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Social touch

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Social touch

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Editorial: Social touch

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Editorial on the Research Topic
Social touch

Is social touch in crisis? According to Jewitt et al. the answer is affirmative. The decline in social touch over the past two decades (amplified during COVID-19) and inappropriate use of social touch are their main arguments. At the same time, we cannot afford to lose social touch, as it is central to relational, psychological, and physiological wellbeing (Figure 1). The crisis for *digital* (or mediated) social touch may even be deeper, as argued by the authors and illustrated by the playfully provocative statements in their "Manifesto for digital social touch in crisis", some of which speak to the challenges raised by other authors who contribute to this Research Topic on Social Touch. These include challenges related to the loss of cultural variation, the socio-economic divide in access to digital social touch, and new social norms emerging from digital social touch, for instance on agency, control, and consent. These challenges require our attention as researchers, engineers, computer scientists, and designers.

Inspired by touch deprivation following COVID-19 restrictions, this issue aimed to collect multidisciplinary perspectives on social touch from theory to design. The flipside of COVID-19 restrictions may be that people's views on mediated social touch changed. Ipakchian, Huisman et al. investigated this in a survey study with 277 participants conducted during the COVID-19 pandemic and found that touch deprivation may have instigated a new openness to using technology to mediate and support touch connections with close others. This finding was not modified by technology readiness and touch aversion. User needs evidently can shape the future development of digital social touch.

Meanwhile, Della Longa et al. notice that touch is often overlooked in the current digital transition. Their review confirms that losing social touch would increase social disconnection and loneliness, something we cannot risk. This concern is not hypothetical, given the increasing use of immersive Virtual Reality and immersive internet (e.g., the Metaverse) for social communication with their typical restrictions to vision and audition. This articles specifically tackle the question of whether digital social touch can help foster social connection when, for example, anorexia nervosa or autism come into play. They conclude that the digital transition brings new opportunities for digital touch, such as mediating social touch between (romantic) dyads separated by distance. Along these lines, van Hattum et al. studied romantic couples using a mediated social touch device over a period of 2 weeks, and saw how they compensated for the channel's rudimentary quality and developed a dyad-specific haptic language to enrich their interaction. They documented how this in turn contributed to an increase in relationship salience, feelings of closeness, and contact quality. Even after prolonged use, the signal could (still) startle a user, underlining the importance of topics like agency, control, and consent.

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FIGURE 1
Covid-19 restrictions and the notice of skin hunger have sparked the research efforts on the importance of social touch and solutions to mediate social touch. See: https://www.shutterstock.com/image-photo/elderly-asian-women-wearing-face-mask-1889789962.

Social touch in crisis may also mean that we may need to reconsider the theoretical framework(s) we apply to (mediated) social touch. Current approaches based on theorizing or simulating others' mental states, for example, do not adequately account for touch being an active sense (contrary to for instance vision and audition). Huisman suggests Interaction Theory, a theoretical approach that accounts for embodiment and interaction, as a framework for investigation. Huisman also argues that the crisis in digital touch is amplified by the low implementation and acceptance rate of technology supporting it. This argument resonates with the comments from Mader et al., who plea for a tinkering approach to design in this space, along with early stakeholder involvement to increase acceptance. Tinkering involves playful and creative exploration, and their paper offers a detailed description of this approach including a comprehensive list of materials in their tool kit. They report that tinkering can result in a broad diversity of developed concepts, indicative for a successful design process.

An important question raised by several authors in this Research Topic concerns the extent to which a digital social touch should (or could) mimic a human touch. To answer this question, we need better instruments to measure and quantify human touches. This challenge is picked up by Xu et al. who describe a 3D visual tracking system and advanced mesh and surface modeling to derive contact area, indentation depth, three orthogonal velocity components, and contact duration of skin-to-skin interactions. To study the emotional components of social touches such as poking, patting, massaging, squeezing, and stroking, Zhu et al. used a closed-loop system consisting of an array of force sensors, algorithms to generate control signals, and an array of voice coil actuators to generate a social touch. One of their findings is that the speed of the touch has a great influence on perceived valence, arousal, realism, and comfort. These results shed light on the design space of mediated social touch, a topic further explored by Rognon et al. and Ipakchian Askari, Haans et al.. Rognon et al. empirically examined the interaction between four social touches (high five, handshake, caress, asking for attention), two or three actuation parameters (different for each social touch including e.g., duration and strength), and two social contexts (specifically tuned to each social touch) on perceived emotional content using the circumplex model of affect. Although all social touches were recognizable above chance, the paper suggests that some may have more universal or intuitive meanings. Ipakchian Askari, Haans et al. took a comprehensive approach to study the design space by reviewing 89 prototype affective haptic devices described since 2019. They identified 17 dimensions in the design space including for instance synchronicity and actuation type.

The papers in this Research Topic illustrate concerns as well as optimism. Social touch is of critical importance for human wellbeing and because of that, it is also vulnerable to misuse or abuse. Digital social touch may bring the importance of inter-human touch interaction back in times of social distancing, geographically separated families, and long-distance relations. This promise inherently raises important ethical and societal questions on, for instance, agency, consent, and acceptance. Collectively these papers make a strong case for the need and benefits of addressing these questions by bringing social touch technical developments and social research on their take up and use, to go hand-in-hand.

Author contributions

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

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Manifesto for Digital Social Touch in Crisis

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This qualitative exploratory research paper presents a *Manifesto for Digital Social Touch in Crisis* - a provocative call to action to designers, developers and researchers to rethink and reimagine social touch through a deeper engagement with the social and sensory aspects of touch. This call is motivated by concerns that social touch is in a crisis signaled by a decline in social touch over the past 2 decades, the problematics of inappropriate social touch, and the well documented impact of a lack of social touch on communication, relationships, and well-being and health. These concerns shape how social touch enters the digital realm and raise questions for how and when the complex space of social touch is mediated by technologies, as well the societal implications. The paper situates the manifesto in the key challenges facing haptic designers and developers identified through a series of interdisciplinary collaborative workshops with participants from computer science, design, engineering, HCI and social science from both within industry and academia, and the research literature on haptics. The features and purpose of the manifesto form are described, along with our rationale for its use, and the method of the manifesto development. The starting points, opportunities and challenges, dominant themes and tensions that shaped the manifesto statements are then elaborated on. The paper shows the potential of the manifesto form to bridge between HCI, computer science and engineers, and social scientists on the topic of social touch.

Keywords: touch, social touch, digital touch, sensory, haptics, design, manifesto, interdisciplinary research

INTRODUCTION

This qualitative exploratory research paper presents a *Manifesto for Digital Social Touch in Crisis* (**Figure 1**). The manifesto's call – to rethink and reimagine digital social touch through a deeper engagement with the social and sensory aspects of social touch, is motivated by concerns that social touch is in crisis (both historically and looking forward). There has been a significant decline in social touch over the past 2 decades with an increase in a culture of "low-no-touching" (Linden, 2015), a decrease amplified by Covid-19 (Field et al., 2020). The problematics of inappropriate social touch, abusive social touch, and the ethics of social touch are well documented (e.g., Field, 2014). This raises

MANIFESTO FOR DIGITAL SOCIAL TOUCH IN CRISIS

This manifesto is for designers and developers working on digital touch across academia and industry. It is a vision designed to challenge and provoke debate, raise awareness, incite questions, inspire and direct research and design on the social and sensory aspects of the digital design of touch.

> Human touch is at risk. Of disappearing. Neglected touch. Low touch. No touch. Not enough touch. Touch hunger. Skin starvation. Touch deprivation. Remote. Distant. Missing. ///Flip -Switch/// Too much touch. Intrusive. Unwelcome. The wrong kind of touch. Feel the cacophony, the weight of fears for technological touch – but don't forget the good dreams.

1. MAKE SOCIAL TOUCH CENTRAL

Human touch matters! Hone in on social touch. Include 'touch matters' at the heart of digital communication. Amidst conflicting social concerns and uncertain futures, we must find routes to navigate the technological realities and promises for social touch. Give life back to the digital: Feel the pulse.

2. DESIGN TOUCH FIRST, TECHNOLOGY SECOND

Touch is at risk in technology. Technology (alone) is not the solution. We need technologies to better realize digital touch. Goals for digital touch should be set by something more than technological availability. Amplify interdisciplinarity to PRESS RESET. Rebalance the dialogue between the social, sensory, tactile aesthetic and technological drivers underpinning digital touch development. Bring nuance to a collective imaginary of future touch.

3. DEMOCRATISE TOUCH: DON'T LOCK IT IN

Touch is political. Touch is infused with power. We are positioned to touch through socio-economic and socio-cultural drivers. Let's interrogate how digital design reshapes touch needs and norms. Digital touch needs to be a felt conversation. Everyone is qualified to have a say on what digital touch might be/become. The touch etiquettes of the 20th century will not suffice. OPEN up 'opportunity spaces' to AVOID imaginations of touch getting 'locked in'. DESIRE HETEROGENEITY. Just say no to 'homogenised touching'. Amplify diversity through haptic encodings.

4. PROTECT TOUCH: KEEP TOUCH PRIVATE AND SECURE BY DESIGN

Touch is intimate. Touch reveals myself and my boundaries. When I touch what do I convey about myself? What did I feel of you? Am I identify-able? Did you feel it was me? Can I touch back? Touch overload. Touch Space Invader. Unauthorised touch. WARNING. Alert! Deceptive touch. Hacked feel. Fake Touch 'Retouchée'. Guarantee me control of my digital touch patterns and preferences. Record. Share. Replay. Mix. Consent. I own my digital touch. Don't wait to tame the haptic 'Wild West'. Develop a haptic business model beyond haptic-monitoring. Let the user decide when, how and where technology touches.

5. MOVE BEYOND VIBRATION: FEEL BEYOND THE HABITUATED

Pay closer attention to the FEEL of touch. Re-encode touch sensations. Create landmarks of felt resistance in the tactile terrain. Materialise touch! ROUGH it up - WARM it up. Give us texture. Soft, bouncy, warm and comfortable. How about a bit of give and take - Material reciprocity beyond the limits of the slick or smooth. Give me a digital touch I don't expect. Negotiate new tactile rhythms. Make time for touch. Ambient S-L-O-W touch. Enrich the shallow vibrating utilitarian feel, venture beyond the hand, beyond the skin, and make digital touch thrive.

6. FOSTER EXPLORATION OF MEANINGFUL TOUCH EXPERIENCES

PERSONALISE TOUCH. Design for a plurality of touch preferences and sensitivity thresholds. Keep it indoors, get mobile, take digital touch outdoors? DESIGN a varied touchy terrain. Include more options. LEAVE SPACE for MUTUAL touch creation. STRETCH the embodied limits of touch socially and functionally to explore new possibilities. A customisable tactile landscape to support the development of social touch languages. Give the user felt feedback to sense their own touch and handle when and where touch lands. Give digital touch value: calculate its biological cost. Allow social touch to extend beyond the immediately comfortable everyday zone.

7. REMAKE, DON'T ONLY REPLICATE!

Free digital touch from the limits of its analogue reflection and let go. Confound and RECALIBRATE touch. Challenge the status-quo. Foster alternative visions. Engage with unfamiliar touch, prepare to touch newly. Trash the touch-screen devoid of feedback. Translate the rich language of non-human touch into the tactile landscape. Rename touch. Reconfigure reliance on visuality. Take a leaf from nature, mimic reality as a stepping stone to remake touch. Or JUMP into the water and wade to a new bank to refresh touch.

8. MANAGE GREAT TECH-XPECTATIONS

Frame users' techy touch expectations. Communicate and contextualise digital touch. Avoid the feel of disappointment. Digital touch is a long-term endeavour. Temper commercial HYPE. No need to over-promise - 'LIKE NOTHING EVER FELT BEFORE!'. Keep possibility alive within an honest sense of promise. Metaphors and imagination can bridge a user to unexpected social, sensory and digital touch. Managing expectations is an important step towards adoption.

