategy to enhance the embodiment of artificial limbs. Future studies are needed to further investigate mechanisms, efficacy and generalizability of the SARB techniques in training a bionic limb embodiment.

Keywords: embodiment, augmented reality, prosthetics, biofeedback, training, breathing

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INTRODUCTION

Artificial limbs are designed to assist and increase the manipulation capabilities of human beings in contexts from teleoperation to virtual rehabilitation, to bionic prosthetics (Makin et al., 2020). In order to nurture the progress of this research domain, scientists considered the results of studies on topics like the proprioceptive illusions in people with a spinal cord injury (Fusco et al., 2016) or the applications of error-related potentials in neuroprosthetics (Iturrate et al., 2015). Through the integration between neuroscience and engineering, interdisciplinary research has offered inspiring strategies like developing neurointerfaces to control virtual and robotic systems (Tidoni et al., 2016) or neuromorphic systems to bring the sense of touch to the prosthesis users (Rongala et al., 2018).

Artificial limbs can be perceived by certain users as tools, while others can feel them as corporeal structures (Murray, 2004). In this second case, these robotic or virtual extensions of the user can trigger the phenomenon of embodiment, i.e., the psychological process occurring when subjects feel external objects as integrated in their own body scheme (Mor and Makin, 2020).

However, the embodiment process is not limited to artificial limbs, and can involve any artifact or tool (Pazzaglia and Molinari, 2016). Initially, this process makes the device more familiar for the users who have become curious about it. Subsequently, the mental representations of the users start to adjust to progressive human-artifact integration (Nelson et al., 2020). Feeling a device as embodied leads to improvements in user's engagement, technology acceptance, control transparency, and, consequently, human-machine system performance (Toet et al., 2020).

Typically, the investigations in this domain aim at establishing effective methods to enhance the embodiment through the manipulation of the stimulus-conditions (Ratcliffe and Newport, 2017) or the active control conditions of artificial limbs (Brugada-Ramentol et al., 2019). However, literature on interoceptive processes (Allen and Tsakiris, 2018) suggests that an individual's psychophysiological control potentially impacts on embodiment components like body ownership. It is hypothesized that respiratory entrainment techniques (Czub and Kowal, 2019) like those used in contemplative mental training and biofeedback (Bornemann, 2017), may influence the embodiment process.

This paper preliminarily investigates whether modulating one's psychophysiological state via respiratory biofeedback can enhance the embodiment of a virtual, computer-generated hand**.** Our research was carried out through a pilot study using common devices like a computer monitor, a smartphone, and a microphone. This last choice was made to explore the potential of a setup that can be replicated at home without the need for special equipment. Evaluating the feasibility of this setup is our second scope for extending the upcoming data collection (bypassing also the restrictions of the current pandemic) (Woolliscroft, 2020) through this innovative "embodiment training" approach.

Abbreviations: AR, augmented reality; BVP, blood volume pressure; EEG, electroencephalography; GSR, galvanic skin response; HR, heart rate; MR, mixed reality; RHI, rubber hand illusion; RR, respiratory rate; SAR, spatial augmented reality; SARB, spatially augmented respiratory biofeedback; SCP, slow cortical potential; VHI, virtual hand illusion; VR, virtual reality; XR, extended reality.

BACKGROUND AND SCOPE

Related Works

As hinted above, several studies on embodiment (Niedernhuber et al., 2018) aim at improving human-machine interaction with special attention to artificial limbs user experience, especially to reducing prosthetic devices abandonment (Beckerle et al., 2019) and promoting their acceptance and integration (Shaw et al., 2018). Indeed, the results of embodiment studies are quite helpful to guide the design of novel artificial limbs through an improved understanding of user experience: a survey involving 2,383 limb amputees highlighted how naturalistic prostheses designed with sensory feedback were associated with higher feeling of prosthesis ownership and reduced phantom pain (Bekrater-Bodmann et al., 2021).

According to literature (Toet et al., 2020), the sensations of ownership (the feeling that non-bodily objects are body parts and sources of bodily sensations, depending on the integration of multisensory inputs), self-location (the feeling of the body location in space, depending on the co-location of fake and real elements), and agency (the feeling of being the cause and the author of observed actions, depending on the efficiency of limb motor control) constitute the embodiment (Kilteni et al., 2012) process itself.

Considering the case of artificial upper limbs, the investigation of their embodiment is usually entrusted to methods for evaluating a well-known phenomenon that demonstrated high potential in experimental and clinical neuroscience research (Ramakonar et al., 2011): the Rubber Hand Illusion (RHI) (Botvinick and Cohen, 1998). RHI is typically induced by the co-occurrence of visual stimulations on an inactive fake limb observed by the subjects and tactile stimulations on their real hand (Kammers et al., 2009).

In particular, RHI studies offer important pointers toward investigating the ownership component of embodiment. The body ownership is especially critical in the acceptance of artificial limbs—see Ehrsson et al. (2008) and Beckerle et al. (2018). This aspect of the embodiment was investigated through multiple studies, considering, for instance, its relationships with sensory stimulations (Ehrsson et al., 2005) and other embodiment components—agency (Tsakiris et al., 2006) and self-location (Romano et al., 2015). Interestingly, RHI can also generate phenomena of disembodiment as the disownership of the hidden real hand (Lewis and Lloyd, 2010). These and other seminal studies have contributed to the research in this area, which embraced topics like the impact of affective processes (Crivelli and Balconi, 2020) or the psychopathological aspects (Prikken et al., 2019) in body ownership representations.

These are just examples of the body ownership literature, which is rich with original methodological solutions to assess how this phenomenon occurs in different conditions. Overall, the body ownership is typically evaluated in RHI paradigms through measures like subjective evaluations (e.g., self-report questionnaires) (Romano et al., 2021) or physiological reactions (e.g., Galvanic Skin Response, GSR) (Grechuta et al., 2017). Another classic measure of ownership is the proprioceptive drift (Tsakiris and Haggard, 2005) toward the artificial limb when the subjects are asked to estimate the actual position of their own hand, usually hidden and apparently replaced by a fake one during the experimental session. This implicit measure is performed in different ways according to the experimental setting—e.g., a virtual version in Ma et al. (2021).

It must be noted that the use of such body ownership measures in RHI studies is still debated: for instance, distinctions between subjective questionnaire scores and proprioceptive drift (Gallagher et al., 2021) should be further investigated to understand different processes underlying the subjective evaluation and the proprioception.

Alongside the research on the heterogenous manifestations and measures of the ownership, literature has also shown structured models to understand its role within the bodily representations. According to Tsakiris (2010), body ownership depends on the interplay between the current multisensory input (bottom-up processes) and the internal models of the body (top-down modulation) that phenomenologically lead to conditions like the RHI (Tsakiris and Haggard, 2005). Specifically, the malleability of bodily representations can depend on interoception (Herbert and Pollatos, 2012), the perception of the internal state of the body. In particular, individuals with low interoceptive sensitivity (assessed through a heartbeat monitoring task) experience a stronger illusion of ownership in RHI (Tsakiris et al., 2011).

Within this research domain, typical methodologies based on purely exteroceptive visuo-tactile stimulations tend to be substituted by combinations of interoceptive and exteroceptive signals, like cardio-visual stimulations (Allen and Tsakiris, 2018). For instance, observing a virtual hand that is pulsating in synchrony with participant heartbeat can induce body ownership changes as reported in RHI experiments (Suzuki et al., 2013). Other studies investigated heartbeat-evoked electroencephalographic (EEG) potentials and their role in bodily self-consciousness (Park et al., 2018).

The role of interoceptive sensitivity in RHI was also investigated in Xu et al. (2018). Specifically, authors studied the effects of meditation and mindfulness practices—like respiratory control or heartbeat control—on RHI susceptibility. Authors highlighted how meditators subjectively rated the RHI less strongly than non-meditators. These results are coherent with the ones of Cebolla et al. (2016) on the agency perceived by meditators in RHI, and with Tsakiris et al. (2011). However, in Xu et al. (2018), no difference in proprioceptive drift was found between these meditators and non-meditators, and different interoceptive awareness factors were associated with RHI intensity in meditators. Thus, it can be inferred that practicing meditation could lead to different embodiment experiences when subjected to an interoceptive training to flexibly shift attention along the body; it makes the person more resistant to abnormal sensations.

This conclusion suggests the possibility that our malleable body representations could be affected by meditation exercises. However, the evidence in Xu et al. (2018) was based on a typically passive RHI procedure executed by people who previously practiced meditation techniques. The prior meditation experience had, apparently, shaped the people's interoceptive sensitivity and body awareness before any RHI experience. This led us to a question: how could certain exercises practiced in meditation affect the embodiment of an artificial limb if they directly contribute to making an artificial limb illusion happen? An answer to this question could lead to novel approaches of embodiment training based on active self-regulation techniques that assist the artificial limb ownership.

In the current study, we targeted a core component of meditation practice, i.e., the breathing (Brenner et al., 2020), particularly slow breathing, which is commonly performed at 6–10 breaths per min. Slow paced breathing produces multiple psychophysiological changes (Zaccaro et al., 2018), characterized by a generalized relaxation across, for instance, cardiovascular and cortical domains, especially with regard to meditation (Yu et al., 2018). Overall, this respiratory exercise has pervasive effects on autonomic functions, downregulating them (Russo et al., 2017). Furthermore, these effects can involve the interoceptive awareness (Weng et al., 2021) through a self-regulation that is relatively easy for a practitioner. Here, we considered respiratory biofeedback (targeting 0.1 Hz respiratory rate)—self-modulating the Respiratory Rate (RR) according to its visualization (Blum et al., 2020)—for its effectiveness in influencing the physical and mental states has been shown in literature (de Zambotti et al., 2019).

In order to proceed with our investigation, we decided to adopt a promising approach for exploring embodiment processes like the body ownership through an interactive solution with high perceptual versatility: the Virtual Hand Illusion (VHI) (Raz et al., 2008). VHIs are produced through a setup that offers a complete experimental control of engaging computer-generated scenarios (Milgram and Kishino, 1994) of Virtual Reality (VR—where the perceptual scenario is fully generated by a computer) or Augmented Reality (AR—where virtual items are placed within a real perceptual scene) or Mixed Reality (MR—where virtual items and real items co-exist, often emphasizing the possibility to interact with the first ones as physical objects, according to some authors) (Speicher et al., 2019). Overall, these systems can be considered as cases of Extended Reality (XR), which is becoming a trend in neuroscientific research as well (Parsons et al., 2020).

Thanks to their versatility in controlling the perceptual scene (Tieri et al., 2017) and to their capability to motivate and engage the subjects through game-based features (Škola et al., 2019), XR systems offer fertile opportunities for body ownership studies as demonstrated by IJsselsteijn et al. (2006) and Slater et al. (2008)—for a review on this topic, read Škola and Liarokapis (2016). Such solutions, extremely valuable in clinical applications too (Matamala-Gomez et al., 2021), demonstrate further potential through their compatibility with other technologically advanced approaches like neuromodulation (Kannape et al., 2019). Furthermore, AR solutions are currently explored to train the control of prosthetic systems (Boschmann et al., 2021).

Interestingly, the study in Monti et al. (2020) adopted a VR-based RR biofeedback approach to generate and investigate an "embreathment" illusion by ecologically mapping the subjects' breaths onto a virtual body observed from a first-person perspective, improving the embodiment of the individual on the avatar. The authors highlight the potential of breathing as a natural, continuous, multisensory self-stimulation. Furthermore, they demonstrate the opportunity of implementing such a self-regulation process through an engaging virtual environment.

Summing up, XR settings can be exploited to investigate the effects of a slow respiratory biofeedback exercise as a method to enhance the embodiment of an artificial limb.

Research Objectives

Our hypothesis is that slow respiratory biofeedback, as a self-regulation strategy, can facilitate the embodiment of a virtual hand during a biofeedback training designed to evoke a VHI. Accordingly, this pilot study aimed at comparing two conditions of respiratory biofeedback—slow breathing and normal breathing—in terms of indices of virtual hand ownership sensation. We considered an interactive setup that enables the person to control the perceptual features of a computer-generated hand without moving it (as in typical RHI and VHI). This allows us to focus on the body ownership component of embodiment as a premise for further studies.

Through this proof of concept, we also investigated the feasibility of a protocol designed for remote use, which only requires a computer, a microphone, a monitor, and a smartphone. If successful, this would provide a portable and affordable solution to enable anyone (for example an amputee waiting to receive a prosthesis) to perform at home a novel biofeedback-enhanced embodiment training. This choice was also driven by the need of creating a remote version of this setup for upcoming studies due to the limitations imposed by COVID-19 (e.g., stay home orders).

MATERIALS AND METHODS

Participants

All participants were volunteers from IIT, signed the informed consent and followed the IIT ADVR TELE01 experimental protocol approved (on March 16th, 2020) by the Ethical Committee of Liguria Region in Genoa, Italy. Before recruiting the participants, the sample size was calculated through G*Power v3.1.9.7 (Faul et al., 2007) according to the results of preparatory tests (involving eight subjects) performed to improve the user-centered design of the setup. These results were based on the differences between two conditions in mean (−2.75) and standard deviation (4.36) of proprioceptive drift scores (see Intructions and Tasks) compared through paired samples *t*-test (more restrictive in terms of requirements than non-parametric tests used for other measures like questionnaire scores). Thus, with $\alpha = 0.05$, power $= 0.8$, G*Power estimated a sample size of 22 subjects.

Twenty-two (six females) adults (Age, mean ± SD: 27.4 ± 2.4 years) without disabilities participated in the study. Twenty subjects were right-handed, one subject was left-handed, one subject was ambidextrous. Only two subjects declared to have had respiratory difficulties (respectively moderate asthma and rhinosinusitis) in past. All individuals were free from sensory and cognitive disabilities, and motor impairments derived from neurological conditions, and psychoactive drugs consumptions in previous 6 months. To avoid any potential RHI-resistance of meditators (Xu et al., 2018), all participants were selected as naïve about mindfulness and meditation techniques.

To assess how prosthesis users could approach this kind of task with the proposed setup within an embodiment training protocol, two (66 and 33 years old) male amputees (users of transradial prostheses for the right upper limb) without respiratory issues were also recruited and performed the same procedure as the 22 participants described above, except for the biosignal data collection (simulating the home setting).

Experimental Setup

All experimental sessions took place at Istituto Italiano di Tecnologia (IIT—Genoa, Italy). However, to design a setup compatible with upcoming home-based data collection, we did not use any head-mounted display typically adopted in highly immersive VHI settings with advanced haptic feedback systems (Beckerle, 2021). Thus, we considered the options offered by Spatial Augmented Reality (SAR) (Raskar et al., 1999) environments, where the real world is enriched by displays (including projections) placed across the real setting instead of being worn by the user as in the most typical AR paradigms based on visors (Bimber and Raskar, 2019). In our case, a computer monitor became a screen-based display for SAR. The final setting (**Figure 1**) was constituted by basic equipment available to anyone at home (monitor, smartphone, headphones) with the addition of professional systems for recording biosignals.