9. DEVELOP OPEN TOUCHY TOOLS

We need diverse collaborative tools, libraries and archives, technical tools, thinking tools and sensitizing tools to expand touch in the digital realm. Shared tools that can travel between users, designers, developers, researchers. Make. Try. Explore. Tools to inspire and educate and bring potential users into the digital touch dialogue. Generate new touch metaphors. Grab at it, pinch and mould it, make our vocabularies work so we can hone new relationships between language and technology to create touch sensations: talk me into feeling it. COMMUNICATE! We need to understand each other better.

10. KEEP SPECULATING

Revisit touch pasts. Interrogate touch presents. Take an E-X-P-A-N-D-E-D view of touch. Forecast the influence of digitally-mediated touch on social interaction. Explore the texture in the space between touchy Dystopias …

FIGURE 1 | A Manifesto for digital social touch in crisis.

questions of the agency, control, and regulation of social touch (in workplaces, schools, healthcare settings etc.), much of which are entangled with the politics of power and gender (e.g., #MeToo) in both institutional and domestic settings (Field, 2002; Halley, 2007; Owen and Gillentine, 2011; Green, 2017; Pihkala et al., 2019). Despite this social touch remains central to human experience (Bull et al., 2006; Field, 2014), communication (Gallace and Spence, 2010), and relational, psychological and physiological well-being (Jakubiak, and Feeney, 2017). The impact of a lack of social touch on communication, relationships and well-being and health is well documented as having demonstrable negative connotations (Gallace and Spence, 2010; Field et al., 2020). The specific and immediate consequences of the Covid-19 pandemic for social touch have amplified

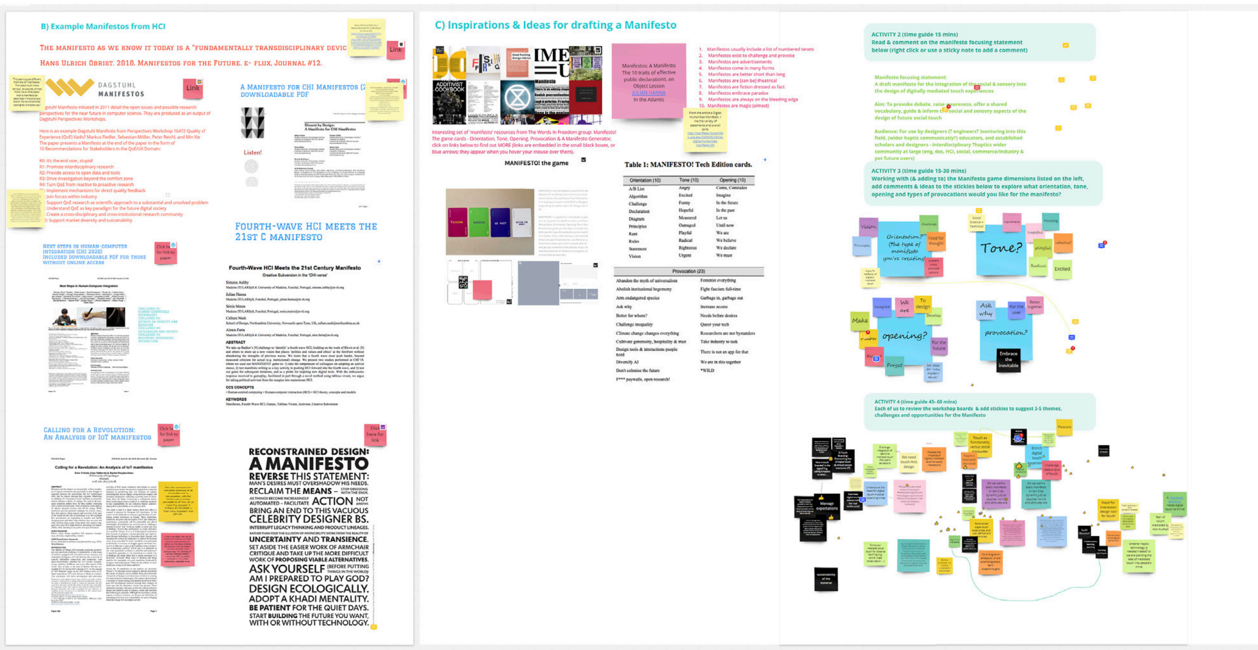

FIGURE 2 | Example manifestos from HCI and inspirations and ideas for drafting a manifesto.

assertions in the media, governments, and health care organizations that social touch is in crisis. In addition, restrictions and regulations prompted by Covid-19 have unsettled and shifted social touch etiquettes, social norms and expectations of social touch (Green and Moran, 2021).

These concerns bleed into and shape the digital realm and raise questions of how and when the complex space of social touch is mediated by technologies and the societal and sensorial implications of doing so. The manifesto was initiated in autumn 2020 during the flux of the Covid-19 pandemic, a point of emergence from (and shortly a return to) global lockdown. A global event that has perhaps more than any other recent one, highlighted the human need for social touch and the paucity of visual technologies for communication in response to this need has felt palpable: unleashing hopes and fears for both social touch and its digital futures. Social touch is a complex space for technology to mediate. Social touch is increasingly central to the digital futures imagined within Human-computer interaction (HCI) (Hoggan, 2013; Huisman, 2017). We are at a point where despite the success of haptics as a field, and its potentials for social touch. Questions about the successful replication of social touch in mediated environments remain (Haans et al., 2014; Willemse et al., 2017; Askari et al., 2020; Ipakchian Askari et al., 2020) including how technology should be deployed and used for social touch. The manifesto thus speaks back to the technological landscape and asks, is digitally mediated social touch itself in a moment of crisis?

The *Manifesto for Digital Social Touch in Crisis* is an outcome of a series of interdisciplinary collaborative workshops, initiated at Eurohaptics 2020, on the social and sensory aspects and challenges of designing digitally mediated social touch. The workshops took place over 6 months with participant collaborators from computer science, design, engineering, HCI and social science within industry and academia. Drawing on the research literature and the expertise of these collaborators, the manifesto takes a broad view of design and development. In doing so it offers routes to navigate the technological realities and promises for social touch amidst conflicting social concerns (e.g., the loss of cultural variations in touch practices through the homogenized effect of hegemonic technology powers or standardization, the social effect of socio-economic divides in access to digital social touch, the new social norms that may emerge through digital social touch) and uncertain futures (e.g., how digital social touch devices will enter the global market, models for storing and sharing digital social touch related data, and what future touch sensations maybe realized digitally and the possibilities for the customization of digital social touch).

The manifesto form has traditionally been taken up and used in politics, the arts (e.g., The Manifesto of Tactilism by the Futurist artist Marinetti, 1921) and design (e.g., Design Justice Network Principles, 2018). The manifesto is an alternative genre and comes in many forms, usually in response to a crisis, and is an urgent call for change articulated through an eye-catching list of challenging and provocative statements. Manifestos are typically short and sharp, often purposefully poetic and ambiguous, with a tone ranging from playful, excited or hopeful through to angry. Manifestos remain less common in HCI in comparison to other disciplines (Hanna et al., 2019), although their take up within HCI appears to have increased recently with the development of manifestos on various aspects of design (e.g., Design Justice Network Principles, 2018), specific technologies, such as Blockchain technology (Elsden et al., 2019) and the Internet of

Things (reviewed in Fritsch et al. (2018)), and futures more generally (e.g., the Dagstuhl Manifesto series initiated in 2011). The manifesto as we know it today is also a "fundamentally transdisciplinary device" (Obrist, 2010).

While manifestos may emerge from or be informed by research, they are not a scientific outcome. Manifestos aim to provoke. The purpose of manifestos is "prompting new ideas by temporarily liberating scholars from the confines of careful speech and rational argument" – to offer a chance to question and imagine possible futures (Hanna et al., 2019:2), and this, it is argued, has the potential to "give new life to" HCI (ibid). They usually emerge from uncertainty, set out to define a moment of crisis and "invite us, loudly, to some new way of thinking" (Caws, 2001: xxix): in short, they signal a desire for change. The *Manifesto for Digital Social Touch in Crisis* offers a set of 10 statements characteristic of the manifesto form, using a playful variety of poetic, ambiguous and provocative formulations to challenge the reader. Phrases such as "///Flip -Switch///" for example, mark the binary extremes that dominant the response to digital social touch technologies as either "lacking/absent" or "overwhelming/wrong"; "Feel the cacophony" is used to point to the noisy debates of what digital social touch should be, as well as the non-stop sound of vibrating devices that we live with; and "Tech-Xpectations," is a play on Charles Dicken's novel *Great Expectations*, which is ultimately about the eventual triumph of good over evil. It takes up the challenge to articulate the "struggle to negotiate between the possibilities that technologies offer, and the concerns that they engender" (Fritsch et al., 2018: 1) and proposes paths toward future roadmaps or directions for digital social touch in society.

The qualitative work (including the manifesto) presented in this article is explorative rather than experimental. Qualitative research is defined as an iterative process through which improved understanding of the scientific community is achieved by making new significant distinctions resulting from getting closer to the phenomenon studied (Aspers and Corte, 2019). Here, the purpose of iteration is as a reflexive process to spark insight and develop meaning (Srivastava and Hopwood, 2009). Using this approach, we sought to understand the concepts, opinions, and experiences raised by the complex "real-world" challenges and opportunities faced by designers in relation to the social and sensorial aspects of designing digital social touch. Our focus, in line with the characteristics of qualitative research, was on building categories, patterns and themes from the ground up (inductive) to capture the participant collaborators' meanings – here in the innovative form of a manifesto. The manifesto is thus developed through and rooted in the interdisciplinary expertise of social touch designers/developers/researchers: a research outcome of a qualitative iterative design process (Sale and Thielke, 2018). Rather than providing a starting point for the manifesto, the literature on the contemporary landscape of social touch and haptics (reviewed below) situates the manifesto within the wider debates and challenges of haptics and serves to contextualise the concerns crystalized within the manifesto. The article sets out the process that shaped the manifesto development, the curation of its statements, and discusses the opportunities and challenges and the dominant themes and tensions that informed the manifesto.

BACKGROUND

The manifesto emerges in response to the contemporary landscape of social touch. It situates itself within the larger field of haptics, addressing both the study of human touch and technology that stimulates the senses of touch and motion (Hannaford and Okamura, 2016; Jones, 2018). Social touch refers to the many forms of touch in social communication – e.g., greetings, intimate communication, corrections (van Erp and Toet, 2015). It can comprise one or multiple sub-modalities: touch, temperature, itch, pain, and affective touch. We use the term 'digital touch' to denote digitally mediated touch sensations, digital social touch and haptics (both referring to the study of the human sense of touch, and its submodalities, touch, temperature, itch, pain, and affective touch, as well as the use of technology that stimulates the senses of touch and motion (Hannaford & Okamura, 2016; Jones, 2018)) more broadly. We outline this landscape below.

Social Aspects of Touch and Haptics

Social touch is part of the human socio-affective, communicative repertoire in the form of interpersonal touch (Gallace and Spence, 2010; McGlone et al., 2014; Jewitt et al., 2020). Social touch, in the form of, for example, hugging, hand holding or stroking, plays a critical role in human development (Cascio et al., 2019), is related to improved overall well-being (Field, 2019), can reduce stress (Ditzen et al., 2007), blood pressure and resting heart rate (Light et al., 2005), and pain (Goldstein et al., 2016), plays a role in communicating emotions (Hertenstein et al., 2006), can enhance a positive mood (Debrot et al., 2013), and has positive effects on pro-social behavior (the Midas touch effect; Haans et al., 2014). Social touch is typically experienced as signaling intimacy and occurs particularly frequently between people in a romantic relationship (Guerrero and Andersen, 1991), or between parents and children (Chopik et al., 2014). Social touch is considered a cross-cultural phenomenon that, although different in form and in its embedding in social practices (see Carra et al. (2014)), occurs across the globe (Sorokowska et al., 2021). Variability in social touch practices can relate to differing environmental aspects (e.g., climate), cultural aspects (e.g., prevalence of religion), and social norms (Sorokowska et al., 2021). Moreover, individuals' history of touch interactions from early on in life influence how they experience touch in later life (Bales et al., 2018), and there are differences between individuals in how comfortable they are with touch in general, which can be captured by touch avoidance (Ozolins and Sandberg, 2009) or longing for touch questionnaires (Beßler et al., 2020). The Covid-19 pandemic has made palpable that a lack of social touch can have negative consequences for well-being, with research into "touch hunger" (Field et al., 2020; Durkin et al., 2021) finding that the majority of people profoundly miss being touched by others. Prior research has highlighted the negative effects of prolonged absence of social touch on well-being (Field, 2010), and these findings are supported by research on other mammals (Ardiel and Rankin, 2010).

While the mechanisms behind the effects of social touch (also known as socio-affective touch) are not fully understood, they are assumed to involve an interplay between social, cultural, neural, and opioid factors (Cascio et al., 2019). For example, part of this interplay of factors involves the importance of social touch in the early life of infants to maintain homeostasis and bond with a caregiver, which through a process of reinforcement-learning cements touch as an especially intimate and salient social signal in later life (Fotopoulou and Tsakiris, 2017; Cascio et al., 2019). It is also suggested that there is a prominent role for C-Tactile afferents (CT-afferents) in social touch (Olausson et al., 2010; McGlone et al., 2014). These are low-threshold nerve-fibers that are particularly sensitive to slow stroking touches, that is the types of touch that are judged as particularly pleasant (Löken et al., 2009; Olausson et al., 2010) and considered to signal socially relevant touches. This further distinguishes "CT-touch" from touch involved in tasks such as object manipulation (Cascio et al., 2019). Effects of social touch, such as those on stress reduction, might thus be strongest when CT-optimal touch is applied (Morrison, 2016). Finally, there is also research to implicate opioids such as oxytocin (which are released during social touch) as accounting for positive effects of social touch such as pain reduction (Walker et al., 2017).

Work on the effects that social touch has on well-being and the role it plays in communication has inspired investigations into the use of haptic technology for social touch interactions (Huisman and Darriba Frederiks, 2013). The current state-of-the-art in haptic technology showcases the efforts of designers and engineers to create compelling digital touch sensations by making creative use of existing or the design of new actuator technologies. In one strand of research, haptic technology is used to mediate human-human social touch with the aim to reproduce some of the effects of actual social touch (Haans and IJsselsteijn, 2006). For example, Haans and IJsselsteijn (2009) used vibrotactile feedback during an online chat conversation as a form of mediated digital social touch to investigate whether receiving this type of feedback would affect helping behavior by the recipient of the feedback (i.e., the Midas Touch effect (Crusco and Wetzel, 1984)). Although the authors found an initial effect of digital social touch on helping behavior similar to that of the unmediated Midas touch effect, later research indicated that this might reflect a potential confederate bias, where the effect only occurred when the confederate was aware of the experimental condition (Haans and Ijsselsteijn, 2014). Other studies have looked into how mediated social touch affects interpersonal trust (Erk et al., 2015), can be used to communicate emotions (Huisman and Darriba Frederiks, 2013; Rantala et al., 2013), and examined how textual tone affects the evaluation of mediated social touch (Ipakchian Askari et al., 2020). Embedding digital touch into social sensory contexts of established social touch communication remains complex and raises key design issues for effective mediated social touch.

Research closely related to work on mediated social touch looks at how touch could also serve as a modality for virtual agents and social robots to communicate with humans (Huisman and Darriba Frederiks, 2013; van Erp and Toet, 2015). Here, sensors are used to grant virtual agents or robots the ability to detect touch and haptic technology serves as a way for these artificial social agents to apply touch to humans. For example, Huisman et al. (2014) used vibrotactile actuators to enable a virtual agent in augmented reality to apply touches to a participant's upper arm, which was found to affect participants' perception of the agent's personality. In other research, where a social robot was used to apply touches to participants' upper arms, it was found that touches by the robot attenuated physiological stress responses induced by watching movie clips (Willemse and Van Erp, 2019). Similar work with robots and virtual agents has focused on the expression of empathy through robotic touch (Bickmore et al., 2010), the communication of emotions (Cang et al., 2015; Obrist et al., 2015), and on improving well-being (Block et al., 2021). The integration of digital social touch interactions in these kinds of artificial social agent systems is not straightforward, however, since multimodal cues, including, facial expressions and speech prosody, can overshadow the effects of touch (Bickmore et al., 2010). These efforts all fit within a broader view on affective computing where touch is seen as another modality that could be used to gather emotionally relevant information from users as well as to apply emotionally salient stimuli to users (Eid and Al Osman, 2015).

Efforts to mediate social touch through haptic technology or to enable artificial social agents to engage in social touch often have the aim of reproducing aspects of naturalistic social touch, the idea being that technologically mediated social touch can have positive effects on well-being (Huisman, 2017). With the Covid-19 pandemic resulting in increased experiences of touch hunger (Field et al., 2020; Durkin et al., 2021), it has been suggested that haptic technology can help to alleviate touch hunger to some extent (Prattichizzo, 2021), for example, by enabling affective touch interactions over distance (den Dekker et al., 2021). How touch is conceptualised matters in shaping technical advancements, bringing opportunities and challenges for development and design and raising questions for how touch experience is reconfigured. Recent work on touch in VR, for example, suggests that while the area is dominated by notions of touch as replication and illusion, interpretive designs of touch can disrupt established "real world" socialities of touch and their renegotiation by users in the space of digitally mediated touch in VR (Price et al., 2021). However, current research into the exact effects of digital touch technologies on the reduction of Covid-19 induced touch hunger are non-existent.

Touch Technology

Haptic experiences and devices (using force, tactile, vibrotactile feedback) have been increasingly applied in HCI and the development of immersive touch experiences is now relatively commonplace. A recent survey (Saleme et al., 2019) details the range of commercially available haptic devices including wearables (e.g., Tesla Suit, Dexmo, ARAIG, KOR-FX and Subpac[1]); handheld devices (e.g., Vibrotactile mice and

[1]Tesla suit available at https://teslasuit.ioDexmo available at https://www.dextarobotics.com/en-usARAIG available at https://araig.comKOR-FX available at http://www.korfx.comSubpac 101 available at https://subpac.com/subpac-101/

joysticks), desktop devices (e.g., Phantom Omni (Danieau et al., 2012), and Ultrahaptics, (Limerick et al., 2019; Rakkolainen, et al., 2021)), and haptic chairs. Haptic technology has found its way into various commercial applications, such as gaming (Orozco et al., 2012; see also Parisi, 2018), virtual reality (Srinivasan and Basdogan, 1997), tele-operation (Hirche and Buss, 2012), haptic gears (Shah et al., 2014; Prasad et al., 2014), automotive interfaces (Harrington et al., 2018; Breitschaft et al., 2019), digital signage (Limerick et al., 2019), mobile (Kwon et al., 2010) and wearable devices (Pacchierotti et al., 2017; Parisi and Farman, 2019), augmented reality (Romanus et al., 2019) and (inevitably) sex toys (Döring and Pöschl, 2018; Liberati, 2017).

The industry standard for high-resolution touch input is capacitive touch contact sensing. Such sensors have been available inside rigid touch screens and mobile devices for a while. Technologies for haptic output can be subdivided into approaches for kinesthetic and for cutaneous feedback, the former delivering forces and torques and the latter delivering tactile skin sensations directly on the skin (e.g., vibration, skin stretch, thermal cues). Early haptic devices were mostly grounded and often focused on kinesthetic feedback (Culbertson et al., 2018). Haptipedia provides a comprehensive overview of grounded force-feedback devices (Seifi et al., 2019). Recent research in haptic technologies puts particular emphasis on cutaneous feedback, in part due to the lower complexity and lower cost of cutaneous feedback devices and their improved mobility (Prattichizzo et al., 2012).

Today, vibratory feedback is most widely used and most popular in commercial devices. The typical approach of binary on-off feedback or simple arrays to convey directional information (Meier et al., 2015) is arguably too restricted for rendering social touch. By controlling detailed parameters of vibration, such as amplitude and frequency, more expressive and nuanced output can be generated. Prior work has demonstrated various vibrotactile illusions, such as rendering directional cues (Culbertson et al., 2018), rendering the impression of compliance (Heo et al., 2019) or a specific surface texture (Strohmeier and Hornbæk, 2017; Strohmeier et al., 2020). While force mapping sensors are important to capture the nuances of touch (Kim et al., 2011), multi-modal sensors (Roberts et al., 2013) allow a strong personal and emotional way of interaction.

Feel-through tactile interfaces allow for new forms of tactile augmented reality, where real-world objects are superimposed with synthetic tactile renderings (Withana et al., 2018). Integrating touch sensors into deformable surfaces such as textiles (Orth et al., 1998), elastic polymers (Wessely et al., 2016; Teyssier et al., 2020) and even human skin (Weigel et al., 2015; Nittala et al., 2018) has enabled more expressive touch interaction. Emergent technologies are being developed to enrich digital social touch interactions and embed other input modalities such as force, shear, twist, and squeeze (Weigel et al., 2014). For example, tactile feedback can even be contactless and rendered in mid-air (Hoshi et al., 2010; Carter et al., 2013; Rakkolainen et al., 2021). Going beyond vibration (a point we make in the manifesto and return to later in this paper), skin deformation has been shown to add to the expressiveness and realism of haptic output. For instance, cutaneous haptic devices for the fingertip make use of skin indentation (Pacchierotti et al., 2014) or lateral stretching (Leonardis et al., 2015); haptic renderings with larger-scale skin deformation have been realized using adhesive skin patches with embedded artificial muscles (Hamdan et al., 2019). Moreover, flexible electronic skins are promising for conveying social touch; prior work covers vibratory (Yu et al., 2019) and electro-tactile (Withana et al., 2018) feedback amongst other modalities. It can be expected that advances in new materials (Biswas and Visell, 2021) and soft robotics will further expand the richness of multi-sensory haptic feedback (MacLean et al., 2017). In short, technological boundaries of what can be rendered, especially in cutaneous feedback, are continually being pushed. Novel actuators at different stages of maturity are in development that render a variety of tactile experiences (e.g., thermal feedback, pain, stickiness etc.) with potential for mediated digital social touch.

Adoption of Haptic Technology: Haptic-Hype and Visions

Against the rich backdrop of successful haptic devices outlined in the previous section, the integration of active haptic feedback (i.e., computer-controlled stimulation of the sense of touch via various actuators (Srinivasan and Basdogan, 1997; Hayward et al., 2004; Culbertson et al., 2018; Parisi, 2018)) in digital technology has been part of many visions on what interacting with these digital technologies should or could be like. Haptics has been envisioned as crucial to developing “the ultimate display” (Sutherland, 1965), has been described as vital for enabling “computing with feeling” interactions (Atkinson et al., 1977), has been called the “holy grail” of telepresence (Stone, 2000) or more recently, has been made central in the next generation of the Internet in the form of Tactile Internet (Fettweis, 2014). While many of these visions have been brought to full fruition others remain, for the time being, out-of-reach (Culberston et al., 2018; Parisi, 2018). Without diminishing the success of haptics as a field and within a variety of domains, there remains considerable debate on the claims made for haptic technology and what it can deliver in terms of social touch (Parisi et al., 2017; Parisi, 2018). Parisi (2018, p.32) argues that the promise of a haptic revolution in HCI is yet to be fulfilled: “[...]haptic interfaces are suspended in this state of perpetual immanence, always just on the horizon, always only five short years away [...].” Some have argued that haptic design tools (and their availability to interface designers) are too limited (Schneider et al., 2017), and that standardization of haptics is low in comparison to other modalities (Van Erp et al., 2010). Efforts are, however, underway within the industry to address these challenges. For example, Apple has recently formulated haptic design guidelines for developers creating applications for Apple products; Google has released guidelines for haptic design in Android applications; and manufacturers of haptic actuator technologies have united in a “Haptics Industry Forum” (https://hapticsif.org) to collectively address challenges in the field, including the standardization of “high definition” haptics. Other notable examples include MPEG which develops standards for coded representation including haptics (https://www.mpegstandards.org/standards/Explorations/40/) and the Tactile Internet (https://standards.ieee.org/project/1918_1.html).