To use the setup, the participants (**Figure 1A**) were positioned in front of a monitor (21" with 16:9 ratio, laid-out horizontally, slightly tilted toward them), wearing a headset with a microphone placed in front of their mouth. Black blankets covered the subjects' arms and surrounded the monitor to make the subject focus on the non-immersive virtual scenario presented by the screen (**Figure 1B**)—for the same reason, during the experimental session the environmental light was dim. A laptop (Alienware M15; Windows 10 Home 64 bit) was used to perform real-time processing of the audio data and extract breathing information used for visuo-tactile biofeedback. All participants wore photoplethysmography sensors to collect Blood Volume Pressure—BVP—data (providing a second estimation of breathing events, thus the RR in Hz, in respect to our custom microphone-based system) and skin conductance sensors collecting GSR data (source of potential embodiment-related reactions, expressed in μS) on left hand fingers. Specifically (**Figure 2A**), the BVP sensor was placed on the middle finger, the GSR sensors—Ag/AgCl electrodes mounted without conductive gel as in Visnovcova et al. (2020)—were placed on the middle phalanges

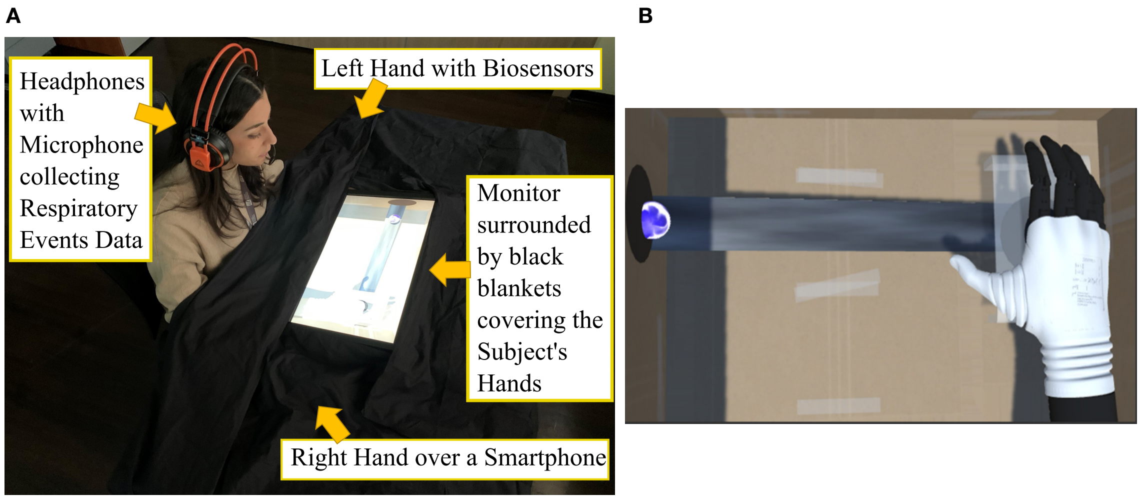

FIGURE 1 | Experimental setting with **(A)** participant and **(B)** scene on the display.

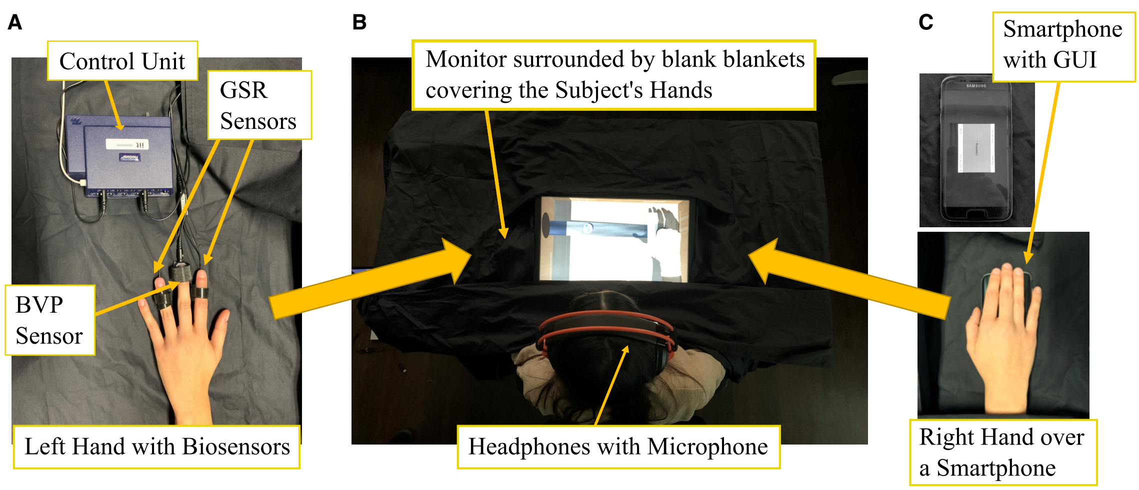

FIGURE 2 | Experimental setup. **(A)** Physiological recording equipment. **(B)** Display and headset. **(C)** Vibratory feedback device.

of the index finger and the ring finger as in Gümüslü et al. (2020).

These sensors constituted an acceptable compromise to record biosignals without excessively altering the individual experience (this reason led to exclude the use of a chest belt). All biosensors were connected to the FlexComp Infiniti control unit (**Figure 2A**), connected to the laptop enabling the SAR scene (**Figure 1B**) and setting (**Figure 2B**). A smartphone (Samsung S7) for vibratory stimulations was placed under their right hand (**Figure 2C**).

Coherently with the SAR concept, this setting showed a continuity between the subjects' body and the virtual hand presented by the display, just like a prosthesis would replace a missing limb or a rubber hand would be placed in the typical RHI studies. Specifically, the screen presented an interactive environment developed in a Unity (https://unity.com) game project comprising 13 scenes per experimental condition.

This environment represented the inside of a cardboard box containing, on the right half, the 3D model of the Hannes (Laffranchi et al., 2020) prosthetic hand (**Figure 1B**). The choice of using the model of an actual prosthesis was made to allow for upcoming comparisons with real settings including the actual Hannes system in RHI-like studies. The hand model was created with the 3D design program Blender (https://www.blender.org) starting from single-part STL files of the Hannes prosthetic hand to preserve the real joint axes and related joint movements of the human hand. The Blender object was, then, imported in the Unity scenes, maintaining the properties of its different parts.

Inside the virtual cardboard box, a blue sphere "made of energy" (an engaging game-like design imported from a Unity package: ArtStation—Glowing orbs VFX, Vladyslav Horobets) slid from left to right on an inclined surface, coming out from a hole on the left side of the box. In 1 min, the sphere reached a black area (designed to magnify the position of the trial goal) with a hole placed under a right virtual hand, leant on a support that represents the presence of the smartphone under the real limb of the subjects. A hole through the virtual support enables the "contact" between the computer-generated hand and sphere. **Figure 1B** depicts the scene.

This SAR setting was then enriched by respiratory biofeedback features (based on RR data collected through the microphone of the earphones) within a Spatially Augmented Respiratory Biofeedback —SARB—paradigm. In this SARB implementation, the subjects modulated their own RR according to a target frequency in order to minimize the transparency (managed through a Unity package: Unity Stipple Transparency Shader—Alex Ocias Blog) of the virtual hand (**Figure 3**) according to the biofeedback procedure described in sub-section Experimental Setup. If the transparency index was over a certain threshold, the hand was visible enough to trigger a visuo-tactile event when the sphere approached the hand. In that case the virtual hand on the screen showed a "shaking" animation and the smartphone under the real hand of the subject vibrated. Overall, the SARB is characterized by gamification features (from the challenge to the set of feedback) designed to engage the user in self-regulation activities (Pacholik-Zuromska, 2021) that will be described in next paragraphs.

Respiratory Biofeedback and Data Acquisition

The SARB was adopted to evaluate two experimental conditions: slow RR and normal RR. The following sub-sections describe how the data were collected and processed for implementing the SARB and assessing the presence and the entity of the expected effects of slow RR.

Breathing Data

Breathing data was extracted by analyzing audio signal acquired during the experimental sessions. The procedure aims to detect the current breathing state of the subjects, and their changes: Rest, Inhalation, Exhalation.

The breath states detection was based on the loudness of the signal using an automated custom software (based on C# within a Unity project). The values used depended on this implementation of the SARB system, and they were manually defined by adjusting the values in Avalur (2013). Specifically, we classified the breath events with respect to the maximum amplitude of the recorded breath signal.

A headset was provided to the subjects to be used as an audio recording source. This allowed to comfortably keep a microphone close to the breathing sound source. The headset is a Canyon CORAX Gaming Headset CND-SGHS5, representative of entry level, non-professional devices which might prove affordable for home setups. The experimental setup is positioned in a controlled room to exclude major sources of noise. After acquiring the audio signal, a custom software evaluated current breath states of the subjects: Rest, Inhalation, Exhalation. This step was performed by computing the signal loudness and testing it against a set of threshold values. Starting from the signal loudness, the baseline noise allows to detect the Rest State: *Loudness* < *InhaleMin*. Small amplitude variations determine the Inhalation State: *Loudness* ϵ *[InhaleMin, InhaleMax]*. Big amplitude variations determine the Exhalation State: *Loudness* > *ExhaleThresh*. The thresholds chosen for the present experiment are: 0.05 for *InhaleMin*, 0.1 for *InhaleMax*, 0.3 for *ExhaleThresh*. A different microphone setup might require an adjustment of these values, since they strictly depend on the characteristics of the analyzed signal, which is itself heavily influenced by the audio acquisition factors mentioned above.

Breath frequency detection was performed over audio signal blocks of the duration of 1 s each. This analysis was executed by design at 50 Hz (every 20 ms): this implies an overlap of 980 ms between consecutive audio signal blocks. The sequential steps to detect the breathing frequency were: (i) acquisition of an audio signal block of the duration of 1 s, (ii) calculation of the envelope of the signal representing the loudness (expressed as the root mean square of the raw signal) of the microphone signal multiplied by a scale factor of 10 and the pitch (power spectrum of the signal), (iii) detection of the breathing phases (Rest, Inhalation, Exhalation), (iv) removal of artifacts, (v) computation of the breathing frequency.

Artifact removal (step iv) is required since, despite the controlled setup (headset microphone + controlled room), the recording arrangement for this experiment is still extremely sensitive to background sound and to speech. As a consequence, artifacts had to be removed by filtering the signals and excluding what had to be considered false breathing states triggers. In particular, a rejection procedure was implemented which excluded all the Exhalation and Inhalation state change triggers that were produced by a sound pitch out of the 500–4,000 Hz band. Artifact removal was performed through our custom software solutions, developed in C#.

The exhalation loudness is considerably higher than the inhalation loudness. Therefore, the exhalation event is easier to detect and for each of them a time stamp (Te_t) is saved to finally determine the frequency of breath (Fb_t):

$$Fb_t = \frac{60}{Te_t - Te_{t-1}} \quad (1)$$

where *Fb* is the new breath frequency at the time *t+1*, Te_{t+1} is the time stamp event of exhalation at time *t+1* and Te_t is the time stamp event of exhalation at time *t* (time in s, breathing frequency in breaths per min).

Respiratory Biofeedback

The biofeedback depended on the condition of the task, asking the subjects to keep a "Slow Breathing" rate (about 6 breaths/min) (Schwerdtfeger et al., 2020) or "Normal Breathing" rate (about 14 breaths/min) (Fonkoue et al., 2018).

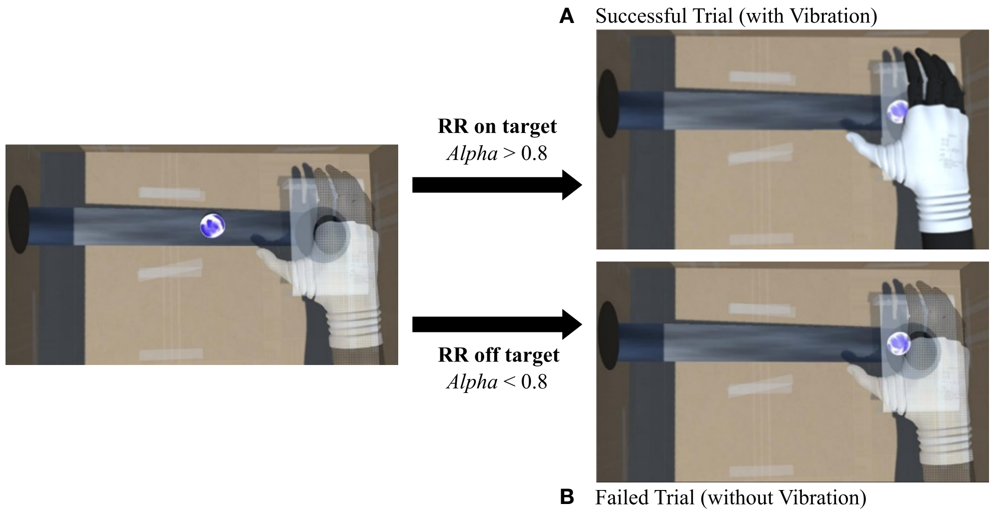

FIGURE 3 | Examples of **(A)** successful trial (the sphere reaches the virtual hand in fully visible state) and of **(B)** failed trial (the sphere reaches the virtual hand in transparent state).

For both conditions, when a new frequency of breath was detected, it was compared with the target breathing rate (*Fopt*) to produce a value between 0 (transparent) and 1 (opaque) of transparency (*Alpha*):

$$Alpha_t = \left\{ \begin{array}{ll} \frac{Fopt}{Fb_t}, & Fb_t > Fopt \\ \frac{Fopt}{(2^*Fopt) - Fb_t} & Fb_t < Fopt \end{array} \right\} \quad (2)$$

For the success of the task in each trial (fully visualizing the 3D model of the prosthesis before the sphere disappears), the hand transparency (*Alpha*) needs to be higher than 0.8 (**Figure 3A**). When transparency was lower than 0.8 (**Figure 3B**) at the end of the trial, the sphere fell down the hole and the task was considered failed. Each trial started with an $Alpha = 0.5$.

During preparatory tests of the initial prototypes of the setup, the quick changes in the hand visibility often constituted a serious obstacle to the subjects' training to perform the task, especially when the sphere was approaching the hand.

Consequently, a facilitation ($f = 0.05$) of the task was introduced to increase the degree of success in case of occasionally breathing rate far from the target during the entire task:

$$Alpha_t = \left\{ \begin{array}{ll} Alpha_t, & Alpha_t > Alpha_{t-1} \\ Alpha_{t-1} - f & Alpha_t < Alpha_{t-1} \end{array} \right\} \quad (3)$$

If *Alpha* was >0.8 at the end of the trial, the visuo-tactile vibration feedback was generated as co-occurrence of the visual shaking of the virtual hand on the screen and the vibration of the smartphone, placed under the real right hand, as caused by the collision of the sphere and the hand.

To enable such a haptic event, an API was developed for allowing the control of smartphone vibration and to set up wireless communication (based on a local network) between the laptop and the smartphone. This connection was based on a Unity (Windows) desktop app sending to a Java back-end (running on a Tomcat server) a request for a Unity (Android) mobile app that triggers the vibration of the smartphone when the virtual hand-sphere collision happens.

It must be noted that latency is expected when triggering events across a network. Even for a LAN network, latency is usually negatively affected by wirelessly connected components (e.g., the smartphone used for the experiment). Nonetheless, such latency was not noticeable (under 100 ms) when triggering the events required by this experiment, even more so given the slow pace of the tasks.