MATERIALS AND METHODS

As set out in the introduction the qualitative work presented in this article is explorative and uses an iterative process to get closer to and reflect upon (Srivastava and Hopwood, 2009; Aspers and Corte, 2019) the complexity of designers in relation to the social and sensorial aspects of designing digital social touch. This involved inductively building categories and themes to capture the participant collaborators' meanings to understand the "real-world" experiences, concepts, opinions, and challenges and opportunities that they face. This served to root and develop the manifesto in and through the interdisciplinary expertise of social touch designers/developers/researchers. The *Manifesto for Digital Social Touch in Crisis* was initiated at an Eurohaptics 2020 workshop titled "*Designing Digital Touch: Social and Sensory Aspects and Challenges.*" The workshop itself was sparked by an interdisciplinary dialogue on touch between the social science team of the InTouch project (University College London, United Kingdom) and the computer science and engineering-oriented Interactive Skin project (Saarland University, Germany).

Participants

The workshop was targeted at researchers, interaction designers and developers interested in the challenges, methods and techniques of designing the social and sensorial aspects of digital social touch. The workshop call was disseminated and participants were recruited via relevant listings (e.g., ACM), a workshop website, and the Eurohaptics2020 conference. The 16 participants who attended the workshop have backgrounds in engineering, informatics, computer science, and HCI, academia and industry and were based in France, Germany, United Kingdom, the Netherlands, Switzerland, India, China, and the United States. Ten participants (herein, they are referred to as participant collaborators) attended an optional follow-on collaborative workshop focused on the Manifesto, six of whom continued to contribute to the development of the manifesto (and are co-authors of this paper).

Interdisciplinary Workshops

The manifesto was developed over the next 5 months through a series of workshops, iterative feedback and revisions. Throughout the process Miro, a collaborative online platform was used to support, share and capture brainstorming, the outcome of activities, and discussion. The Miro boards provided data with which to map the process of the manifesto development, alongside facilitator notes, and group reflections on the process (**Figure 2**).

Workshop 1: Designing Digital Social Touch

Participant position papers, and 2 min introduction videos (stating their discipline, research focus and interest in the workshop) were shared prior to the workshop. Three 10 min "scene setting" talks were shared before the workshop: first, an overview of new haptic technologies and interfaces for skin (Steimle); second, a presentation of key issues concerning the sociality and sensoriality of digital social touch (Jewitt); and third, an introduction and demonstration of the "Multi-Touch Kit" (Pourjafarian et al., 2019), an open-source touch sensing toolkit. The workshop facilitated a group mapping activity (on Miro) to identify points of connection, contradiction and compatibility between these different perspectives on the designing digital social touch.

This collective map laid the groundwork for a second activity exploring the social and sensorial challenges of digitally mediating social touch using the Multi-touch toolkit, and the Designing Digital Touch Toolkit. These resources provided a grounding and springboard for the collective interrogation of digital social touch. Each group was facilitated by an interdisciplinary pairing (one socially orientated the other computer science/engineering orientated) and used design scenarios as prompts to elicit participants' experiences and to generate design considerations and key themes, challenges and opportunities for digital social touch design. The activities laid the groundwork for a "Manifesto" for digital social touch.

Workshop 2: Manifesto

The optional follow-on manifesto workshop comprised of pre-workshop activities centered on understanding and exploring the manifesto form including working with the Manifesto Game (Ashby et al., 2019), and reviewing Workshop 1 Miro boards to suggest three to five themes for the manifesto. This helped to crystalize the issues and prioritize areas of the social and sensory design of digital social touch for the manifesto.

The workshop activities facilitated debate of the purpose of a manifesto for digital social touch, and collectively agreed a manifesto focusing statement. The rationale and starting point for "social touch in crisis" emerged from this debate. The consequences of different manifesto orientations, tones, openings, and provocations were explored. The right "feel" for a manifesto on digital social touch was agreed to be a challenging vision, playful, excited and hopeful, questioning and future-facing, and provocative. The themes prioritized by participant collaborators were discussed, sifted, clustered and connections made across them to create higher-level themes. The interdisciplinary mix of participant collaborators, their cultural and political experiences, and immersion in different disciplinary and industry research/literature combined to produce a creative fusion on social touch and the digital. This was a lively process of debate that brought key concepts, challenges and opportunities to the fore and seeded a set of initial themes that were later developed into statements for the manifesto.

Manifesto Development Process

The *Manifesto for Digital Social Touch in Crisis* itself was developed through a collaborative and iterative cycle of review and revision. Initial themes, comments and ideas on the Miro boards were used to develop 12 draft manifesto statements: Manifesto Version 1. These were reformulated and consolidated into 10 statements in version 2, during which the workshop Miro boards were used to compile a complete collection of comments and ideas around each statement. These collections were used to compile a short paragraph elaborating on each manifesto statement, including some verbatim comments from the boards. Manifesto versions 2 and 3 were reviewed by the group, and revised to produce Manifesto Version 4 which was externally reviewed by six established international experts in haptics (collectively nominated by the authors) from HCI, design, media and cultural studies, computer science, and engineering. They offered critiques of the manifesto form, questions of audience, terminology, definitions, language use (e.g., the exclusion of the word "human"), and highlighted statements or aspects of digital social touch (e.g., privacy) that they considered required more development or emphasis. The reviewers' feedback and a final review by participant collaborators informed the final manifesto (version 5) at the center of this paper.

FINDINGS: CURATING THE MANIFESTO STATEMENTS

In this section, we make the history of the manifesto statements visible by describing the process of how the statements were curated, reordered, clustered and consolidated to realize the shape and flow of the final manifesto. The quotes used are written comments on the Miro boards or, if indicated, from the expert reviewer comments.

Throughout, a key consideration was getting the right tone for the manifesto statements through the collective iteration and development of the heading and content of each statement. For example, statement 2 was initially titled "Balance Touch and Technology" and as the manifesto developed, participant collaborators felt that title was not strong enough: "*This could use a more provoking title, the priority is the experience of touch, technology is just a tool to achieve it.*" It was amended to "Touch first, technology second." Conversely, for Statement 5 the original formulation of "Lose Vibration! Feel Beyond the Habituated" was later considered to be too strong, and was changed to read, "Move beyond vibration: Feel beyond the habituated." Similar remarks were made about the content of other manifesto statements. For example, the text for Statement 7 "Remake, Don't Only Replicate!" included the statement "Trash the touch-screen," which a participant collaborator noted, "*I would perhaps add "devoid of feedback" or something like that, as touchscreens per say in HCI have opened up many avenues in education, accessibility to information, etc.*," a suggestion that informed the iteration of the manifesto.

A key aspect of the external review was the sense of how the manifesto might "land" within the research field. The manifesto format was quite new and somewhat confounding for some: "*. . . the form of writing serves another purpose than having a scientific discussion about what we know and which facts we know about touch*". At the same time, however, the manifesto was found stimulating, and the reviewers were positive about the format: "*The style of the manifesto is very new to me and although initially confusing (just the way it is written and words used, syntax and semantics), I see how it can draw in attention*"; "*I found it highly inspiring, not only in its content but also in the structure; I felt it was controlling my train of thoughts, in creative ways.*"

These iterative cycles of review, comment and revision led to the *Manifesto for Digital Social Touch in Crisis* presented in full at the beginning of this paper **Figure 1**, each statement is presented and discussed below.

Statement 1: Make Social Touch Central

This statement (initially named - Keep touch central) reflects the collective view that there is a need to bring an urgent emphasis to social touch, linking to the significance of the social aspects of touch interactions (set out in the background literature), for well-being and communication (Gallace and Spence, 2010; McGlone et al., 2014) and development (Cascio et al., 2019) and how these have inspired investigations into the use of haptic technology for social touch (Huisman, 2017).

One expert reviewer noted that "*the word "Human" is mentioned only once, for "non-human." In my opinion, it is quite central and should be mentioned.*" In response, "human" was included in the text of the statement. There was a broader sense of the need to ensure that social touch – not only its technical realisation - remains "center stage," both in the context of visual and audio prominence in digital spaces and the Covid-19 pandemic. The "at risk" sense arose from the notion of "poor" social touch interactions due to the way technology is designed, for example the prominence of flat screens, or "minimized" touch effects such as the buzzing of smartphones (Culberston et al., 2018; Parisi, 2018). The statement also reflects the priority that is generally given to visual and auditory modalities, while the tactile is more difficult to realistically achieve in digital social touch devices accessible to the public (due to cost, form factors, functions/roles, etc., so in turn limited to buzzing), and as a result, is perceived as superfluous or not as convincingly necessary as audio or vision.

Statement 2: Design Touch First, Technology Second

This statement combines what were originally (in earlier versions of the manifesto) two statements - *Marginalize the technology* and *Amplify interdisciplinarity*. This highlights the need to foster the richness of haptics set out in the background of this article, and to encourage the ongoing development or realization of "better" digital social touch, and the value of interdisciplinarity (Jewitt et al., 2020). *Marginalize the technology* related to a sense that technology dominates the haptics scene (e.g., conferences, papers, projects), shaping digital social touch in particular ways and aimed to argue for less technology-driven development: it generated significant debate among the participant collaborators. The intention was to emphasize that technology should not be the (sole) driving force, however, while recognizing the need to reduce the dominance of technology, "marginalize" was considered too strong a term, since technology *is* important. As one participant collaborator wrote, "*Right now technology seems to be driving development of applications and user experiences involving digital touch, but at its core technology is supposed to be a tool to achieve a goal, and maybe we want that goal to be set by something else than just the availability of certain techs?*" Rather than a "techno-push" the manifesto also points to a need to ensure users are included in the design process and remain at the core of the technology. Alternative statement suggestions included "Touch first, tech second," and "Avoid technology dominance." An expert reviewer with a design background liked this statement: "*This is my favorite! I always use this as the only teaching rule for my wearable technologies course. Design experience first, technology second. I think it's great*!." The other statement *Amplify interdisciplinarity* that was folded into this final manifesto statement, again to mark the insufficient attention to the creative arts and sought to redress the dominance of Computer Science and Engineering in the development of touch technology. Promoting interdisciplinarity was considered one effective way to avoid technology dominance.

Statement 3: Democratize Touch: Don't Lock It In

This statement links with the discussion of social touch as a cross-cultural (Carra et al., 2014) global phenomenon (Sorokowska et al., 2021) in the background literature section. It was also inspired by Lanier's description (Lanier., 2010, p7-9) of "lock-in" as a process which causes "digital designs to get frozen into place…culling the ambiguities of flexible thoughts as more and more thought structures are solidified into effectively permanent reality." The statement went through a variety of title changes - *Democratize touch* and later, "*Don't lock touch in: desire its heterogeneity*," in an effort to highlight the potential role people can play in the creation and definition of touch. It involved much discussion: "*…when we say everyone should be involved, do we then mean everyone in the field or also the average user?*." The consensus was that democratization meant involving all people - "*if you have a sense of touch, you are pretty much automatically qualified to contribute to defining what digital touch can become*." This statement had social and political connotations, raising many questions for participant collaborators including who drives the norms around touch? How do we make sure we all have a say in how touch gets "created"? How do we address power imbalances? While for others the statement arose from the need for touch to be designed such that end-users would have the agency to personally define and develop their own touch language.

Ultimately, this manifesto statement speaks to a need to develop "opportunity spaces" that support exchange between users and developers and designers, prior to "creator" notions of touch, social touch and digital social touch get "locked-in." Touch cultures were seen to be at risk from the (digital) touch norms that were established by one culture developing the technologies of digital touch: notably the risk of hegemonic companies "flattening" culture and individuality. However, there was also a recognition of diversity needing to be brought into balance with notions of digital social touch design standardization (Van Erp et al., 2010). This statement highlights the need to keep cultural distinctions or even to amplify the (cultural) diversity of touch that exists (Remland et al., 1991). As one participant collaborator noted, "*Touch is a conversation and like a conversation it should be open to develop and is made by interaction*."

Statement 4: Protect Touch: Keep Touch Private and Secure by Design

This statement speaks to critical concerns of privacy, security and ownership of touch communications, such as maintaining ownership and share-ability rights over one's touch "record and replay." These concerns run like a thick seam through the strata of all technologies (Kamleitner and Mitchell, 2019), are never far from the surface of haptics, and were consistently raised as important throughout the process of developing the manifesto. That process brought out different, although related specificities, highlighting the complexity of privacy of touch. For example, concerns were expressed regarding the need to account for privacy "*when you start recording and sharing touch gestures*" and the need to "*protect touch ownership*" and guarantee control over p*rivacy with participant collaborators suggesting they would want* "*control over what information about me and my way of interacting through touch becomes public or not*" as well as "*what touches me, how it touches me, and what information is conveyed to me through touch*." There was agreement that touch data, "*perhaps even more than other types of data given the connotations with intimacy*" needed to be protected. Similar to issues raised about how users can be identified through their body posture/motions this could also apply to touch (see Miller et al. (2020) for an example in the context of VR; Ornati., 2022. A comment by one of the expert reviewers raised the phrase "*Keep touch private and secure by design*" from the explanatory text to the statement heading. While another expert reviewer comment helped us to reshape the manifesto framing of touch ownership: "*It starts too negative, when this ownership is actually so liberating and empowering. Would there be scope to start with something on the flip side of this ownership? E.g.: Touch is intimate. Touch reveals myself and my boundaries. Touch can be intrusive.*" This helped us to rewrite the opening paragraph of this manifesto statement.

Statement 5: Move Beyond Vibration: Feel Beyond the Habituated

This statement emerged in response to the dominance of vibration and the emergence of new actuators for social touch (see the background section), as well as participant collaborators' express desire to disrupt technological interfaces (e.g., through notions of "touchless touch" (mid-air haptics) or extending touch beyond the hand to a whole body experience) that create a reduction of sensation in types of touch, touch feedback (e.g., primarily vibration motors) or touch experiences. It was agreed in order to bring the richness of "real" touch into the digital, that there is a need to move out of the restricted range of both actuation technologies and interface materials that are available in current digital social touch implementations. A variety of possible formulations of this emerged: "Move beyond vibration and glass," "Move beyond flat, move beyond vibe," "Move beyond a rigid surface," or "Touch beyond vibration." However, we recognized the need not to assume touch research is only about flat surfaces and vibrations, and to include work on grounded force-feedback (Seifi et al., 2019) and skin deformation (Hamdan et al., 2019). (For further examples, see also Tibbits (2017)). This consideration led to the final manifesto statement.

Statement 6: Foster Exploration of Meaningful Touch Experiences

This statement (initially named "*Create responsive touch experiences*") focuses on personalizing touch to enable touch to be responsive to the individual (touch preferences) and context. This statement links to the need for digital social touch to respond to on touch cultures, the variation and levels of intimacy of social touch, and the importance of embedding digital touch into social sensory contexts of established social touch communication – all of which are complex issues that raise questions for the design of effective mediated social touch (see *Background* section). Discussion of this statement involved suggestions of using the term *reciprocal* to be more explicit that touch interaction concerns bi-directional communication rather than being a technical property. Participant collaborators considered an emphasis on the *personal* to be critical, or the *adaptive* which captures both reciprocity and personalization. The contextual needs of touch experience were foregrounded, such as in mobility, static, outdoors vs. indoors. The adaptability to context was also highlighted, particularly in terms of privacy, with possible noise or simulations generated by touch technologies. These aspects are encompassed in the "meaningfulness" of touch experience.

Statement 7: Remake, Don't Only Replicate!

This statement - originally named *Stop replicating touch* and later *Don't just replicate touch, remake it,* highlights a tension in the design and development of social touch between a drive to replicate or mimic touch (Price et al., 2021) versus designing new forms of touch experiences (see *Background*). It is aimed at encouraging a move beyond replication to forms of more innovative and creative digital social touch experiences. Participant collaborators noted that replicating is, however, sometimes needed or desired and saw the real issue as being that digital social touch should not be limited to replication: "*. . .remaking is making anew, which I tend to associate with technology. So perhaps it should be made clear in the explanation that it is not only about technologizing touch in yet to be imagined spaces*." The statement is an offer of inspiration and an invitation to think outside the box.

Statement 8: Manage Great "Tech-Xpectations"

This statement concerns the need to manage both user expectations of technology in relation to commercial hype and marketing and the vision and promise of digital social touch (Parisi et al., 2017; Parisi, 2018) (see *Background*). It is informed by discussion of how personal experience can lead to predictions of how "digital social touch" should feel, and result in disappointment or surprise if/when the actual feeling is different. Suggestions involved offering clarity on what is technologically possible, and both the lowering of expectations by avoiding overly hyperbolic advertising and the changing of user expectations through education and communication on new forms of haptic feedback. Touch technologies were, it was argued, a long-term endeavor. The statement was seen as "*offering a user counterpart to statement 9*" and an invitation to designer/developers "*to try crazy new things (i.e., don't worry, go try these new ideas, the digital touch you are designing should feel different from what's already out there/what people expect)*." One collaborator noted that in French law (Republic Francaise, 1994), if a photograph is used in the media is retouched it must declare that it is "*photo retouchée*" and they suggested that the same could be required of touch, as in "*toucher retouchée*" as a way to temper the hype of digital social touch promises and to reframe expectations.

Statement 9: Develop Open Touchy Tools

This statement focuses on the need for new design tools for the development of touch experiences that expand our perception of touch and touch vocabularies. Participant collaborators agreed that a diverse range of technical tools is needed to enable designers to include touch more broadly (Schneider et al., 2017; Seifi et al., 2020), and to help broaden thinking about touch: "*to build shared resources for designing and talking about touch*." For example, design tools to engage with the social and sensory aspects of touch (e.g., Designing Digital Touch Toolkit https://www.in-touch-ucl.design). The statement focuses both on tools and the need to share these (discussed in the *Background* section), as one participant collaborator noted, "*it is also about making it accessible to anyone or with various levels (public, tech experts, designers), in transparency of the device(s) used, with adaptation to the context of use (mobile phone, VR, etc.)*." The significance of access was incorporated in the final manifesto statement, as was the need for tools to be "open" to resonate with design and engineering communities.

Statement 10: Keep Speculating

This final manifesto statement was motivated by a need to draw attention to wider social and political responsibilities for technology development, particularly given the lack of social forecasts for touch, and the often-unintended negative consequences of existing applications. Some highlighted the need to outline future utopian and dystopian scenarios for digital social touch. The statement can be read in two ways: first, "keep speculating" in terms of imagining digital social touch; and second, a wider political use of the term speculation in relation to a lack of regulation and social responsibility in which manifestos are seen as calling "for political or judicial reconfigurations" rather than placing such responsibility for action on designers and developers (informed by Fritsch et al.'s (2018) analysis of IoT manifestos). This statement is also a call to users, decision-makers and regulators to consider how to develop and regulate digital social touch design in its nascent stages, to be imaginative, and to actively think through future scenarios and potential consequences as part of the design process. The call to speculation is aimed at energizing the field to: "Move beyond the Feelies" (Huxley, 1932)!

The above 10 statements comprise the *Manifesto for Digital Social Touch in Crisis.*

DISCUSSION

Through analysis and reflection on the process of developing the manifesto, opportunities and challenges, and key themes were identified as foundational to engaging with the social and sensory aspects of designing digital social touch. These informed the manifesto development. Each is discussed below (the quotes used are written comments on the Miro boards).

Opportunities and Challenges

Throughout the development of the manifesto, digital social touch was considered to offer growing opportunities in terms of bringing new awareness to the importance of touch and haptics more broadly. The global Covid-19 pandemic was understood to have increased awareness of the value and importance of touch communication (particularly in contexts of social isolation) and prompted people to question their touch needs. A need for digital social touch and an appreciation of the way it can provide a sense of closeness when apart, particularly for those who cannot leave their homes was seen as an opportunity. One consequence of this is a new context for understanding the design of digital social touch. The potentials of technology were seen to offer opportunities for new ways to develop remote touch, from integrating touch functionality "*into virtually any surface and material*," to haptic illusions (Hayward, 2008), or robotic skin and autonomous systems that can sense touch. Digital social touch was felt to open up new and different ways of engaging, such as through physical interaction not possible with "analogue" touch (e.g., replay touch or record/saving of tactile memories), generating software frameworks for prototyping and implementing different haptic interfaces or parameterizing haptic design for people from other fields to design digital social touch.

Emerging challenges for engagement with the social and sensory aspects of digital social touch through design were also identified.

The conceptualization of touch, that is, how researchers, designers, engineers, or lay people conceptualize touch was a challenge in the development of digital social touch. People's general understanding of touch was perceived as being limited oftentimes to ritualized human-human touches (e.g., handshakes). This serves to foreground touch in terms of functional rather than social encounters or touch as utilitarian as opposed to aesthetic (e.g., touch that is pleasurable). It also excludes touch with other entities as one participant collaborator noted, "*I feel I have a rich language of touch with my cats but this seems to be "forgotten" when we think about touch tech*." This prompted conversation around mimicking or replicating touch. Should we or *can we* mimic social touch through technology? Challenges around which features of touch were important and how to manage these, were linked to the ways that touch was conceptualized (Price et al., 2021). For example, how to manage sensory input and output or how to integrate contextual factors surrounding touch. Of particular prominence were notions of control: how to allow options of control (e.g., touch on which body parts, and the right to be unavailable), finding haptic encodings that are comprehensible and acceptable to users across different genders and cultures, and how long to keep a recording of a digital social touch, similar to the "right to be forgotten" (https://gdpr-info.eu/art-17-gdpr/).

Several technical challenges were identified, including how to identify the most appropriate interface for a specific social touch experience or end-user. Other challenges centered on the early development of digital social touch design. For example, content design tools for haptic sensations whilst recognised through some significant commercial successes (see *Background*), were nonetheless considered less mature than visual and auditory modalities, which somewhat limits possibilities for people in non-technical fields to creatively explore the medium. Further considerations concerned knowing what is and is not "*designable*" and a lack of extensive data sets for a wide range of "*real haptic stimuli*."

Three methodological challenges in the design of digital social touch were discussed. First, the challenge of how to undertake sensory measurements to collect data on people's touch sensations at scale, that is to build libraries of different kinds of sensory feedback around the body, including the measurement of people's thresholds for negative and positive touch, and the development of standards or benchmarks for digital social touch. Second, a need for more interaction design tools for digital social touch. These included a need for a common language of touch (developing libraries) and developing metaphors for design; recognizing the different affordances of haptic technologies for digital social touch. Third, challenges were raised related to a need the design of digital social touch interfaces to support end-user customization; the development of software frameworks for prototyping and implementing interfaces to support creatively "playing with" digital social touch concepts and foster design. Interdisciplinarity was felt to be key to overcoming these challenges. Collaborations that brought together "*engineering, material, experience designers, and social scientists (and others) from an early stage*" and built "*relationships across academia and industry*" were valued as highlighting the importance of developing "*A shared vocabulary when describing touch (users, designers, researchers).*" This was seen as valuable to "*Avoid techno-push attitude: more communication or steps to opening minds on disciplinary collaborations/users at the center, not solely the beauty of the technology*."

A number of *socially orientated challenges* emerged in relation to user expectations and the digital translation of aspects of social touch. The management of user expectations drew attention to the need for the design of digital social touch to consider users' prior social touch experiences and how this shapes expectation. As one participant collaborator put it, "*Users have personal experience and might predict that the "digital touch" feels a certain way and be disappointed/surprised when the actual feeling is different from this expectation*." The notion of branding was highlighted as needing careful consideration, particularly in terms of what brands convey, and how they manage users' "fears" of digital social touch, and whether and how people "should" be encouraged to overcome such concerns.