In-session Data Collection and Processing

During the experimental sessions, both data collection programs (Unity custom program and BioGraph) were running on the same laptop, allowing for a data synchronization based on the laptop-generated timestamps. The data generated by the Unity software were collected in a text file, named with the ID of the subject and containing the list of breathing events with their time stamps during the experiment. The data collected through the FlexComp Infiniti system were recorded and exported in a text file through the BioGraph software at 2,048 Hz. Downsampling at 256 Hz was performed to allow data synch with the breathing data generated by the Unity software.

The power spectrum of each BVP sequence was reconstructed through the Welch method (eight Hamming windows with 50% overlap). Frequencies in the 0.05 to 0.5 Hz (corresponding roughly to 3 to 30 breath per min) have been considered as generated by respiratory activity, thus the center of the frequency bin with the highest power provides a good estimate of the RR. The RR value, expressed in breaths per min, was then simply estimated by multiplying the obtained frequency by 60.

GSR in each trial was compared for checking potential anticipatory responses to upcoming virtual stimuli (possibly related with the hypothetical different degrees of embodiment in slow and normal breathing conditions): each sequence was normalized as to have a mean value of 0 and a standard deviation of 1, then the value at time 0 was subtracted from each sequence. Normalized sequences were then averaged over trials and subjects for each experimental condition. It must be added that, in RHI studies, skin conductance typically offers information on individual reactions to threatening events (Senna et al., 2014). However, this signal increases to both aversive (Armel and Ramachandran, 2003) and appetitive stimuli (Le et al., 2019): thus, we decided to adopt it to evaluate potential anticipatory reactions to the (uncertain) outcome of the trial, when the hand could vibrate (marking a successful trial) or not.

Experimental Procedure

Instructions and Tasks

Session Preparation

Initially, the subjects were asked to wear the (appropriately sanitized) headset and biosensors comfortably. All participants were asked to sit in front of a desk and to place their hands at the sides of a monitor lying (slightly tilted on a foam support toward the subject) on it.

Then, their right hand was placed on the smartphone (the amputees did not wear any prosthesis during the session, thus they placed the right stump on the phone). The position of the phone was marked with tape as a reference for the post-session estimation of the proprioceptive drift.

After this, the subjects agreed to start the experimental session, allowing the experimenter to begin the acquisition of the respiratory events and the physiological data and to change the Unity scenes (observed through a secondary screen) according to the commands of the participants during the session itself. **Figure 4** shows the main Unity scenes and phases of the experimental procedure.

In the first scene (**Figure 4**, scene 1), the experimenter inserted the subjects' number, set the connection between the laptop and the smartphone through the local network, and chose the breathing condition. In the second scene, the investigator filled the subjects' personal data while reading aloud the different sections to properly transcribe the subjects' answers.

After this, the first instructions scene introduced a 3-min video (**Figure 4**, scene 2). This video had the goal to induce a neutral mental state before initiating the actual experimental session. The investigator asked the subjects to stay still while fixing the cross in the middle of the screen.

Training and Testing Trials

Subsequently, the second instructions scene was read aloud by the experimenter (**Figure 4**, scene 3), who explained the upcoming short training sample. This scene contained different instructions about the task according to the experimental condition of the ongoing session:

- in the Slow Breathing (low RR) condition, the subjects were asked to maintain the respiratory rate at a slow pace (about 6 breaths/min) to make the virtual hand "materialize" (become visible) enough for feeling the energy of the sphere when it approached the virtual limb,
- in the Normal Breathing (typical RR) condition, the subjects were asked to maintain the respiratory rate at a normal pace (about 14 breaths/min) to achieve the same goal.

In both cases, the subjects were invited to blow on the microphone when they were breathing out. This instruction was given to help the participants in maintaining the expected pace and to produce a sound correctly interpreted by the SARB system.

As described before, by maintaining the right RR of the assigned condition (Slow Breathing or Normal Breathing), during the sliding of the energetic sphere from the hole on the left wall to the hole under the Hannes 3D model, the participants were able to decrease the transparency of the virtual hand to make the virtual hand solid enough to "feel" the energy of the approaching sphere as a vibration. This event meant that the trial was successfully accomplished (**Figure 3A**). This task was expressed by asking the subjects to "make the hand visible and solid enough to intercept and the sphere and feel its energy." The duration of each trial was 1 min: the time spent by the sphere to move from the left hole to the right hole on the screen.

Once a training session constituted by two trials (**Figure 4**, scene 4) was completed, the subjects had to decide to repeat the training or proceed. There was no limit in the repetition of the training trials.

When the participants declared to be ready to start the experimental session, a series of 16 trials started (**Figure 4**, scene 5), each one based on the 1-min animation and the respiratory biofeedback task described above.

Each trial started after the end of the previous one within the same scene: the sphere disappeared into a hole under the virtual right hand and re-appeared on the left side of the screen. The resulting visuo-haptic events are far less frequent than the ones in typical RHI and VHI studies: this choice depended on the need to perform the biofeedback exercise over an appropriate time to reach the target respiratory pace.

Subjective Questionnaire

After completing the experimental trials, the subjective questionnaire scenes appeared instantaneously (**Figure 4**, scene 6).

The experimenter read aloud the questionnaire instructions, asking the subjects to rate their experience during the session through a score from 1 for "Total Disagreement" to 5 for "Total Agreement" per each statement. Through this, the participants defined how much they disagreed/agreed with the following 14 statements that represented different aspects of virtual hand ownership (items 2, 3, 4) and real hand disownership (items 9, 10, 11) and individual experience—stress (item 1), emotional engagement (item 12), interoceptive intensity (item 13), perception of the relationship between virtual hand visibility and breathing rate (item 14) (**Table 1**). Control items (5, 6, 7,

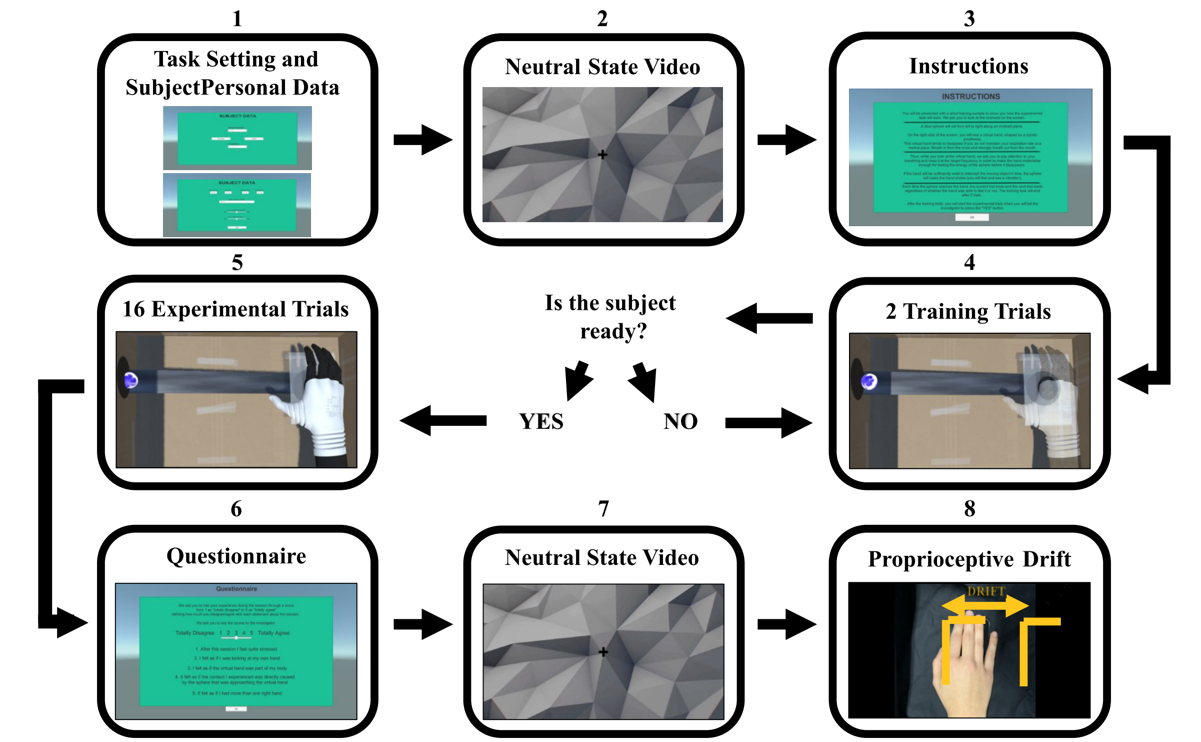

FIGURE 4 | Experimental phases.

8) were included for checking the subject's compliance with the experimental instructions.

The subjects read silently by themselves each of the 14 statements, divided in 3 scenes, and told the investigator the different scores. To conclude, the experimenter asked the subjects to estimate the duration of the experimental session (in min) for evaluating further potential effects of the breathing condition. The questionnaire was partially adapted to the case of the amputees, referring to their "limb" instead of their "hand."

Proprioceptive Drift Measurement

After collecting the questionnaire answers, the experimenter moved to another instruction scene concerning the final 3-min video to induce a neutral state (**Figure 4**, scene 7) for restoring the neutral state before measuring the proprioceptive drift (**Figure 4**, scene 8). Once the video was over, the participants were asked to close their eyes, and the black blanket on the right arm was removed. The reference position of the phone (previously marked by tape) was checked after removing the blanket. If the phone had been moved during the session by more than 5 mm in any direction the following measure of the drift would have been considered unreliable. Otherwise, the researcher marked this position of the phone as final reference position, representing where the phone (thus, the right hand) was during the experiment. After this, the participants were asked to raise their right arm while holding the smartphone and to wave it around to briefly stretch.

Thus, the participants were asked to relocate the smartphone in the perceived initial position, always while keeping the eyes closed. Differently, the prosthesis users only raised their right limb (always with closed eyes) and, after the experimenter removed the smartphone to avoid obstacles, they placed the stump where they felt it was during the session. The estimated position of the phone (which, in the case of the prosthesis users was re-placed by the experimenter under the relocated stump) was marked with tape to facilitate the measurement of the drift from the reference position, previously marked with tape too.

The lateral distance between the reference position of the phone and the one estimated by the participants were measured by the experimenter, together with the direction of the deviation (**Figure 5**). To measure the drift we assumed the reference position of the phone during the session as 0 point of a continuous horizontal scale with negative values to the left (toward the virtual hand) and positive to the right.

This strategy to estimate a proprioceptive drift was specifically devised for this setup, considering how it could facilitate this part of the experiment in home training sessions: marking with tape the position of a rectangular object representing the hand position is far easier than performing the same operation with the hand itself as a reference.

After this, the sensors, the headphones, and the blankets were removed, and the subjects were free.

TABLE 1 | Subjective questionnaire scores (median, Mdn; median absolute deviation, MAD; mean, M; standard deviation, SD).

N	Questionnaire items	Slow breathing				Normal breathing				
		Mdn	MAD	M	SD	Mdn	MAD	M	SD	
1	After this session I feel quite stressed	2	1	2.55	1.26	3	1	3.00	0.93	
2	I felt as if I was looking at my own hand	2	0	2.14	0.71	2	0	1.91	0.53	
3	I felt as if the virtual hand was part of my body	3	0	2.50	0.60	2	0	2.05	0.65	*
4	It felt as if the contact I experienced was directly caused by the sphere that was approaching the virtual hand	3	1	2.95	0.90	2	0	2.27	0.83	**
5	It felt as if I had more than one right hand	1.5	0.5	1.77	0.92	2	1	1.68	0.72	
6	I felt as if my real hand was turning virtual	2	0	1.91	0.53	2	0	1.73	0.63	
7	I felt as if I could move the virtual hand	2	0	1.95	0.58	2	0	1.82	0.59	
8	It felt as if the contact I experienced came from somewhere between my own hand and the virtual hand	2	1	1.91	0.81	2	0	1.86	0.56	
9	It seemed as if my hand had disappeared	2	0	2.23	0.87	2	1	2.32	0.89	
10	It seemed as if I could not really tell where my hand was	3	0	2.50	0.80	2	1	2.36	0.95	
11	It seemed as if I was unable to move my hand	3	0	2.77	0.75	2	0.5	2.36	0.73	*
12	I felt emotionally involved in the situation	3	1	3.05	1.00	3	1	2.95	1.09	
13	I perceived intensely my bodily sensations	3	1	3.14	1.21	3	1	3.18	1.01	
14	I felt the relation between my breath and my virtual hand	3	1	3.18	1.22	4	1	3.55	0.96	

**, $p < 0.05$; **, $p < 0.01$ (Wilcoxon signed-rank test between conditions of Slow Breathing and Normal Breathing).*

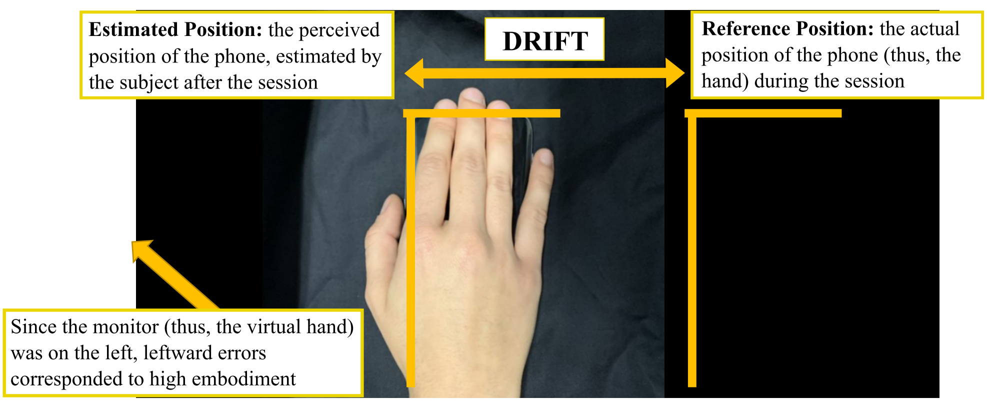

FIGURE 5 | Proprioceptive drift measurement—only the lateral error from the actual phone position (reference position) was considered.

Experimental Design and Statistical Analysis

In a within-group experimental design, all participants performed the tasks under Slow Breathing and Normal Breathing conditions. Each condition was experienced by the participants in different days with max 14 days between sessions. The order of sessions was counterbalanced, by also accounting for gender and age (as much as possible) to compose the resulting two sub-groups: 11 (3 females) subjects (Age, mean ± SD: 27.6 ± 2 years) who were presented the Slow Breathing condition in first session and the Normal Breathing condition in second session, and 11 (3 females) subjects (Age, mean ± SD: 27.2 ± 2.8 years) who were presented the condition in the opposite order. Following the exploratory function of this preliminary study, we used two-tailed tests for observing potentially significant differences in both directions.

The questionnaire data were analyzed via Wilcoxon signed-rank test with the breathing condition—Slow Breathing vs. Normal Breathing—as factor. The scores of each item were compared. Further comparisons were based on average scores per sub-set of questionnaire items as global indices of ownership, disownership, and control as in Pyasik et al. (2020).

Session time estimation and proprioceptive drift were analyzed via paired samples *t*-test with breathing condition as a factor.

The frequency of respiratory events was analyzed to assess the feasibility of this setup by evaluating the participants' capability to control their own number of breaths per trial (being each trial 1-min long) according to the instructions. The breathing condition being the factor, the breaths per trial were analyzed via *t*-test. The same comparison was performed for the number of successful trials as a performance measure (the number of trials in which the subjects made the virtual hand vibrate).

GSR signals have been analyzed to identify possible time segments for which responses differed significantly from the end-point value, implying a possible anticipatory response. Given the normalization described in In-session Data Collection and Processing, this analysis consisted simply in testing grand-averages across subjects and trials to identify time segments with median values different from zero. Specifically, a Wilcoxon signed-rank test for zero median has been conducted on the skin conductance signal. In order to prevent possible false positives due to slow signal drift, this analysis has been limited to the last 10 s of recording before each visuo-tactile event.

All analyses were performed using JASP (https://jasp-stats.org) (Love et al., 2019), R (https://www.r-project.org), and Matlab (MathWorks, Inc.), and $p < 0.05$ was considered significant.

The next section focuses on the significant results in all comparisons, with statistically relevant information like the effect size (Cohen's d for the parametric tests, rank-biserial correlation for the Wilcoxon signed-rank test) (Kerby, 2014) and the test assumption check (only Shapiro-Wilk test of normality for repeated measures parametric tests with one 2-level independent variable).

EXPERIMENTAL RESULTS

Virtual Hand Ownership

In the Slow Breathing condition, participants reported stronger feelings that the virtual hand was part of their body (item 3, with $W = 106$ and $p = 0.035$), that the contact experienced was directly caused by the sphere that was approaching the virtual hand (item 4, with $W = 122$ and $p = 0.003$), and that they were unable to move their own right hand (item 11, with $W = 96$ and $p = 0.022$), compared to the Normal Breathing condition (see **Table 1**). Rank-biserial correlation was used to estimate the effect size and the related confidence interval, respectively with values of: (item 3) 0.559 and 95% CI [0.074, 0.83], (item 4) 0.794 and 95% CI [0.482, 0.927], (item 11) 0.6 and 95% CI [0.117, 0.853].

Significant differences were found between the control (5, 6, 7, 8) items average score and, respectively, the ownership (2, 3, 4) items average score ($W = 220.5$ and $p < 0.001$ in Slow Breathing, $W= 195$ and $p = 0.027$ in Normal Breathing) and the disownership (9, 10, 11) items average score ($W= 206.5$ and $p < 0.001$ in Slow Breathing, $W= 223.5$ and $p = 0.002$ in Normal Breathing). Rank-biserial correlation was used to estimate the effect size and the related confidence interval. For the ownership-control comparison: 0.909 and 95% CI [0.776, 0.965] in Slow Breathing, 0.542 and 95% CI [0.128, 0.794] in Normal Breathing. For the disownership-control comparison: 0.967 and 95% CI [0.912, 0.988] in Slow Breathing, 0.767 and 95% CI [0.489, 0.903] in Normal Breathing.

A significant difference ($W = 153.5$ and $p < 0.001$) was also found between the ownership average scores in each breathing condition (**Table 2**). According to rank-biserial correlation, the effect size and the related confidence interval are respectively 0.795 and 95% CI [0.508, 0.923].

Overall, the participants estimated the total duration of the task (16 min) as: 11.55 ± 5 min in Slow Breathing, 12.77 ± 4.03 min in Normal Breathing (no significant difference between conditions).

Considering the proprioceptive drift, no subject moved the phone during the session (before the drift estimation) by more than 5 mm in any direction: thus, all measures were included in our analysis. According to the collected data, the breathing condition significantly affected the proprioceptive drift: $t(21) = -3.558$, $p = 0.002$, $d = -0.759$, CI [-1.23, −0.276] (**Figure 6**). The drift comparison between Slow Breathing and Normal Breathing successfully passed the Shapiro-Wilk test of normality, with 0.975 ($p = 0.824$). The participants estimated the position of the smartphone, i.e., their right hand, to the left of its actual location (averagely by 0.91 ± 2.58 cm) and closer to the monitor i.e., the virtual hand, in the Slow Breathing condition. The same estimation was to the right of its actual location (averagely by 1.45 ± 2.45 cm) in Normal Breathing condition.

The analysis of GSR (planned as in Experimental Design and Statistical Analysis) shows that, in the considered time window, the measured values are significantly different from the end value at the 0.05 significance level only in Normal Breathing condition (between 1.7 s and 1.3 s before the end of the trial).

SARB Feasibility

Figure 7 highlights how the subjects followed the instructions for each condition according to the data collected through the microphone and processed by the custom Unity software. No significant difference can be found considering both the breathing condition and the trial repetition as factors. However, in the Slow Breathing condition participants maintained 5.8 ± 2.5 breaths per trial, overall. This value was significantly lower

TABLE 2 | Average scores of items on ownership, control, disownership (median, Mdn; median absolute deviation, MAD; mean, M; standard deviation, SD).

Questionnaire items average scores	Slow breathing				Normal breathing				
	Mdn	MAD	M	SD	Mdn	MAD	M	SD	
Ownership (items 2, 3, 4)	2.67	0.333	2.53	0.54	2.17	0.167	2.08	0.52	**
Control (items 5, 6, 7, 8)	1.88	0.375	1.89	0.45	1.75	0.25	1.77	0.42	
Disownership (items 9, 10, 11)	2.67	0.5	2.5	0.66	2.33	0.5	2.35	0.75	

***, p < 0.01 (Wilcoxon signed-rank test between conditions of Slow Breathing and Normal Breathing).*

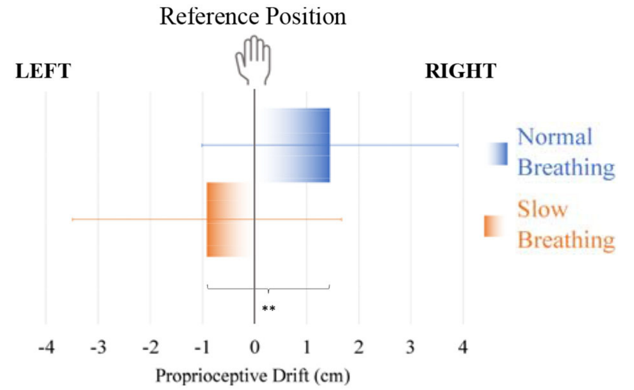

FIGURE 6 | Comparison of proprioceptive drift (cm) from the reference position of the hand (0) in conditions of Slow Breathing and Normal Breathing, with means and standard deviations. $^{**}p < 0.01$ (pairwise t-test between conditions of Slow Breathing and Normal Breathing).

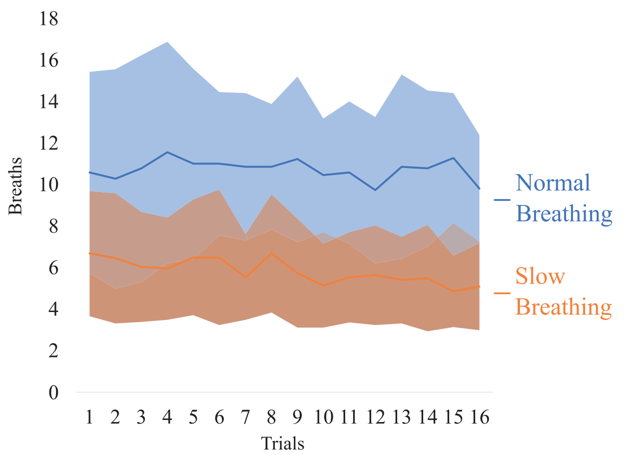

FIGURE 7 | Means (continuous lines) and standard deviations (shaded areas) of breaths per trial in conditions of Slow Breathing and Normal Breathing, along the 16 trials (1 trial per min).

than the Normal Breathing condition, 10.7 ± 2.6 breaths per trial, as expected: $t(21) = -8.382$, $p < 0.001$, $d = -1.787$, CI [−2.459, −1.098]. The comparison successfully passed the Shapiro-Wilk test of normality, with 0.951 ($p = 0.335$).

Additionally, an exploratory analysis of BVP values was performed for extracting the frequency of respiratory events and comparing it to the data collected by the Unity software, showing no significant difference between them in each breathing condition.

Before moving on to the experimental session, 4 participants asked to repeat (1.75 ± 0.5 times, by average) the training session in Slow Breathing condition. Three of these subjects needed to repeat (1.33 ± 0.58 times, by average) the training session in Normal Breathing condition too. Then, over 16 total trials, the participants were able to make the virtual hand "shake" (when, at the end of each trial, the transparency index $Alpha > 0.8$) by average (without significant differences): in 10.77 ± 4.94 trials under Normal Breathing condition, and in 9.36 ± 3.44 trials under Slow Breathing condition.

Preliminary Test With Users of Prostheses

Both the users of upper limb prostheses involved in this study followed our instructions in terms of breath control. In Slow Breathing condition, one subject (who repeated the training session two times) had a mean 6.3 ± 2 breaths per trial and the other (one repetition of the training) had 4.94 ± 2.5 breaths per trial. In Normal Breathing condition, they respectively had (after repeating two times and one time the training) a mean number of breaths per trial of 11.31 ± 2.5 and 13.19 ± 3.02. About task performance: in Slow Breathing condition they respectively achieved 8 and 12 successful trials over 16, and in Normal Breathing condition 15 and 11. These preliminary tests with two amputees suggested the potential for implementing home-based embodiment training systems with affordable solutions for respiratory biofeedback.

Overall, their questionnaires showed higher scores than the individuals interviewed for the main study, surpassing the middle value of the 5-point Likert-type scales. The scores (**Table 3**) demonstrate medium-high values of ownership and engagement with a minimal stress. The session time estimation reported by each subject in both conditions was lower than the actual 16 min of trials, respectively: 10 min and 15 min in Slow Breathing, 5 min and 10 min in Normal Breathing.

The proprioceptive drift of each subject tended in both conditions toward the virtual hand, respectively: 3 cm and 4.7 cm in Slow Breathing, 3 cm and 2.5 cm in Normal Breathing.

DISCUSSION

This study provides preliminary evidence of how self-regulation techniques (via respiratory control) can increase the processes of body ownership underlying the embodiment of a virtual right

TABLE 3 | Post-trials subjective evaluation questionnaire scores reported by the two users of upper limb prostheses.

N	Questionnaire items	Slow Breathing		Normal Breathing	
		Subject A	Subject B	Subject A	Subject B
1	After this session I feel quite stressed	1	2	1	2
2	I felt as if I was looking at my own limb	4	3	4	3
3	I felt as if the virtual limb was part of my body	5	2	4	3
4	It felt as if the contact I experienced was directly caused by the sphere that was approaching the virtual limb	5	4	3	4
5	It felt as if I had more than one right limb	1	1	2	1
6	I felt as if my real limb was turning virtual	5	1	3	1
7	I felt as if I could move the virtual limb	3	2	2	3
8	It felt as if the contact I experienced came from somewhere between my own limb and the virtual limb	1	2	1	4
9	It seemed as if my limb had disappeared	1	1	5	2
10	It seemed as if I could not really tell where my limb was	1	1	1	3
11	It seemed as if I was unable to move my limb	5	3	5	2
12	I felt emotionally involved in the situation	4	3	4	3
13	I perceived intensely my bodily sensations	5	3	5	3
14	I felt the relation between my breath and my virtual limb	5	3	5	3

hand. It also highlights the feasibility of the implementation of SARB within the boundary of remote studies.

Our results (questionnaire scores, proprioceptive drift) indicated that our slow breathing biofeedback (vs. normal breathing) may improve the ownership process, i.e., increasing the sensations that the virtual hand was part of the subject's body and that the vibration experienced by the subject was caused by the sphere on the screen. While both aspects are directly connected to the embodiment process (which depends on the perceived relation between self and body), the last one could also be related to the feeling of presence: the experience of "being there" in a mediated environment (Riva et al., 2003).

Thus, we can infer that the Slow Breathing condition made the participants feel that their body was extended (through the artificial limb) into the digital on-screen component of the SARB environment, when compared to Normal Breathing condition. Such an effect needs further investigation while studying the role of Slow Breathing in improving presence and avatar control, also considering the relationships between embodiment and presence (Rosa et al., 2020). Interestingly, the assessment of certain subjects' feeling (reported through questionnaire responses and spontaneous remarks) of being unable to move their own right hand, unveils a side-effect of Slow Breathing in terms of disownership.

The SARB setup was effective in monitoring individuals' breathing, processing the respiratory rate and providing the desired feedback to the users. The subjects were able to follow the instructions properly, generating two different condition-specific breathing rates. However, we noticed that the subjects tended to have a lower respiratory rate than the target, and their performance in terms of successful trials was quite variable across the subjects (highlighting how maintaining an appropriate RR to trigger the vibration can become complex to manage). These observations point at the need of a task re-design for facilitating the execution of the biofeedback training, especially considering the high inter-subject variability of the successful trials in this study (pointing at potential usability issues for certain participants) and the potential effects of workload on body ownership measures (Qu et al., 2021).

Furthermore, such a re-design should also focus on improving the user engagement, since the setup was just moderately able to stimulate the participants through its current gamification features. Indeed, most questionnaire scores did not overcome the middle point of 3 in the 5-point Likert-type scales, and anticipatory responses were just weakly detected in GSR patterns only under Normal Breathing condition. This could depend on the fact that our implementation of SARB was based on a limited number of tactile events: 16 occurrences (1 per min) just in case the person performs the task correctly in each trial. In classic RHI studies, these stimulations are more frequent and numerous in a shorter time, making most people experience the illusion within the first minute of the session (Kalckert and Ehrsson, 2017). Furthermore, our SAR environment was probably less immersive than the ones used in most VHI settings, affecting both the strength and the variability of the embodiment measures (in particular the proprioceptive drift). VHI studies typically provide a strong perceptual continuity between computer-generated body parts (hand and arm) of the subject within the same immersive context, with advantageous effects on the embodiment measures. However, our goal was to observe if these measures were significantly different in Slow Breathing condition and Normal Breathing condition within the same setting, and this was confirmed by our preliminary data. In any case, the role of the attentional effects of respiratory control needs to be also considered by, for example, separating focus-attention on breathing from the feedback-control components.

Considering its methodological value, our SARB-based procedure can be considered an original addition to the heterogenous family of RHI studies (Riemer et al., 2019). Specifically, SARB can constitute an affordable home training system for the embodiment, but it needs further design improvements, possibly exploiting more game-based features to engage the users. This can be a promising strategy, especially if validated through long-term home experiments (Garske et al., 2021), even within wider and engaging digital health protocols (Winkler et al., 2019). The opportunity of using this kind of approach for developing novel strategies to investigate psychopathological conditions will also be considered, especially when the interoceptive processes are involved, as in Grynberg and Pollatos (2015), for example.

Being aware of the limitations of this initial study, we are anyway encouraged by the current preliminary results: SARB constitutes a viable approach in implementing a self-regulation of psychophysiological states to promote the embodiment of an artificial limb through a Slow Breathing condition. Furthermore, this study offered the opportunity of preliminarily testing our hypothesis and our setup before proceeding with further laboratory investigations and with extensive home data collection sessions.

Accordingly, the dual value of the investigation presented in this paper suggests two possible directions for the next steps of this research (envisioning their subsequent convergence too).