This speaks to a tension between users' generally high expectations of technology versus what is realistically possible with current touch technologies, and a need to balance these two factors to avoid user disappointment or manage surprise when tactile sensations differ from prior touch experiences. Relatedly, the challenge of individual differences in people's touch experiences was raised as a challenge, with the recognition that touch is socially and culturally bound and idiosyncratic to some extent, raising the challenge of how these experiences could be responded to from a "fixed" engineering or design perspective. Linked to this point, the question of how to frame digital social touch, which can allow us to touch differently from the "physical" world, was seen as significant in fostering users' responses to it: from an open-acceptance versus evoking fear. This links directly to *models of the commercialization, branding and business* that digital social touch is embedded within, and raises the challenge of how to avoid haptic-monitoring and control of haptic content (likened to Facebook type models) and/or the use of haptic data as yet another source of data for building user-profiles for the targeting of individuals (e.g., for advertising).

Key Themes

The need to enrich digital social touch experience: the need to move beyond vibrotactile applications and the status-quo of touch to make digital social touch a richer experience was consistently expressed. "*Status-quo is touch in the form of touch screens. A way of thinking perpetuated by tech companies selling devices + apps. Thinking about touch seems mostly visual in this situation (also in the addition of touch to AR/VR). How do we break this way of thinking*?" It was suggested that in order to do this there is a need to rethink what digital social touch is, what it means, and could be. That is, participant collaborators felt the need to extend beyond realism and known experiences of touch to consider and design new forms of touch (whilst balancing user expectations and acceptability): to extend haptic technology beyond mimicking human tactile experiences. Some participant collaborators questioned whether it is possible to mimic social touch through technology. Ultimately there was a sense that rethinking digital social touch demands a more nuanced understanding of touch, whether by collecting people's touch sensations at scale, understanding individual and cultural touch needs and perceptions, or identifying and mapping the nuances of touch and reviewing potential use-cases for digital social touch.

The need to engage with the wider socio-political context of touch: Social distancing practices resulting from responses to the Covid-19 pandemic newly underscored the need for digital social touch and prompted discussion of the political character of touch and physical proximity. As one participant collaborator noted, "*I'm also reminded of how COVID strikes those in poorer communities harder because they do not have the opportunity for social distancing. In a way their physical proximity/touch practices are determined by their socio-economic status. How do we see touch technologies when taking these aspects into consideration*?." The "medium" of touch (i.e., the skin) and the question of who gets to touch what and who and when was considered a significant theme.

The design of touch privacy spoke to issues of consent, control, and ultimately human agency. The debate of these issues involved consideration of how designers and developers can incorporate consent into touch technology. This raised questions of when and where the user (including the receiver of a touch message) is in control, with the right to be unavailable, and manage monitoring or privacy of communication. Participant collaborators concluded that digital social touch needs to develop acceptable haptic encodings, as noted from the discussion (and on stickies) "*that are comprehensible and acceptable for different users (gender, culture etc.)*" and which foster a sense of user agency in giving and receiving digital social touch.

Drawing on these opportunities, challenges and themes, the manifesto for digital social touch in crisis aims to provoke and prompt new ideas by opening an interdisciplinary space to question and imagine newly digital social touch. The manifesto seeks to be a bridge between HCI, computer science and engineers, and social scientists engaged with digital social touch - to "give new life to" (Hanna et al., 2019:2) the design of digital social touch.

CONCLUSION

This paper has offered a provocative call to action to designers, developers and researchers to engage more deeply with the social and sensory aspects of digital social touch in the form of the *Manifesto for Digital Social Touch in Crisis*. Drawing on the research literature and analysis of data from this interdisciplinary collaboration – centered on a series of workshops and collective iteration of the manifesto, the paper has highlighted the key opportunities, challenges and central themes that provided foundational steps in the development of the manifesto. These included the growing opportunities for touch offered by technologies, and increased awareness of the significance of social touch, the technical, methodological, and socially orientated challenges of designing digital social touch, including the development of design tools to enrich digital social touch experience, and engage with the wider socio-political context of touch. The paper has made visible the collective iterative process of curating, clustering and consolidating the manifesto statements, making the process transparent and signaled the potential of placing the social and sensory aspects of touch at the centre of the design and development of digital social touch.

As society engages with and emerges from the uncertainty of touch in Covid-19 times, the *Manifesto for Digital Social Touch in Crisis* signals a desire for change and offers a set of 10 provocations to support a rethinking and reimaging of the social and sensory aspects of touch through the design process. The ten manifesto statements offer designers, developers and researchers across different disciplines routes toward future roadmaps or directions for digital social touch in society.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not made publicly available because the identity of workshop participants/data (Miro boards) is linked to specific statements and participant log-in info in Miro and it is not possible to anonymise that data. Further queries regarding the datasets should be directed to c.jewitt@ucl.ac.uk.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by IOE, University College London ethics board. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

CJ, SP, and JS contributed to the conception and design of the study. CJ, SP, JS, LG, NP, and GH organized the research workshops. CJ and SP and GH performed the qualitative analysis of the study data. CJ led the drafting and writing of the manuscript. SP, JS, and GH wrote sections of the manuscript. All authors contributed to the development of ideas, manuscript revision, read, and approved the submitted version.

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REVIEW
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Interpersonal Affective Touch in a Virtual World: Feeling the Social Presence of Others to Overcome Loneliness

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Humans are by nature social beings tuned to communicate and interact from the very beginning of their lives. The sense of touch represents the most direct and intimate channel of communication and a powerful means of connection between the self and the others. In our digital age, the development and diffusion of internet-based technologies and virtual environments offer new opportunities of communication overcoming physical distance. It however, happens that social interactions are often mediated, and the tactile aspects of communication are overlooked, thus diminishing the feeling of social presence, which may contribute to an increased sense of social disconnection and loneliness. The current manuscript aims to review the extant literature about the socio-affective dimension of touch and current advancements in interactive virtual environments in order to provide a new perspective on multisensory virtual communication. Specifically, we suggest that interpersonal affective touch might critically impact virtual social exchanges, promoting a sense of co-presence and social connection between individuals, possibly overcoming feelings of sensory loneliness. This topic of investigation will be of crucial relevance from a theoretical perspective aiming to understand how we integrate multisensory signals in processing and making sense of interpersonal exchanges, this is important in both typical and atypical populations. Moreover, it will pave the way to promising applications by exploring the possibility to use technical innovations to communicate more interactively in the case of people who suffer from social isolation and disconnection from others.

Keywords: interpersonal affective touch, loneliness, virtual reality, autism, anorexia nervosa, interpersonal violence

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INTRODUCTION

Human beings constantly seek to stay one close to another and interact suggesting the need to feel connected and establish emotional bonds with others to create and maintain interpersonal relationships (Baumeister and Leary, 1995), which have the potential to shape biological responses and behaviors that are consequential for health and psychological well-being (Pietromonaco and Collins, 2017). Physical contact, mediated by the sense of touch, is an essential part of social communication providing the experience of actual togetherness, which can be defined as social presence (van Erp and Toet, 2015). In case of prolonged periods of social distancing and isolation, such as during the COVID-19 pandemic when physical distancing has been prescribed in order to limit the diffusion of infections, deprivation of interpersonal touch has been associated with greater loneliness and anxiety and people showed to crave intimate tactile interactions, underlining the importance of feeling the physical presence of others for psychological well-being (Banerjee et al., 2021; von Mohr et al., 2021). Like never before, social distancing measures have been globally imposed, offering a new lens through which the psychosocial impact of deprivation of tactile interactions should be examined. This reevaluation of the importance of physical presence and interpersonal touch is particularly important considering an increasing use of virtual environments that strongly rely on vision and audition, but scarcely involve tactile stimulations. Indeed, current communication systems, such as videoconferencing, social media use and engagement with virtual reality activities, do not support sensory feedback through the sense of touch and they have been shown to be not sufficient to prevent social isolation and loneliness (Usta et al., 2014; Twenge et al., 2019; Boursier et al., 2020). More specifically, people reported to spend more time on social media and virtual reality activities during prolonged periods of isolation and physical distancing, which helped users keep themselves occupied and active (Siani and Marley, 2021). Feelings of loneliness have been shown to predict time spent using social media that probably strengthened the need to be part of a virtual community; however, the facilitated and prolonged access to Internet and social media risked further increasing anxiety, generating a vicious cycle between loneliness and excessive social media use, that in some cases may require clinical attention (Boursier et al., 2020). In this regard, social media use highlights both opportunities for individuals to face isolation through virtual communication and risky behaviors, depending on its specific use or misuse (Livingstone, 2008). Especially among young people, higher feelings of loneliness have been shown to predict an increased social media use to keep in touch with peers and family, however it was not associated with happiness (Cauberghe et al., 2021). Considering the extensive diffusion of digital technologies, an increasing amount of social interaction is now mediated by communication devices, substituting direct physical contact (Twenge et al., 2019). Virtual exchanges have the advantages of allowing communication between people physically distant, providing a feeling of social presence, named the perception of being present with others within an environment mediated by communication technologies (Triberti et al., 2018). However, if such a perception does not manifest, it may result in an increasing sense of loneliness and social disconnection between people. This suggests that now is an important time to begin intervention efforts targeting especially those people at risk for feeling lonely and unable to connect with others. In this perspective, the development of multisensory virtual environments may also represent an innovative tool for assessing and training social abilities and the sense of social connection, focusing on the role of interpersonal touch in enriching mediated exchanges with crucial social and affective information.

The present narrative review aims to consider interpersonal affective touch as an essential component of perceiving social presence during virtual interactions, which may critically modulate the sense of social connection and prevent loneliness. By reviewing the current literature about the social function of tactile stimulation and the advanced opportunities of social interactions in virtual environments, we propose an integrative perspective on the applicability of interpersonal affective touch in VR as a potential driver of self-other connection (**Figure 1**).

In the first section, we will describe the neurophysiological properties of interpersonal affective touch that support self exploration and social exchanges, specifically assessing the implications of tactile stimulation in modulating feelings of loneliness. In the second section, we will critically examine whether interactive technologies play a role in contributing to or mitigating loneliness. Importantly, we will discuss current challenges in advancing virtual reality by including other sensory channels that may represent new opportunities for communicating socio-affective significance and increasing the feeling of social presence and connection between people who are physically apart. Finally, in the last section, we will explore the most promising technical perspectives to support more interactive communication in the case of people who suffer from social isolation and disconnection from others.

In order to search and select relevant contributions to the body of knowledge of the current review, we combined three strings referring to the main topics of the review, with three additional strings related to the example cases reported in the second part of the manuscript. Thus, we defined six different strings, one for each of the key-words of this manuscript (**Table 1**). Given the fact that we aimed to link different topics of research that have been rarely studied all together, we used all possible pair combinations of the aforementioned strings in order to provide a broad understanding of the state of the art (e.g., affective touch and loneliness; affective touch and virtual reality; virtual reality and loneliness). Moreover, as we intended to select the contributions focusing on the social connection and virtual communication between individuals, we also included the keywords "Social connection" and "Virtual communication" in our search. In the first step, we searched for references listed in PsycINFO and PubMed. In a second step, we searched reference lists of articles identified by this first search and selected those describing studies that included a specific focus on the topics described above. For the detailed description of the most relevant research studies on which we based this review, see the Table reported in **Supplementary Materials**. Several review articles and book chapters were also included.