- Psychophysiological studies (in laboratory) would allow to investigate specifically the EEG correlates of the virtual hand embodiment (Kanayama et al., 2021) in a SARB setting (using chest belts to precisely monitor RR). A potential target could be the study of Slow Cortical Potentials (SCPs, 0.01–0.1 Hz) (Hinterberger et al., 2019) correlated with the heartbeat and the respiration cycle, thought to be also implicated in stimuli integration (Northoff, 2016).
- User experience studies (in laboratory and in remote contexts) on the SARB setting would initially help to improve the usability of the setup, making the task easier and more engaging (possibly personalizing the target RR through adaptive and co-adaptive features) for the participants in upcoming remote online sessions (even as daily game-like training) (Ratcliffe et al., 2021). The visual scene will be improved with further graphic details to achieve a more compelling experience (e.g., substituting the black area around the right hole with a more realistic texture). Next studies will include amputees exploiting the respiratory biofeedback strategy for training the embodiment of artificial limbs.

Extending the sample size will allow for controlling factors based on the subjects' traits and habits (e.g., playing videogames or sports, smoking). Importantly, their body image and interoceptive awareness should be assessed (Mehling et al., 2012) alongside the personality features (Burin et al., 2019).

Further investigations must also demonstrate if the effects of the SARB-based training persist over time, and if an actual generalization of the embodiment of the 3D model of a prosthesis can be observed for the actual device (Laffranchi et al., 2020), possibly exploiting the latter in game-like XR remote trainings designed to engage the users. This solution (alongside with the adoption of ecologically valid settings as in neuroergonomics research) (Dehais et al., 2020) could counter the apparent lack of RHI-susceptibility in subjects who feels prosthetic limbs ownership mainly when the devices are used in daily life (Zbinden and Ortiz-Catalan, 2021).

As discussed above, this kind of RHI-resistance was found in meditators (Xu et al., 2018). However, differently from previous studies, we explored the embodiment as a process affected by an active respiratory control within a biofeedback protocol instead of just presenting a typically passive RHI-like test without asking to perform any respiratory task. Accordingly, we hypothesize that the fine control of RR matured through meditation practices could be advantageous in SARB procedures, possibly working as a preparatory activity to our respiratory biofeedback for embodiment training—especially for patients attending telerehabilitation protocols and amputees waiting for their prosthesis.

CONCLUSION

This pilot study presented a novel, affordable strategy for empowering the feeling of owning a virtual hand through an individual self-regulation method based on a respiratory control aiming at slow breathing. The design of the setting, targeting remote studies, showed the feasibility of implementing such a system with common devices owned by users like a computer, a monitor, a smartphone, and a microphone. Thus, this proof of concept offered a preliminary (methodological and technological) background for developing novel user-centered strategies in research and design to facilitate the embodiment of artificial limbs.

DATA AVAILABILITY STATEMENT

The dataset generated for this pilot study may be available to readers upon reasoned request to the corresponding author.

ETHICS STATEMENT

The study followed an experimental protocol, involving human subjects without sensory, cognitive, and neuromotor impairments (exclusion criteria referred to any neurological condition affecting the capability of the individual to perform the tasks). The protocol was reviewed and approved (March 16th, 2020) by the Ethical Committee of Liguria Region in Genoa, Italy (IIT ADVR TELE01, Register Number: 229/2019 - ID 4621). All subjects provided their own written informed consent to participate in this investigation and to publish any anonymized image and data collected by the researchers.

AUTHOR CONTRIBUTIONS

GB conceived the research hypothesis and the interaction paradigm adopted in this study, reviewed literature on related topics, designed the task and the visuo-tactile feedback, defined the experimental design, and the research methodologies. AM, GC, MdZ, JT, LA, NB, MF, DM, and MB contributed to improve the experimental design, the interaction paradigm, and the research methodologies. GB and MF performed preparatory activities to implement the paradigm and the investigation, including the sample size calculation. NB, MF, DM, ND, CF, MB, EG, ML, and LDM contributed to define the research perspective according to its potential applications. AM and GC designed and developed the experimental setup and the interactive environment. AM devised and implemented the systems enabling the breath detection and the spatially augmented respiratory biofeedback. GB and GC recruited the subjects and managed the experimental sessions with data collection. GB analyzed the data and wrote the first draft of the paper, subsequently improved by AM, GC, and MdZ. MdZ, JT, and LA performed further data analyses to check additional results. GB, GC, and NB worked on figures and graphs. Finally, all authors worked on the results interpretation and on the final manuscript writing, and they read and approved the submitted version.

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Impact of Shared Control Modalities on Performance and Usability of Semi-autonomous Prostheses

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Semi-autonomous (SA) control of upper-limb prostheses can improve the performance and decrease the cognitive burden of a user. In this approach, a prosthesis is equipped with additional sensors (e.g., computer vision) that provide contextual information and enable the system to accomplish some tasks automatically. Autonomous control is fused with a volitional input of a user to compute the commands that are sent to the prosthesis. Although several promising prototypes demonstrating the potential of this approach have been presented, methods to integrate the two control streams (i.e., autonomous and volitional) have not been systematically investigated. In the present study, we implemented three shared control modalities (i.e., *sequential*, *simultaneous*, and *continuous*) and compared their performance, as well as the cognitive and physical burdens imposed on the user. In the *sequential* approach, the volitional input disabled the autonomous control. In the *simultaneous* approach, the volitional input to a specific degree of freedom (DoF) activated autonomous control of other DoFs, whereas in the *continuous* approach, autonomous control was always active except for the DoFs controlled by the user. The experiment was conducted in ten able-bodied subjects, and these subjects used an SA prosthesis to perform reach-and-grasp tasks while reacting to audio cues (dual tasking). The results demonstrated that, compared to the manual baseline (volitional control only), all three SA modalities accomplished the task in a shorter time and resulted in less volitional control input. The *simultaneous SA* modality performed worse than the *sequential* and *continuous SA* approaches. When systematic errors were introduced in the autonomous controller to generate a mismatch between the goals of the user and controller, the performance of SA modalities substantially decreased, even below the manual baseline. The *sequential SA* scheme was the least impacted one in terms of errors. The present study demonstrates that a specific approach for integrating volitional and autonomous control is indeed an important factor that significantly affects the performance and physical and cognitive load, and therefore these should be considered when designing SA prostheses.

Keywords: prostheses, semi-autonomous, performance, workload, upper-limb

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INTRODUCTION

To increase the autonomy of affected users and to meet their requirements (Cordella et al., 2016), upper-limb prostheses have become more dexterous, further enabling the user to perform up to 36 different grasps (i-Limb® Quantum Bionic Hand, Ossur, Reykjavik, Island). However, the standard commercial control based on two-channels and switching was not designed to efficiently accommodate multiple degrees of freedom (DoFs) (Jiang et al., 2012). Myocontrol methods based on machine learning have been investigated for decades (Scheme and Englehart, 2011) to bridge the gap between advanced functionality and poor control. Recently, pattern classification systems have become commercially available (e.g., COAPT engineering and MyoPlus from Otto Bock). They allow users to control several DoFs directly. However, they are sensitive to multiple factors (e.g., muscle fatigue, sweating, and electrode shift), require calibration (retraining), and allow only sequential activation of the DoFs. Regression can be used for simultaneous control, but it can reliably activate only a small number of functions (Hahne et al., 2018, 2020). Finally, machine-learning-based approaches allocate the cognitive burden to the user, who is required to preshape every DoF of the prosthesis to obtain an optimal grasp and avoid compensatory movements.

One approach to improve the control of dexterous prostheses while easing the cognitive burden on the user is to introduce semi-automatic control. This approach is based on enhancing the prosthesis with exteroceptive sensors that allow it to estimate context information. Then, such information can be used to enable the prosthesis to perform certain functions automatically. Semi-autonomous (SA) control was first developed in other fields of assistive robotics (e.g., smart wheelchairs) (Carlson and Demiris, 2012; Novak and Riener, 2015); however, its application in prosthetics is relatively novel. Nevertheless, this approach has recently gained significant momentum both in upper- and lower-limb prostheses (Zhang et al., 2019; Zhong et al., 2021).

Different sensor modalities have been used to automate prostheses during the entire reach-and-grasp sequence. Tactile sensors embedded on the fingers (Tavakoli et al., 2017) help them autonomously adapt to the shape of an object (Zhuang et al., 2019). Inertial measurement units were used to make the prosthesis autonomously react to the orientation of the sound hand in bimanual tasks (Volkmar et al., 2019) or for compensatory movements by rotating the wrist to reduce the need for shoulder elevation (Markovic et al., 2015). A camera, attached to either the prosthesis or to the user's body, can provide information regarding the shape of the object, which can be used to adjust finger aperture, grasp pattern, and wrist rotation (Došen et al., 2010; Markovic et al., 2014, 2015). The RGB data, alone or in combination with depth information, were processed *via* machine (deep) learning to classify objects according to the grasp types that are appropriate for the object (Degol et al., 2016; Fajardo et al., 2018; Hundhausen et al., 2019). In a recent study, computer vision was employed to build a three-dimensional model of the environment while tracking the prosthesis (Mouchoux et al., 2021). This allowed the prediction of points of interaction and automatic preshaping of the hand with an active wrist according to its position relative to the objects in the scene.

Other methods based on sensor fusion were also used to predict reach-and-grasp tasks. They combined gaze tracking with hand tracking (Carrasco and Clady, 2012), electroencephalogram (McMullen et al., 2014), computer vision (Shi et al., 2020), forearm EMG (Krausz et al., 2020), or the movement of a hand-mounted camera (Zhong et al., 2020). Finally, a database of multimodal sensor data was recently published to encourage further development of "intelligent prosthetics" (Cognolato et al., 2020). Importantly, all SA control approaches combine autonomous and volitional control. The former provides "intelligence" to the system, whereas the latter allows the user to gain control when required. However, an excellent method to integrate the two control streams remains an open question, and studies have adopted different *ad hoc* solutions. This question is even more important as there is no guarantee that autonomous controllers will always reliably predict user intention. Several systems implemented "traded autonomy" wherein manual and autonomous controls were activated strictly and sequentially, following an explicit user trigger (Markovic et al., 2014; Fajardo et al., 2018; Volkmar et al., 2019; Mouchoux et al., 2021). More simultaneous approaches were also proposed, where autonomous systems complete the DoFs not controlled by the user (Sherstan et al., 2015) or control all the DoFs of a device if the computed solution agrees with the partial command from the user (Zhuang et al., 2019). However, the effect of these different shared control modalities on the interaction between the user and his/her prosthesis, as well as on the overall performance of the SA system, has not been investigated thus far.

The present study implements three representative shared control schemes (i.e., simultaneous, sequential, and continuous) using the "Wizard-of-Oz" paradigm (Viswanathan et al., 2014; Strazdas et al., 2020). The paradigm is used to compare them in terms of performance and physical and cognitive workload. This approach is often used to study the interaction between a human and a complex or autonomous system. In it, the participant interacts with a computer system that he/she believes to be intelligent, whereas the system in fact "simulates" the intelligence by relying on predefined scenarios and hard-coded interactions. Here, the subjects used an SA prosthesis to conduct reach-and-grasp tasks while reacting to audio cues (i.e., the subject performed a dual task). Specifically, the autonomous controller relied on the "Wizard-of-Oz" approach to automatically and "ideally" adjust prosthesis wrist and hand appropriately for grasping a predefined target object. In some conditions, systematic errors were introduced in the autonomous control module without any knowledge of the subject. This aims to investigate how the shared control approach affects the subject behavior when a mismatch occurs between the intentions of the autonomous controller and the subject.

MATERIALS AND METHODS

System Implementation

The SA system (**Figure 1**) comprises (1) an *ideal volitional control module* that implements sequential and proportional control of multiple DOFs, (2) an *ideal autonomous control module* built using a state-of-the-art motion capture system, and (3) *a control fusion module* that integrates the decisions from the two control streams (i.e., the volitional and the autonomous modules) to produce the final command that was transmitted to a prosthesis. The "ideal" modules mimicked the state-of-the-art autonomous (computer vision; Mouchoux et al., 2021) and volitional [pattern classification using EMG (Iqbal et al., 2018)] control. However, they were implemented using a reliable and well-controlled setup. The Wizard-of-Oz paradigm was adopted because the focus of the study was on the subject behavior and interaction with the system. Hence, the aim was to avoid confounding factors related to the performance of specific implementations.

Both the autonomous and volitional control modules were capable of driving all three DoFs (i.e., rotation, flexion/extension, and palmar open/close) of the left-hand prosthesis (Michelangelo, Ottobock, Austria). The control fusion module processed volitional and autonomous commands according to one of the predefined shared control schemes, as explained in Subsection Control Fusion Module.

Ideal Volitional Control Module

This module comprises (1) a custom-made mechanical adapter to map the subject's hand and wrist movements into the prosthesis functions (DoF selection) and (2) a myoelectric (EMG) armband to provide a proportional control signal (see **Figure 2**).

The state-of-the-art approach in myocontrol is to use the EMG pattern classification to estimate the subject motion intention and map it into the prosthesis functions. This method allows intuitive control, but is also prone to misclassifications. To implement a reliable command interface, we did not rely on interpreting the myoelectric activity; instead, a custom-made adapter was produced to fully encompass the subject's hand and detect the movement intention *mechanically*. The adapter identified the movements through push-buttons triggered by performing selected gestures (wrist flexion/extension, thumb triggering, and fingers opening/closing), as illustrated in **Figure 2**. Hence, it allowed the user to reliably select the desired *class* by physically performing a given hand motion. The push-buttons were connected to an Arduino Nano board that streamed their states to the host PC *via* a Bluetooth connection at 100 Hz.

In addition, the myoelectric activity was recorded using eight surface EMG electrodes placed around the forearm (Myoband, Thalmic Labs, Inc., Waterloo, Canada) to implement a proportional speed control of the selected DoF. The Myoband streamed the EMG data at 200 Hz to the host PC *via* a Bluetooth connection. To smoothen the signal, the root mean square (RMS) of EMG was computed over 150 ms windows with an overlap of 10 ms between consecutive windows. Then, the RMS from the eight EMG channels was averaged to estimate the overall magnitude of muscle activation along the forearm. The average RMS was normalized to 80% of the maximum voluntary contractions (MVC) and mapped to the normalized movement speed of the selected DoF.

Ideal Autonomous Module

The ideal autonomous control system automatically preshaped the prosthesis' wrist (rotation and flexion/extension) during the object reaching phase and simultaneously maintained the hand of the prosthesis opened at 90% of the full aperture. To this end, the module used prosthesis position, orientation, and internal states (i.e., artificial proprioception), along with the position and orientation of the target objects (i.e., artificial exteroception) to calculate the commands for each prosthesis DoF (**Figure 3**). Typically, the pose and orientation of the target object can be estimated using an RGB sensor (Markovic et al., 2014) or an RGB-D sensor (Mouchoux et al., 2021). However, the present study aimed to obtain reliable control; hence, these parameters were predefined. Similarly, the *target object's desired grasping configuration* (flexion/extension and rotation) was calibrated according to the user preference at the beginning of each session, as explained in subsection Experimental Protocol.

The velocity of each prosthesis DoF was set proportional to the speed at which the subject moved the lower arm (to which the prosthesis was attached) toward the target object, thereby mimicking the smoothness of natural movements during pre-shaping (Jeannerod, 1984). To implement this in a robust and reliable (i.e., *ideal*) manner, the artificial exteroception block employed a state-of-the-art motion capture system (Qualisys Ltd., Gothenburg, Sweden), which tracked the prosthesis and pose of the target objects and streamed it at 100 Hz. Similarly, the artificial proprioception was achieved using (1) the motion tracking to infer the prosthesis position and orientation in space, (2) prosthesis position encoders to retrieve the state (angle) of each prosthesis DoF, and (3) the pressure sensor of the prosthesis thumb to detect contact with the target object. The tracking information (i.e., speed and direction) was extrapolated using quadratic splines based on the data from the previous 2 s to compensate for the occasional marker occlusions.

To achieve gradual progression from the initial to the final stage of the prosthesis's configuration, the module divided the travel distance of the prosthesis from the starting point (see Section Experimental Setup and Protocol) to the target object position into three phases (**Figure 4**): (1) initiation, (2) flight, and (3) pre-grasping. The movement's progress at any given time was defined as the ratio of the distance traveled by the prosthesis to the total distance. When the travel distance was below 15%, the movement was in its initiation phase, and hence the autonomous module was disabled. This stabilized the behavior of the system by preventing the autonomous controller from abruptly reacting to a small arbitrary movement of the user, unrelated to the reaching motion. By initializing the autonomous control only when the 15% of the traveled distance has been reached, the system gave the impression to the user that it has actually reacted to his/her grasping intention. Since during natural prehension movement, the wrist and fingers reach their final position at ∼75% of the movement distance, the flight phase was set to last from 15 to 75% (Jeannerod, 1984). During this phase, the system activated the prosthesis DoFs to ensure that they reached the final state at the end of the flight phase (75%). To do so, the DoF speed was set based on the estimated remaining time to complete the flight

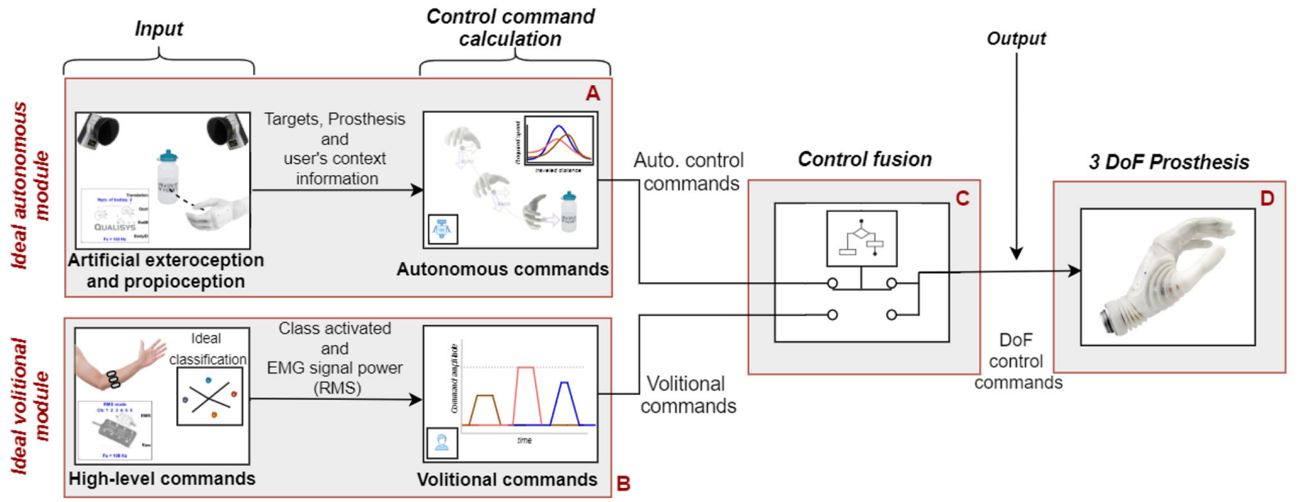

FIGURE 1 | Overall working principle of the implemented SA system. The *ideal autonomous module* **(A)** uses object properties, prosthesis pose tracking (motion capture), and embedded sensor data to calculate control commands to preshape the prosthesis on the fly. The *ideal volitional control module* **(B)** uses an ideal "classification" method (using push-buttons) combined with myocontrol signals to provide sequential and proportional volitional control. The *control fusion module* **(C)** merges the control commands from the two modules into a single command stream to drive the prosthesis DoFs **(D)**. The fusion was performed according to a selected set of rules (shared control modality), as explained in subsection Control Fusion Module.

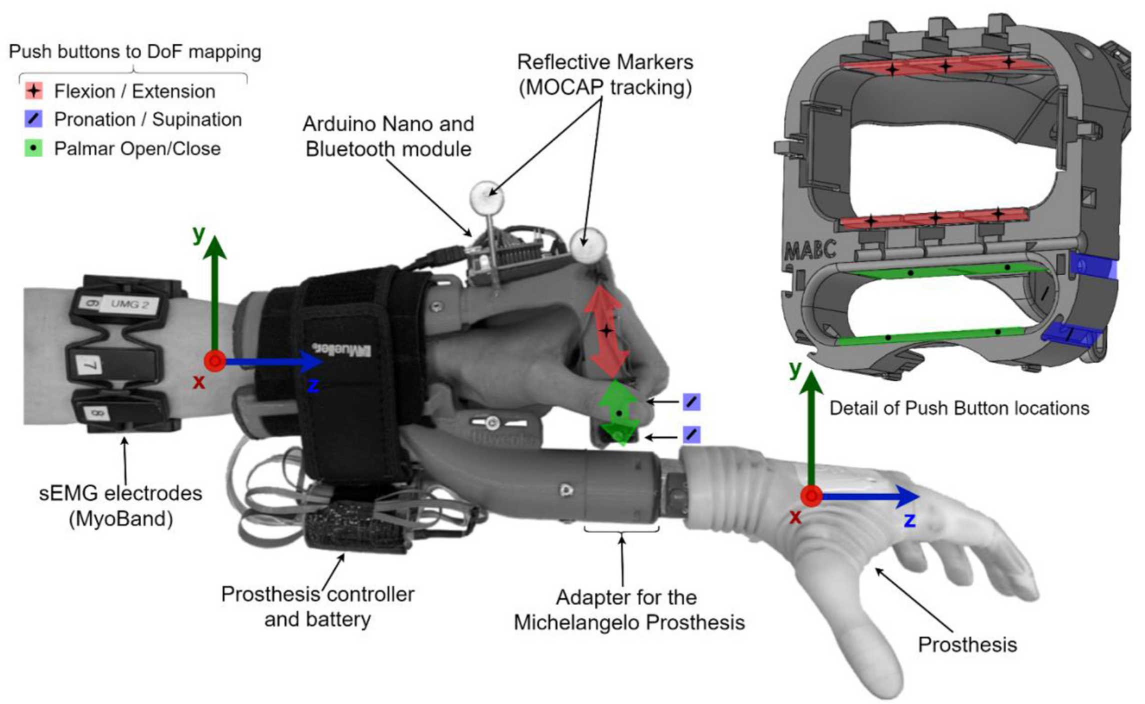

FIGURE 2 | Sensorized prosthesis adapter. The left-hand Michelangelo prosthesis was attached to a three-dimensional printed adapter fixed on the left forearm of the able-body participant. Three infrared markers enabled the tracking of the adaptor in space. Push buttons were embedded in the adaptor around the hand, under the fingers, and under the thumb to detect movement patterns associated with a specific prosthesis DoF. Eight surface EMG electrodes provided proportional control.

phase (**Figure 3E**):

$$Speed_{DoF} = Forearm_{speed} \times \frac{|Pose_{Final} - Pose_{Current}|}{Dist_{total} - Dist_{traveled}}, \quad (1)$$

where $Pose_{Final}$ is the normalized final DoF angle; $Pose_{current}$ is the normalized current DoF angle; $Dist_{total}$ and $Dist_{traveled}$ are the total and traveled distances, respectively;

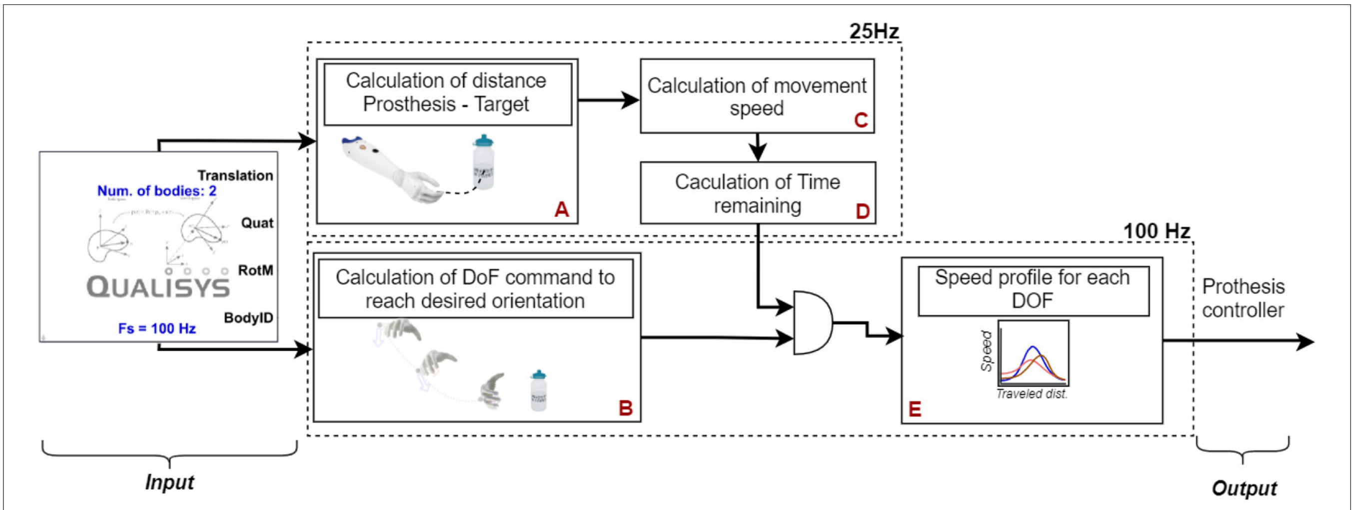

FIGURE 3 | Components of the ideal autonomous module. The tracking information from the motion capture system was used to calculate the current distance from the prosthesis to the target object **(A)**, as well as the difference between the current prosthesis orientation and the desired grasping orientation **(B)**. The module calculated the derivative of the prosthesis position to determine its movement speed **(C)**. The time remaining to reach the target object was computed from the movement speed and current distance to the target object **(D)**. Then, the remaining time (output of **D**) was combined with the difference between current and desired configuration (output of **B**) to compute the speed required for each DoF to reach its target pose at the end of the reaching movement, to accompany the movement of the forearm **(E)**.

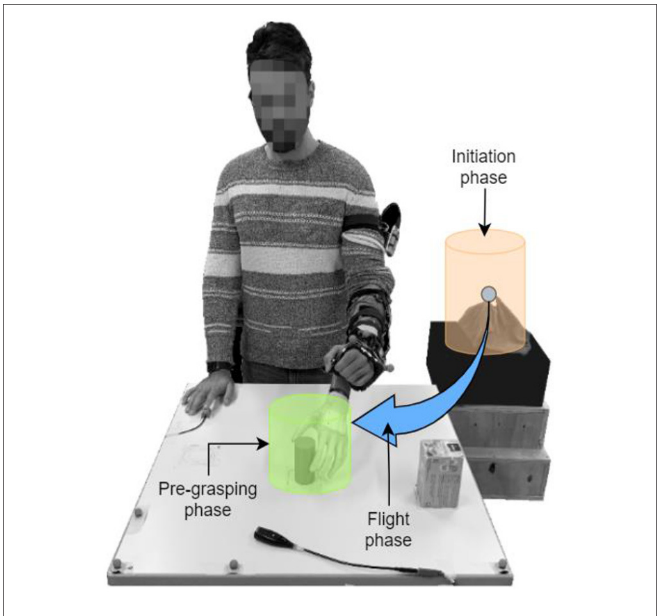

FIGURE 4 | Phases of pre-shaping. The three phases of pre-shaping are defined as the ratio of the distance traveled by the prosthesis to the total distance. The distance of [0, 15]%, [15, 75]%, and [75, 100]% of the total distance corresponds to initiation, flight and pre-grasping phase, respectively.

and $Forearm_{speed}$ is the speed at which the prosthesis moved toward the target computed as the derivative of its position.

Finally, in the *pre-grasping* phase, the autonomous system compensated for the subject's variations in the limb position to maintain the *desired grasping configuration*, which minimized the difference between the *desired grasping configuration* and the actual prosthesis state at any given time, further ensuring a steady pose of the hand with respect to the target object regardless of the forearm movements. The orientation (represented in quaternion) of the prosthesis (Q_{Prosth}) (Equation 2) was computed using the orientation of the forearm ($Q_{forearm}$) and the current state of the prosthesis wrist DoF according to the coordinate system of the prosthesis socket ($Q_{Prosth_{wrist}}$).

$$Q_{Prosth} = Q_{forearm} * \left(Q_{forearm} * Q_{Prosth_{wrist}} * Q_{forearm}^{-1} \right) \quad (2)$$

The current orientation of the prosthesis (Q_{Prosth}) was then compared to the *desired grasping configuration* ($Q_{DesiredGraspConf}$) to determine the difference in orientation that had to be compensated ($Q_{Compensation}$) (Equation 3).

$$Q_{Compensation} = Q_{DesiredGraspConf} * (Q_{Prosth} * Q_{forearm} * Q_{Prosth}^{-1}) \quad (3)$$

Then, the compensated orientation ($Q_{Compensation}$) was transformed into a three-angle representation, and the autonomous control module activated each DoF accordingly. The actuation speed in this phase was set to the maximal speed (78°/s in rotation and 90°/s in flexion). The prosthesis DoFs were driven at their maximum speed to ensure that the required orientation was attained at the earliest to ensure that the prosthesis was prepared for the imminent grasping action. The movements in this phase were typically triggered if the automatic controller did not have enough time to fully complete the preshape during the preceding flight phase and/or if the subject performed unexpected movements (e.g., "wobbling" around the object).

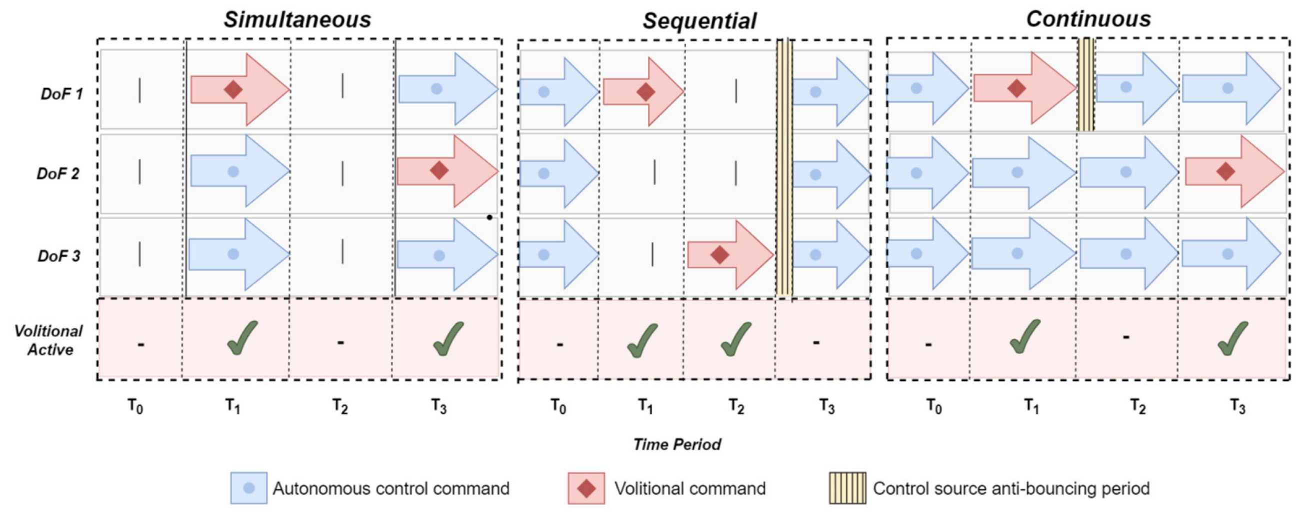

FIGURE 5 | Shared control modalities. Three different approaches to fuse volitional and automatic control tested in this study: *sequential*, *simultaneous*, and *continuous* (see text for details). The horizontal axis (columns) represents the consecutive time periods. The switch from manual control to automatic control is always proceeded by an off period to avoid oscillating between the control sources.