SOCIAL CONNECTION THROUGH TACTILE EXPERIENCES

Early sensory experiences and interaction features, mediated by physical contact and interpersonal touch, provide the neurobehavioral mechanisms supporting the development of social connections and affective bonds (Dunbar, 2008; Su and Su, 2018). Shared sensory experiences may promote the development of predictive internal models concerning others' affective states and behaviors, critically shaping the ability to feel close and connected with others during interpersonal exchanges (Maister et al., 2015). In particular, interpersonal affective touch, which

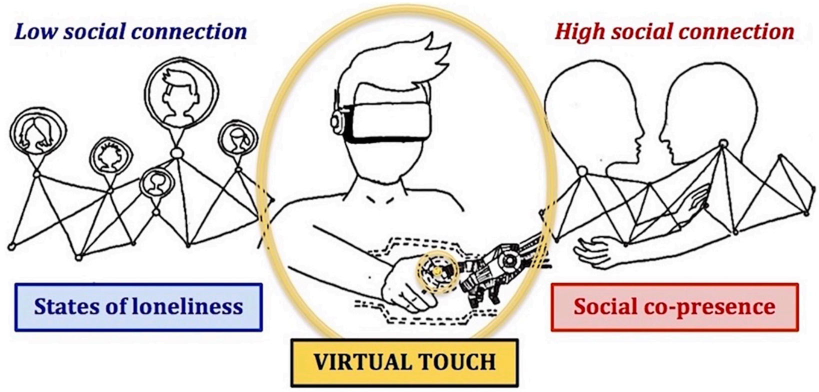

FIGURE 1 | Schematic representation of an integrative perspective on the applicability of interpersonal affective touch in virtual reality (VR) as a potential driver of self-other connection.

refers to the emotional and motivational facets of tactile exchanges between social partners, has been shown to modulate psychological boundaries between the self and the others (Gallace and Spence, 2014), thus critically impacting the feeling of social connection. A unique characteristic of tactile interactions is the fact that touch is reciprocal in nature, as it consists in a shared sensory experience between individuals, and so it represents a privileged channel of communication that can convey immediate socio-emotional meanings and reinforce social bonds (Morrison et al., 2010). The dynamics of interpersonal touch rely on different mechanisms and various levels: sensory properties of tactile stimulation, physiological responses (including changes in hormone levels), and emotional experiences (Cascio et al., 2019). All these processes interact and possibly reinforce each other, thus providing the complex sensation of feeling in touch and connected with another person.

Neurophysiology of Interpersonal Affective Touch: A Bridge Between the Self and the Others

The skin is the largest sensory organ surrounding the whole human body and it is innervated by a wide array of sensory fibers supporting the transduction and processing of thermo-mechanical stimulation on the body surface (McGlone and Reilly, 2010). This strategic position makes the skin an important point of interchanges between the body and the surrounding physical and social environment, suggesting that the sense of touch serves as a sensory anchor on which the bodily self extends (Bremner and Spence, 2017) and a channel of communication with other individuals (Morrison et al., 2010). Indeed, the sense of touch is more than a sensory input for haptic exploration, identification, and manipulation of objects in the environment (sensory-discriminative dimension), it also represents one of the most direct means of contact and social interactions, allowing positive and rewarding experience of tactile sensation (affective-motivational dimension; McGlone et al., 2007). More specifically, each tactile experience is processed in terms of sensory-discriminative properties that specify precise information about the spatio-temporal dynamics of mechanical stimulation and texture features of the external object touching the skin toward activation of fast-conducting myelinated Aβ afferents that project to somatosensory cortical areas, and in terms of socio-affective properties that specify the internal state of the organism (e.g., how the experience of been touched feels like; Bremner et al., 2012; McGlone et al., 2014). This second dimension of touch, named affective touch, is mediated by a specialized system of slow-conducting, unmyelinated peripheral afferents (C-tactile afferents) that selectively respond to gentle and caress-like touch (Olausson et al., 2008; Löken et al., 2009). More specifically, C-tactile afferents are activated by dynamic tactile stimuli delivered at slow velocity (1–10 cm/s), low force (0.3–2.5 mN) and neutral (skin-like) temperature (Vallbo et al., 1999; Ackerley et al., 2014). Importantly, activation of C-tactile afferents positively correlates with subjective reports of pleasantness (Löken et al., 2009) and elicit implicit positive reactions (Pawling et al., 2017), implying that the C-tactile system is related to positive affect and to the rewarding value of social interactions, thus providing a link between external sensory information and internal affective states in order to support social connection (Morrison et al., 2010). Additionally, C-tactile afferents project directly to the posterior insula and

TABLE 1 | String used to search and select relevant contributions of this review.

	Topic	String
Main topics	Touch	Affective touch OR social touch OR interpersonal touch
	Loneliness	Loneliness OR social isolation OR social exclusion OR lonely
	Virtual reality	Virtual reality OR immersive virtual reality OR VR OR IVR OR Head Mounted Display OR HMD
Example cases	Autism	Autism OR ASD OR autism spectrum disorder OR autistic disorder
	Anorexia	Anorexia nervosa OR anorexia OR anorexic OR eating disorder
	Interpersonal violence	interpersonal violence OR ipv OR aggressive behavior

to other crucial nodes of the social—brain network involved in interoceptive and social processing, including the posterior superior temporal sulcus, medial prefrontal cortex, and dorsal anterior cingulate cortex, (Gordon et al., 2013; Voos et al., 2013; Björnsdotter et al., 2014; Morrison, 2016), suggesting affective touch represents a fundamental link between the self and the others. The neurophysiological properties of C-tactile system may thus constitute a privileged peripheral pathway for tactile stimulation that is likely to act as a selector for picking out and encode socially relevant touch, reflecting a disposition of seeking close affective contact with others and to maintain social bounds (Morrison et al., 2010). Notably, interpersonal affective touch has been shown to critically contribute to communicative behavior and social cognition processing (Olausson et al., 2010). Humans are indeed accurate in discriminating different categories of emotion, even when they are communicated exclusively through touch (Hertenstein et al., 2006). Moreover, interpersonal affective touch can increase the salience of emotional information from other sensory modalities, intensifying the evaluations of other social signals on the basis of the emotional valence of the context. This indicates that the value of touch is intrinsically related to both the physical characteristics of tactile stimulation (i.e., softness, temperature, force, and velocity) and top-down mechanisms that modulate the relevance and affective valence of the stimulation (Ellingsen et al., 2016). Specifically, affective touch has been demonstrated to modulate social appraisal of facial expressions making smiling faces seem more friendly and attractive, and angry faces less friendly and attractive (Ellingsen et al., 2014), suggesting that affective touch can mediate and shape social perceptions in various ways.

Missing the Touch With the Others: The Growing Problem of Loneliness

The affective and rewarding value of touch in social interactions, mediated by the activation of the C-tactile system, promotes physical contact as a biologically necessity form of stimulation (McGlone et al., 2014). Therefore, one may ask what the consequences of diminished opportunities for tactile social interactions could be. In conditions of physical isolation, people may start feeling a sense of disconnection and loneliness, which critically impact their psychological wellbeing and quality of life. Interesting evidence derives from studies of isolation and confinement, such as Polar expeditions and spaceflights. Indeed, prolonged experiences of physical and social deprivation have been shown to produce psychological changes (e.g., disturbed sleep, negative affect, and interpersonal tension; Palinkas and Suedfeld, 2008) and to impact cognitive ability and brain plasticity. More specifically, reductions in the hippocampal volume of the dentate gyrus were observed from before to after polar expeditions, suggesting that variations in physical and social environments influence hippocampal plasticity, which was associated with lower cognitive performance in selective attention and spatial processing (Stahn et al., 2019). Moreover, decreases in gray matter volume have been evidenced in the right dorsolateral prefrontal cortex and left orbitofrontal cortex, which are involved in executive control, emotional and behavioral regulation (Stahn et al., 2019). Finally, alterations of white matter of the right temporoparietal junction, which is critically associated with social processing, have been found after prolonged isolation (Brem et al., 2020). These results raise interesting questions about the effects of sensory and social deprivation on the brain during periods of isolation. However, it is important to notice that the feeling of loneliness is a more complex experience that goes beyond physical distance. Even though loneliness has been strongly associated with objective physical isolation, this is not a sufficient condition for loneliness, which consists in the subjective feeling of being alone and socially isolated (Russell, 2014). This perceived distance between the self and the others is not necessarily coherent with objective measures of individuals' social networks (features of the social environment, such as presence/absence of a spouse, amount of contacts with friends and family, participation in social groups), suggesting that some individuals may perceive themselves to be alone even when among other people; on the contrary, others individuals may choose to be alone at times while still feeling connected to others, which is referred as solitude (Hawkley and Cacioppo, 2010). In this view, loneliness is driven by the perceived quality of social relationships and the difficulties in feeling close and connected with social partners, which may be reflected at the neural level by the overlap between self and others' representations (Courtney and Meyer, 2020). Interestingly, feeling disconnected from others can compromise mental and physical health in both neurotypical and clinical groups (Cacioppo et al., 2006; Kwan et al., 2020) and predict the increased mortality even after adjusting for objective social isolation (Cacioppo et al., 2015). In particular, loneliness has been consistently associated with increased inflammation and higher levels of activation of the hypothalamic-pituitary-adrenocortical (HPA) axis, as reflected by salivary cortisol levels (Cacioppo et al., 2000; Pressman et al., 2005) suggesting that perceived social isolation represents an important stressor for humans. Beside the impact of loneliness on physical health and mortality, it has been shown that perceived isolation dramatically affects also mental health and cognitive functioning (Hawkley and Cacioppo, 2010). Growing evidence indicates that loneliness increases attention to negative stimuli, impacting on emotions, behaviors, and interpersonal interactions, possibly linking loneliness and morbidity through changes in brain structure and function (Cacioppo and Hawkley, 2009). In typically developing preadolescents, feelings of loneliness have been shown to mediate the effect of sociocognitive understanding on depressive symptoms, particularly among girls (Caputi et al., 2017), pointing out the importance of identifying early signs of perceived social isolation in order to prevent an escalation of social deprivation and depressive symptoms. According to a social neuroscience perspective, the behavioral and neural effects of loneliness are related to a short-term self-preservation mode that individuals put to use when they perceive themselves as isolated from the others and therefore, they cannot benefit from the mutual protection and assistance of sociality. That is, loneliness is typically a transient aversive signal that motivates people to become sensitive to potential social threats and renew meaningful social connections needed to survive. However, when social connections are persistently perceived as unavailable, loneliness may become chronic producing deleterious effects on cognition and behavior (Cacioppo et al., 2015). This process results in an increased implicit vigilance for social threats, anxiety, and activation of the HPA axis which carry long-term costs for psychophysiological wellbeing. To mitigate the adverse health effects associated with loneliness, innovative interventions are critically needed to specifically address the risk of clinical manifestations associated with perceived social isolation and sensory deprivation.

Until now, the strategies of intervention have been focused on addressing social isolation by increasing opportunities of social interaction and enhancing social support, and on increasing the quality of social interaction by improving social skills and addressing maladaptive social cognition (Masi et al., 2011). However, to our knowledge, no intervention strategies have been considered sensory aspects. Notably, physical contact and affective tactile exchanges may increase the feeling of closeness and social connection (Morrison, 2016), thus promoting the subjective experience of security and comfort that in tune may result in a decrease of stress reactivity (Ditzen and Heinrichs, 2014). Recent evidence suggests that affective touch reduces feelings of social exclusion indicating that physical contact with others lead to interpersonal connection and social support with stress-protective effects (von Mohr et al., 2017). Moreover, participants exposed to physical contact reported significantly lower neglect scores from their close relationships in a short loneliness scale and they also showed a faster reduction in heart rate, interpreted as a sign of physiological wellbeing (Heatley Tejada et al., 2020). In this respect, developmental studies offer an important understanding on the crucial role of interpersonal affective touch in modulating stress reactivity, creating social bonds and shaping the development of socio-emotional and communicative skills (Cascio et al., 2019). Since the very first stages of life, affective touch is a core self-regulatory and social component of early parent-infant interactions, with the potential of regulate infants' emotional and physiological state (Stack and Muir, 1992; Feldman et al., 2010; Della Longa et al., 2021b), reinforce social behaviors (e.g., smiling and mutual gaze; Peláez-Nogueras et al., 1997) and facilitate learning of facial information (Della Longa et al., 2019, 2021a), suggesting that early tactile experiences represent the scaffolding of the sense of bodily self and of social connections with others, through which the social brain develops (Montirosso and McGlone, 2020; Farroni et al., 2022). Therefore, it is possible to speculate that including affective touch into intervention programs could have a soothing function particularly in the context of perceived social isolation, buffering the negative effects of loneliness. Particular attention should be paid to developmental age with the aim of identifying early signs of social disconnection and work multisensory interventions up, in order to prevent the potentially adverse effects of stress and social isolation on the brain and to promote physical contact as a crucial neurophysiological substrate that underlies the positive effects of social experiences.