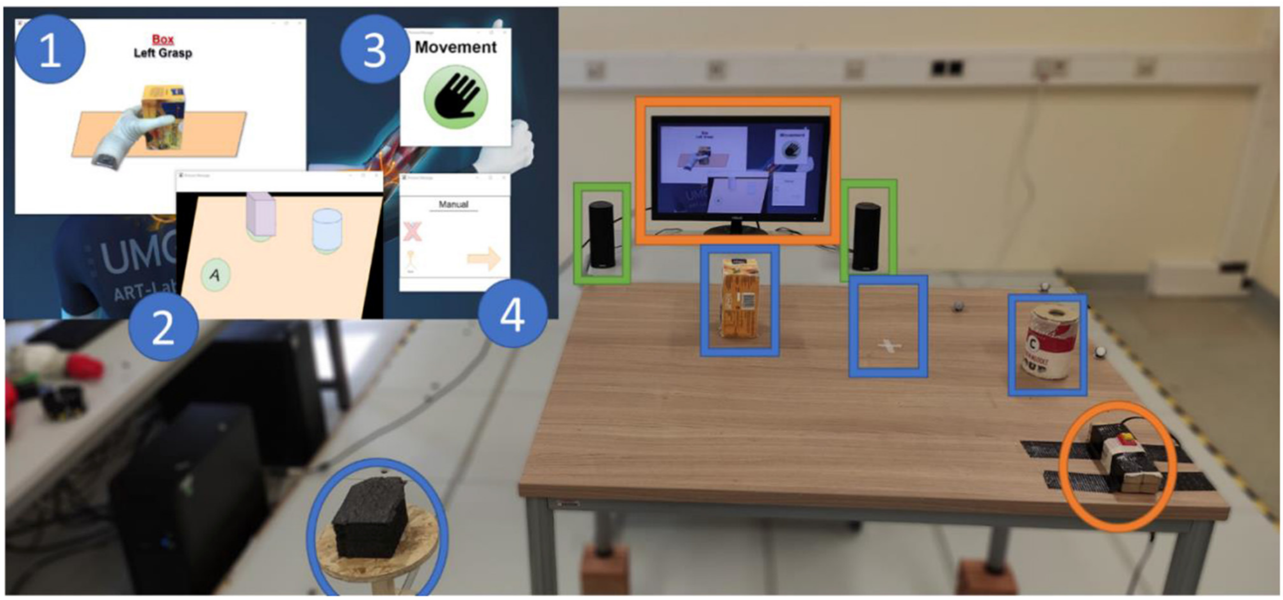

FIGURE 6 | Experimental setup. One rectangular tee box and one cylindrical container were placed on the table in two of the three marked positions (blue squared). The participant started the trial with the prosthesis placed on the rest area (blue circle) and grasped the object as shown on the screen (orange square). In parallel, the participant had to react to each auditory cue delivered by the speakers (green square) by pressing the button on his/her right (orange circle). The screen displayed (1) the instruction on which object should be grasped (box or cylinder) and how the grasp should be performed (from the right, left, top, and front), (2) how the table surface should look like at the end of the manipulation with the object, (3) the visual countdown for the start of the trial indicating when the subject should start reaching toward the object, and (4) the current SA control modality.

Control Fusion Module

Three different shared control schemes were implemented (**Figure 5**): *simultaneous SA*, *sequential SA,* and *continuous SA*.

In the *simultaneous SA* scheme, the autonomous system complemented the subject's actions only while the user actively controlled the prosthesis using a volitional control interface. Whenever a DoF was controlled manually, the autonomous system would control the remaining DoFs. For example, while the user controls the prosthesis aperture, the autonomous module adjusts its wrists.

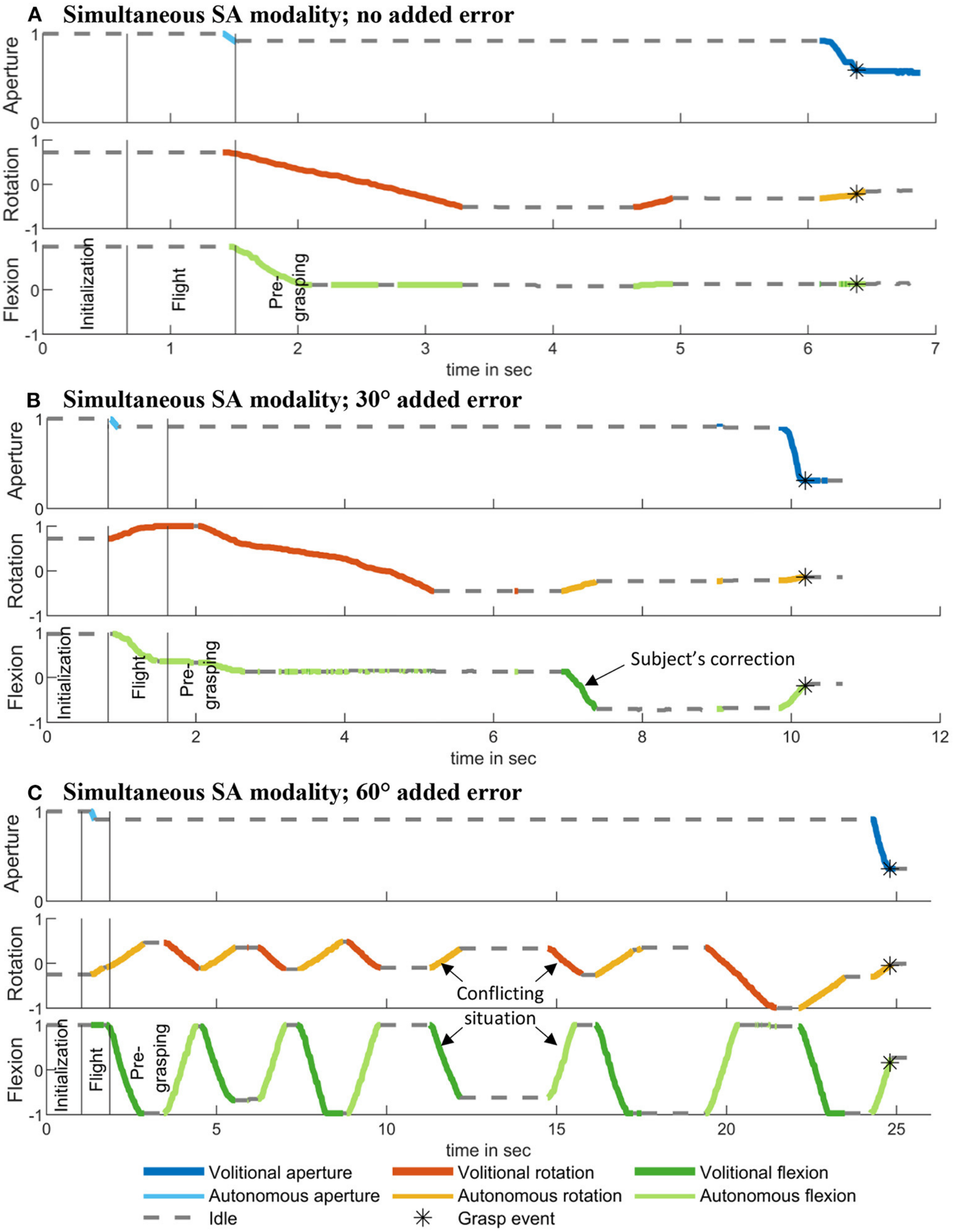

FIGURE 7 | Examples of prosthesis pose during the simultaneous SA modality under 0°, 30°, and 60° added error. Movements due to the volitional control are dark, while those from autonomous controller are light. The bars marking the different phases of the reaching movement correspond to 15 and 75% of the movement. The detection of the grasp is marked with a star. **(A)** Simultaneous SA modality; no added error. **(B)** Simultaneous SA modality; 30° added error. **(C)** Simultaneous SA modality; 60° added error.

In the *sequential SA* scheme, the autonomous system controlled the prosthesis only while there was no volitional input. Unlike the previous approach, the autonomous module was deactivated when the subject controlled the prosthesis aperture. After the volitional input was stopped, the autonomous module resumed the control of all the prosthesis DoFs. To avoid the oscillation between two control modalities, the autonomous system re-activated 1.5 s after the last volitional input.

In the *continuous SA* scheme, the autonomous system *continuously* controlled all DoFs, but relinquished the DoF actuated volitionally by the subject. Therefore, if the subject controlled the flexion/extension, the autonomous module drove the rotation. When the subject stopped generating volitional commands, the prosthesis wrist was fully controlled by the autonomous module. As in the *sequential* scheme, the control was switched to autonomous after a delay of 1.5 s.

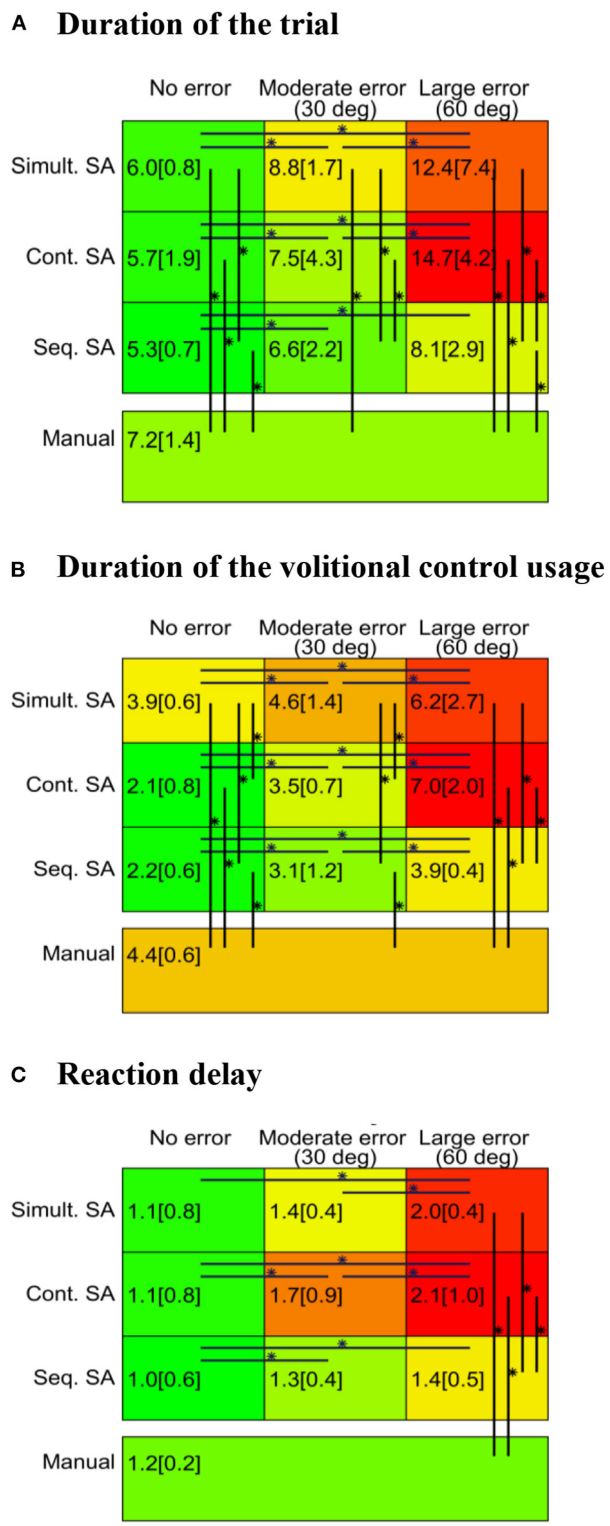

FIGURE 8 | Outcome measures. Duration of the trial **(A)**, duration of the volitional control usage **(B)**, and reaction delay **(C)** for three different SA control modalities (in three different conditions) and the manual control. The depicted values are the medians (interquartile ranges) of the calculated averages for all participants in the respective condition. The green-to-red color scale is *(Continued)*

FIGURE 8 | normalized to the minimal and maximal values of each outcome measure, respectively. "*" indicates significant difference at the *p*-value lower than 0.05 after the correction.

Experimental Setup and Protocol

The experiments were performed in 10 able-bodied subjects (five females and five males), within the age group of 24–55 years, all right-handed. All subjects signed a written consent form approved by the ethical committee of the University Medical Center Göttingen (22/04/16).

The experiment involves reach-and-grasp tasks wherein the subject received specific instructions regarding the techniques by which an object can be grasped using the left-hand prosthesis while reacting to acoustic stimuli (see Subsection Experimental Task).

Experimental Task

The experimental setup from the subject's perspective is depicted in **Figure 6**. The subject stood in front of a table whose height was adjusted to ensure that her elbows would be at an angle of 90° when the hands were resting on it. Two objects, a box and a cylinder, were placed on the table in two of the three marked positions, as illustrated in **Figure 6**. A monitor displayed the instructions in front of the subject, i.e., the target object and grasping side. A platform placed on the left of the participant was utilized as a support for the forearm at the initial (starting) position and served as the resting position to reduce muscle fatigue. After a 3-s countdown that is displayed on the screen, a visual signal was provided to the participant to set the beginning of the trial. The participant was required to reach for and grasp the target object from a specific side (right, left, top, and front) as fast as possible and to reallocate it to the (only) available marked position on the table, thus rearranging the setup in each trial. After the target object was allocated, the participant was instructed to move back her arm with the prosthesis to the initial (starting) position and place it back on the platform. Note that the automation was active only during the reaching phase, and hence the experimental task included only reaching, grasping and simple relocation of the object (i.e., object manipulation was not relevant).

During the execution of the reach-to-grasp task, a pseudo-randomly occurring acoustic stimulus (a continuous monotonous beep of 400 Hz) was played through the computer speakers. Each stimulus was played continuously until the participant reacted to it by pressing a button that was fixed on the right side of the table with her right hand, that is, the hand that was not used for prosthesis control. After the participant had reacted to the auditory stimulus, a new cue appeared after a time interval that was randomly selected to last between 0.8 and 1.6 s. The audio cues continued to (re)play until the user grasped the target object.

Experimental Protocol

The experiment started by calibrating the SA system to match the individual preferences of each subject, including (1) the responsiveness of each DoF of the prosthesis to volitional input and (2) the prosthesis *desired grasping configuration* during the reach-to-grasp task.

To calibrate volitional control, the participant was asked to trigger each movement using maximal contraction (MVC), followed by a light contraction (activation threshold). The myoelectric signal range between the measured activation threshold and 80% MVC for the given movement was then mapped to the full range of prosthesis velocity for that DoF. Finally, the subjects were asked to perform 20 grasps using the ideal volitional interface to familiarize themselves with it. During these interactions, minor adjustments were performed in control responsiveness as per their requirements.

The subject was asked to control the prosthesis using a volitional interface to grasp both target objects placed on one of the marked positions for every grasping side (right, left, top, and front) to adjust the desired grasping configuration. The states of the prosthesis DoFs (flexion/extension and rotation) and the orientation of the subject's forearm at the moment of contact were recorded as the *desired grasping configuration* for the given object and grasping side. This was repeated for all combinations of target objects and grasping sides, and a lookup table of the *desired grasping configurations* was created. The autonomous module used the lookup table to set the final flexion/extension and rotation (see Subsection Ideal Autonomous Module).

After calibration, the subject started the experimental task (described in Subsection Experimental Task). Before commencing each trial, the two DoFs of the prosthetic wrist were rotated 80° from the final position in a random direction (flexion, extension, rotation, or supination). Such random alterations in the initial prosthesis' orientation were used as a pragmatic solution to enforce a multitude of different pathways that the prosthesis had to transverse in order to reach its final orientation, without having to resort to the (tedious) reorientation of the target object itself. Indeed, the combination of four possible object grasp-directions (left, right, top, or front) and four possible perturbations in the prosthesis' initial orientation (wrist flexion, extension, rotation, or supination) yielded 16 unique combinations in the orientation of the prosthesis at the beginning and end of the trial (i.e., between its initial and final orientation). The subjects performed reach-to-grasp tasks using three SA control schemes (*simultaneous SA*, *sequential SA*, and *continuous SA*). Each scheme was employed under three conditions, in which the autonomous controller navigated the hand to the *desired configuration* with no error (SA baseline) and with moderate and large systematic errors, respectively. The systematic error was implemented as a constant offset added to the decisions of the autonomous controller, 30° for moderate and 60° for large errors. Additionally, the subjects performed the experimental task using the ideal volitional control (manual baseline), resulting in 10 conditions.

Ten conditions were performed in two blocks of twelve trials each (24 trials per condition). The subjects performed the blocks in a random order. The shared control modality was announced to the subject each time it changed. A break of 10–15 min was made in every six blocks; hence, there were three breaks in total.

Outcome Measures and Data Analysis

The following outcome measures were employed: (1) the duration of the trial as a measure of performance, (2) the usage of volitional control quantifying the "amount" of a subject's intervention during the task (physical workload), and (3) the user's reaction time to auditory cues as a measure of their cognitive load. Trial duration was defined as the duration between the start signal and the moment of contact with the target object (grasp onset). Volitional control usage was calculated as the accumulated time of volitional control throughout the trial. Finally, the reaction time was defined as the period from an acoustic stimulus until the subject pressed the button.

The first two trials of each block were regarded as an adaptation to a new condition, and these were discarded from the analysis. Therefore, out of 240 performed trials, 200 were used for the data analysis. For each condition, the average values of the outcome variables were computed for each participant. Because none of the outcome variables passed the Kolmogorov-Smirnov test, the difference between the conditions was assessed at first using the Friedman test, and thereafter, in the case of a positive result, using the Wilcoxon signed-rank test for realizing the pairwise comparison. To account for a large number of statistical tests, the p-values were corrected using the Bonferroni-Holm correction. The results in the text are reported as median (interquartile range).

RESULTS

During the experiment, volitional and autonomous controllers shared the control of the prosthesis. The pose of the different DoFs of the prosthesis during three trials (i.e., simultaneous no error, simultaneous 30° error, and simultaneous 60° error) is illustrated in **Figure 7**. Per design, the simultaneous SA modality only allowed the autonomous controller to control the prosthesis when the user actuated one of the prosthesis DoFs. When no error was added to the output of the autonomous controller, the actuation of one DoF was sufficient to preshape the entire prosthesis owing to the autonomous controller complementing the preshape simultaneously (**Figure 7A**). When 30° errors were added, adjustments were occasionally necessary. The solution provided by the autonomous controller was not sufficient to directly grasp the object, and a short volitional correction was required to rectify it (**Figure 7B**). At the maximum level of added error, a conflicting situation appeared where the autonomous controller moved back a DoF previously corrected by the user (i.e., the race condition). This produced repetitive corrections of two DoFs until a graspable prosthesis's pose was found (**Figure 7C**). For the three error conditions, most of the actuation was performed in the vicinity of the object.

Subjects grasped the cylinder and the box object equal number of times (100; ten times per condition) and the grasp distribution of the four grasping directions was uniform - 50 grasps were performed from the left, right, top, and front sides of the two objects. On average, per condition, there were 9.9 unique combinations in the orientation of the prosthesis at the beginning and end of the trial (see section Experimental Protocol). A summary of the results for all outcome measures across different conditions is depicted in **Figure 8**, where the rows are the control modalities and the columns are the error conditions. Statistically significant differences are indicated by horizontal (across error conditions) and vertical lines (across modalities). Regarding the time required to complete the task (**Figure 8A**), the use of the SA control in the no-error condition always resulted in lower task completion times than manual control independent of the SA control modality. In the no-error condition, differences appeared between the SA modalities, as indicated by better performance obtained when using *sequential SA* compared to *simultaneous SA* modality. The addition of systematic errors impacted all three modalities by increasing the task completion time, but the increase was not equal across the modalities. Moreover, the difference in performance between the modalities became more pronounced as the error increased. The increase in task completion time [median (interquartile range)] was significantly higher ($p < 0.05$) for *simultaneous SA* [+6.3 (6.3) s] and *continuous SA* [+9.1 (3.9) s] compared to the *sequential SA* modality [+3.1 (1.5) s]. Overall, the *sequential* control was faster than *simultaneous SA* and *continuous SA* modalities in both moderate and large error conditions. This increase in the time required to complete the task when using SA control corrupted by the systematic error also impacted the comparison with the manual control baseline. In the moderate error condition, the *simultaneous* modality demonstrated worse time performance than the manual baseline, while in the large error condition, all modalities were slower than the manual baseline.

Volitional control usage exhibited similar trends compared to those observed for the trial duration (**Figure 8B**). Compared to the manual condition, the use of SA control with no errors consistently reduced the need for volitional control. However, the increase in the error level increased the use of volitional control for all the three SA modalities. Consequently, the volitional control usage in *simultaneous SA* and *continuous SA* modalities became similar in the moderate error condition and eventually longer in the large error condition compared to the manual baseline. However, the sequential modality resulted in a reduced volitional control usage with respect to the baseline in both no error and moderate error conditions and a similar duration in large error conditions. When comparing the SA modalities to each other, the *simultaneous SA* modality required more volitional control in no-error and moderate error conditions than the two other modalities, which were similar to each other. In large error conditions, *sequential SA* modality required less volitional control compared to the other two similar modalities. From moderate to large error conditions, the use of volitional control increased significantly more ($p < 0.05$) for the *continuous SA* [+3.4 (2.0) s] than for the *sequential* SA modality [+0.7 (0.9) s].

The subject's reaction time (**Figure 8C**) was similar in the no-error and moderate-error conditions across all control approaches (SA and manual). Nevertheless, all modalities demonstrated an increase in the reaction time with an increasing level of error. The *continuous SA* modality seemed to be the most sensitive as the reaction time was different for each combination of error conditions. For *the sequential SA* scheme, the time increased in large and medium error conditions with respect to no-error, whereas for the *simultaneous SA* approach, only the large error condition increased with respect to time. Across the modalities, the only difference was registered for the large error condition, where *sequential SA* control resulted in the smallest time, similar to that achieved in the manual baseline. The reaction time in the other two modalities were higher than those in the manual baseline.

DISCUSSION

We investigated three different schemes for the integration of volitional and autonomous control in a SA prosthesis. To avoid confounding factors related to the performance of specific implementations, an experimental assessment was conducted using "ideal" solutions. The results, collected from 10 subjects, demonstrated clear differences between the SA modalities vs. the manual baseline (volitional control only) and across the SA modalities in performance, volitional control usage, and reaction time. The differences were exacerbated when systematic errors were introduced in the autonomous control.

In the no-error condition, the subject and the autonomous agent had similar goals (the same *desired hand configuration*). In this case, the SA modalities were consistently faster than the pure volitional control (manual baseline). Several studies have demonstrated that SA systems can outperform conventional EMG-based controllers (Markovic et al., 2015; Volkmar et al., 2019; Mouchoux et al., 2021). The present study confirmed that this result also holds in the case of "ideal" implementations. This demonstrates the intrinsic potential of the SA approach, which, if reliably implemented, can outperform even *a reliable* myoelectric controller. The autonomous component of the SA system provides simultaneous activation of the DoFs and supports movement planning and execution. However, with a purely volitional approach, the subject generated commands sequentially, and she moved the prosthesis nearer to the object, as well as adjusted the wrist to orientate the hand toward the object. Thus, she managed two tasks, leading to slower forearm movements or sequential handling of these two actions (first reach and then orient). Notably, the volitional controller in the present study was implemented as an "ideal" class selector; it is still to be investigated how SA control would compare to an "ideal" regression-based approach, which could be realized using a joystick type interface providing simultaneous control of multiple DoFs.

A difference between the three SA modalities was found even in the baseline (no error) condition. In this case, the *simultaneous SA* modality showed the worst time performance and the highest usage of volitional control among the schemes. The reason for this might be that the user was required to activate a DoF to trigger the autonomous module to control the other DoFs. In fact, we observed that the participants often generated redundant commands for the prosthesis opening (even when the prosthesis was fully open) to trigger the autonomous controller to adjust the wrist DoFs. Conversely, in the other two SA modalities, the autonomous control was active without triggering, and the subject only had to bring the prosthesis into a graspable position and then close the fingers. Therefore, the longer task completion time suggests that the SA scheme with triggering (i.e., simultaneous SA) negatively affects not only the volitional control usage but also the time performance. While triggering was used as a predominant approach in the studies that implemented SA prostheses, some recent approaches eliminated this step (Mouchoux et al., 2021) and/or attempted to make it transparent and effortless, that is, naturally embedded in the grasping process (Frisoli et al., 2012; McMullen et al., 2014).

When a mismatch occurs between the goals (*desired hand configuration*) of the user and the autonomous agent (e.g., due to the errors introduced), the results indicate that the design of the shared control modality can have a critical impact on the task performance as well as the physical and cognitive workload. This situation can arise because of erroneous decisions of the autonomous system (e.g., wrong estimation of object properties (Markovic et al., 2014; Mouchoux et al., 2021) and/or class (Ghazaei et al., 2017; Hundhausen et al., 2019; Shi et al., 2020) or because the autonomous system associates another grasping strategy with the target object than the one intended by the user. For instance, autonomous systems based on object recognition are object-focused, whereas humans are manipulation-focused (Rosenbaum et al., 1996) while selecting the grasp strategy. When the goals of the two control agents are similar, they cooperate, making the task faster and reducing the interaction between the autonomous controller and the subject. Therefore, in this case, a specific implementation of the shared control modality has a smaller impact on the performance. However, when the decisions differ, the scenario develops into a control paradigm in which a conflict arises between the two independent agents (see **Figure 7C**). This explains an increase in physical and cognitive workload and the decrease in performance observed in the experiment. This can be so detrimental that SA control becomes substantially worse compared to the manual baseline.

Nevertheless, the results also reveal that some SA modalities are inherently more robust in these situations. The *sequential SA* modality was less impacted by the introduction of errors compared to the two other schemes. When the user noticed the wrong configuration, she engaged in volitional control to correct it. Importantly, in the sequential modality, this also fully disabled the autonomous controller. Therefore, the system gracefully "degraded" to a pure volitional control; indeed, the outcome measures for *sequential* modality in error conditions were similar to those of the manual baseline. Therefore, a *sequential* approach might be the modality of choice, especially because an SA prosthesis is used in dynamic and challenging environments (e.g., at work).

On a more general level, the present study is related to the broader field of human-robot collaboration (Cherubini and Navarro-Alarcon, 2021). The quality of shared control depends on several factors listed by Flemisch et al. (2016), such as the traceability and predictability of abilities and intents in both directions (human-machine and machine-human) as well as the arbitration of conflicts. The importance of considering the potential conflict has also been stressed by Abbink et al. (2018): "*In shared control, conflicts between the human and the robot should be minimized, by modeling robot actions based on human behavior; and in case of conflicts, the robot should ensure that the human has the time and ability to influence the robot's actions.*" The current results demonstrated that these points impact the performance, physical, and cognitive workload and need to be addressed while designing a collaborative control (Sherstan et al., 2015). One solution already tested in prosthetics is to check for concordance between the commands of the two agents and prioritize the user's commands in case of any conflicts (Zhuang et al., 2019). Abbink et al. (2018) stated that *"the control authority can be traded with enough margins for the human operator to get back in the loop and respond adequately,"* which is in line with better performance obtained by using *sequential SA* modality in the present study.

The data collected in this experiment were obtained from able-bodied users. Their relation and experience with the prosthesis are different from those of an amputee relying on a prosthesis in daily life. Not only may the control priorities differ, but the perception of the autonomous system may also be different. Indeed, the embodiment of a prosthesis is a relevant parameter of its acceptance and use (Fritsch et al., 2021). Therefore, it would be interesting to complement the quantitative outcomes measured in this study with the effect that the shared control modality might have on the prosthesis's embodiment in the user's self-representation. Furthermore, the present experiment cannot be directly reproduced in amputee subjects, as the volitional control module uses mechanical switches to achieve intuitive and reliable control ("ideal" implementation). The aim of the present study was not to develop a novel SA system, but to investigate the fundamental impact of different "prototypical" SA schemes on the interaction between the system and its user. To maintain the intuitiveness for amputee subjects, the volitional controller would need to rely on the pattern classification of myoelectric signals. Nevertheless, in this case, the reliability of the control could be improved through a more extensive training. Finally, although the study design introduced substantial within-task variability by combining random perturbations in prosthesis orientation with different object grasping directions, the overall variability of tasks was limited by the fact that the employed objects were of similar size and function. User's interaction with an object greatly depends on its (intended) application; therefore, in order to better understand their strengths and weaknesses, the SA control-sharing modalities (and corresponding SA systems) will need to be evaluated using an extended set of objects that are common in activities of daily living. Such investigation is however outside the scope of the present work and remains a future goal.

CONCLUSION

This study investigated the impact of shared control modalities on performance and workload while using a SA prosthesis. The results indicate that all SA modalities outperformed pure volitional control under ideal conditions. However, *simultaneous* schemes were worse than the sequential and continuous modalities. When the accuracy of the autonomous controller degraded (error conditions), the performance of the SA modalities decreased substantially, even below the manual baseline. However, the most robust approach was the sequential scheme wherein the subject control completely disabled the autonomous controller. This implies that such a scheme is likely the method of choice while implementing upper-limb prostheses equipped with SA control.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethical Committee of the University Medical Center Göttingen. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

JM, MABC and MM conceptualized the study. JM and MABC developed the system and wrote the manuscript draft. JM conducted the experiment and performed the data analysis. SD, AS, and MM contributed to the study design and revised the manuscript. All authors approved the submitted version.

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