INTERACTIVE TECHNOLOGIES: DO THEY CONNECT OR DISCONNECT?

In the last decades, we have started using diverse technological means to communicate and connect with other people, shifting social interactions from in person to virtual-mediated social exchanges. This communication swing has meaningful consequences on different aspects of human interaction, modulating the way people form impressions of one another and come close together (Lieberman and Schroeder, 2020). The massive use of digital technology has attempted to overcome the limits of physical distance providing increasingly more sophisticated devices to connect people who are physically apart, thus making it easier to expand and maintain worldwide social networks. On the other side of the coin, the increased use of mediated communication reduced non-verbal social cues, in particular the opportunities of direct physical contact between people, which may represent a cost in terms of people's understanding of others' thoughts and feelings and perceived closeness (Lieberman and Schroeder, 2020). In this view, the fundamental construct of social presence emerges as the sensation that other people are co-present and socially engaged with us within a technology mediated environment with the potential to establish an actual relationship (Biocca and Harms, 2002; Triberti et al., 2018). In a virtual environment, social interaction occurs between representations of others made accessible to the senses *via* technological devices. The salience of the other person in mediated interactions is influenced by intimacy and immediacy of the medium (Short et al., 1976), indicating the importance of the richness of social cues and feedback that the technological devices allowed to be exchanged (Daft and Lengel, 1986). Beside the features of the tools used to virtually communicate, the quality of the relationship should be also considered, focusing on the communication processes that occur in virtual environments as a strategic form of interaction during which people can negotiate and adjust to one another their identities, information and aims (Donath, 1999). The experience of feeling the co-presence of someone else is based on numerous factors including, sensory aspects as well as mutual understanding and behavioral engagement (i.e., inter-agency; Biocca et al., 2003). Therefore, virtual reality is not considered just a communication channel inferior to other forms of interaction anymore, but rather it has been recently reconceptualized as a social space that has its own rules and a great potential to create a meaningful shared world that contributes to give shape to interpersonal interactions and co-constructed relationships (Galimberti et al., 2010). In light of this, the use of interactive technologies may provide a new lens through which to evaluate the effects of different sensory channels and information exchanges on social interaction. More specifically, it is worth considering the role of tactile sensations, asking whether touch can be efficiently included into virtual environments to modulate the sense of social presence and interpersonal connection. This section will critically discuss such open debate. Considering the massive differences between the variety of technologies that make distinct forms of social interaction possible, we will focus on immersive virtual reality (IVR), that is usually delivered through head mounted displays (HMDs), thus blocking out the external world and fully engaging the user in a lifelike experience of free movement, object manipulation, and social interaction (Bohil et al., 2011; Parsons et al., 2017).

Social Interactions in Virtual Reality

One of the main features that distinguish IVR from other interactive technologies is the possibility of an embodied experience, which increases the sense of presence (namely, the sense of "being there" and being able to enact one's own intentions) into the virtual environment (Slater et al., 2009; Riva et al., 2014). Embodiment entails the sense of self-location, the sense of agency, and the sense of body ownership toward a virtual body (Kilteni et al., 2012), and is achieved through both realism and fidelity (Zopf et al., 2018). Realism comes from the resemblance to the real body, and depends on whether it takes a first- or third-person perspective, tracks and shadows the whole body or restricted proportions (i.e., hands only, hands, and trunk). Fidelity builds upon the co-occurrence of multimodal stimuli in the same spatio-temporal window (multisensory contingency; Murray et al., 2016), and the correspondence between sensory feedback and motor output (sensorimotor contingency; Baldassarre et al., 2018). The sense of embodiment toward a virtual body has been demonstrated to intensify the emotional processing of the virtual stimuli (Gall et al., 2021). This is particularly relevant for children, who are sensitive to embodiment in a virtual body (Dewe et al., 2021) and tend to truly believe in virtual experiences, sometimes confusing them with reality (Segovia and Bailenson, 2009). Notably, the illusion of body ownership toward one's own avatar might be enhanced when users receive synchronous visual and affective tactile stimulation, compared to non-affective touch conditions (de Jong et al., 2017). However, the role of affective touch in promoting embodiment remains controversial and would need further investigation (Carey et al., 2021).

Virtual bodies are also employed to create a sense of co-presence with an interactive partner, namely the feeling of being there with a "real" person (Oh et al., 2018). The virtual partner can be either an avatar, namely a virtual representation of a real human user who interacts online, or a virtual agent, which is a digital animation that behaves in a pre-specified way or is controlled by the computer (von der Pütten et al., 2010). People are able to discriminate between virtual avatars and agents, with avatars being more easily identified as such and perceived as likeable, thus inducing higher levels of co-presence and emotional activation (Hoppe et al., 2020). However, also when interacting with virtual agents, users' experience is sensitive to non-verbal communication cues, such as interpersonal distance, which is the comfort space between social partners and depends on cultural norms and individual differences (i.e., level of social anxiety; Kroczek et al., 2020). Fostering parasocial relationships with virtual characters can be a powerful educational tool for children, who are exceptionally open to making these kinds of connections (Brunick et al., 2016).

The modality that enhances the possibilities for social interaction in IVR are the so-called collaborative virtual environments (CVEs), which enable several users to interact with the environment at the same time, being represented by their unique avatar, acting, moving, and navigating the environment independently, thus communicating directly when they are close enough to another user's avatar. Such communication is mainly verbal and occurs through the audio system of each device but can also involve vision to different extents (facial expressions and body gestures can be implemented depending on how sophisticated the system is). It is therefore possible to use IVR for remote peer interaction (i.e., peers are actively working together on a shared task or activity, but are physically separated), or even in person interaction (i.e., multiple users work on the same virtual activity, but also share the real space). It is a fascinating option to promote learning from childhood (Bailey and Bailenson, 2017), and also for children with atypical development (Parsons and Cobb, 2011).

Impact of Interpersonal Virtual Interactions on Loneliness

Like any innovation, IVR has opened the debate about possible social consequences, eliciting on one hand fear and resistance to change and on the other enthusiasm and great expectations. Since Internet and digital technology has become a pervasive means of communication, researchers have begun to investigate the social impact of new interactive technologies on people's network of relationships and related levels of loneliness (Coget et al., 2002). On one hand, IVR may represent the ultimate connecting tool, which increases the realness of virtual communication providing people with new opportunities to meet and communicate with people physically distant. On the other side, critics of the IVR point out its possible opposite effect of disconnecting people from their bodies and reducing face-to-face interactions. In this way, IVR seems to have the potential for both positive and negative effects on psychological wellbeing and social connection, as people may experience a paradoxical situation in which mental and virtual mobility counterposes physical distance and social separation (Daniel et al., 2018), resulting in a tension that is gradually changing social communication and interpersonal interactions (Lieberman and Schroeder, 2020). Specifically, there is not yet a consensus about the impact of virtual communication on loneliness and psychological wellbeing (Orben and Przybylski, 2019; Odgers and Jensen, 2020). Higher feelings of loneliness among young people have been shown to predict an increased social media use to keep in touch with peers and family, however, it was not associated with happiness (Cauberghe et al., 2021). Some studies found that young adults who use more social media seem to feel more socially isolated than their counterparts with lower social media use (Primack et al., 2017), while other studies suggest that high social media attitudes were associated with decrease of reported loneliness among college students (Pittman, 2015) as well as older adults (Shillair et al., 2015). The inconsistency of results suggest that other variables may mediate the effects of interactive technologies on loneliness, such as the perceived intimacy that makes people feel connected when interacting through virtual technology (Pittman, 2018). Indeed, people's belief that virtual platforms are a good way to connect with others has been shown to be a more meaningful predictor of decreased loneliness than the frequency of social media use (Pittman, 2018), suggesting that the emotional benefits of virtual communication critically depend on perceiving a real connection and intimacy with the other. Therefore, besides the great opportunity to create an extensive social network, it is possible that people interacting through IVR might still feel alone and perhaps find it difficult to create meaningful social interactions. Moreover, it is also worthy considering possible negative interactions that may take place in virtual environments, including experiences of harassment, bullying and minors's exposure to inappropriate content (Maloney et al., 2020). Indeed, a participatory observation study revealed similar aspects of bullying found in social VR compared to traditional games, which may be particularly risky given the online anonymity (Maloney et al., 2020). In this regard, high levels of engagement may represent a risk especially for the developmental population and should be carefully examined to design virtual spaces that can guarantee safer and more socially satisfying virtual experiences (Maloney et al., 2020). Additionally, virtual exchanges can induce experiences of cyberostracism, which is an act of social ignoring and exclusion occurring in a virtual environment that lead to negative feelings, reduced perception of control and losing a sense of belonging (Williams et al., 2000). In this context, tactile stimulation has recently drawn attention as a valuable means of social bonding that can modulate the perception of social separation or rejection. Indeed, it has been shown that affective touch is effective in reducing negative feelings of social exclusion experienced during a computer ball-tossing game specifically manipulated to induce ostracism, pointing to a soothing function of touch in a situation of virtual social rejection (von Mohr et al., 2017). In this perspective, tactile interchanges may represent a critical aspect to ameliorate the sense of social presence and intimacy between people interacting in a virtual environment to the aim of creating a positive and enjoyable virtual social experience. The new challenge of developing multisensory and more immersive social VR platforms raises interesting questions about the impact of virtual tactile interactions on the perceived virtual version of oneself identity and the capacity to create self-other meaningful connections. The next paragraph will explore possible benefits and challenges in including tactile stimulation in IVR.

Bringing Interpersonal Affective Touch Into Virtual Reality

Being primarily visual and auditory, the virtual experience is usually impoverished of touch, a communication channel with unique potential for social interaction and connection. Over the last years, researchers tried to bring touch into virtual experience by understanding the many different aspects of tactile processing and communication across the body surface (Gallace et al., 2007). The world of art and dance is one of the most receptive to the potential of virtual touch, which has been employed to engage people in shared IVR, while also being in the same physical space. This interactive modality embeds the possibility for shared experiences between co-present bodies that can touch one another (Thomas and Glowacki, 2018). Despite the promising complementarity between "real" tactile, proprioceptive, interoceptive sensations, and the primarily visual and auditory inputs of IVR, the combination of modalities has received little consideration in the literature (Cerritelli et al., 2021). Therefore, little is known about the potential effects of receiving real human touch while immersed in IVR. This is probably since this line of research has taken as its main challenge that of fixing IVR as a remote communication tool, which is therefore independent of the physical proximity of the users. To this end, many attempts are being made to design and develop hardware and software that can encode, reproduce and communicate, or simulate interpersonal affective touch. Importantly, different tactile devices induce different feelings, with force feedback actuators being evaluated as more natural and resulting in greater co-presence and emotional sharing than vibrotactile devices (Ahmed et al., 2016). When touching in IVR, people adjust the touch intensity according to the target (i.e., less force for touching virtual agents than objects, less force for touching the agent's face than the torso area, less force for touching male than female agents; Bailenson and Yee, 2008). On the other hand, both virtual agents and avatars are perceived as having higher agency in case they can touch the users through an artificial hand, which also make participants reporting increased co-presence (Hoppe et al., 2020). Overall, mediated or computer-generated affective touch can intensify the perceived social presence of remote partners, modulate physiological responses, increase trust and affection, help connecting humans and virtual characters, and foster prosocial behaviors (van Erp and Toet, 2015). Indeed, affective touch is fundamental in giving life to the virtual experience, as it is closely linked to emotions, in a mutual influence that nurtures social encounters. When asked to express emotions through handshaking of haptic devices, participants' kinematics are able to differentiate distinct emotions, which allows other participants to receive another person's handshake *via* haptic devices and capture its emotional content (Bailenson et al., 2007). Moreover, researchers asked neurotypical adults to observe virtual agents' emotional faces while seeing a virtual representation of their own hand touching the virtual partner. They were instructed to touch the agent's hand by squeezing a controller, and to use the same force as when touching a real person, using the same type of touch regardless of the agent's emotion. Participants applied more force when the agent expressed negative or aroused emotions, and this was mediated by the participant's own emotional and physiological state (Ahmed et al., 2020). Therefore, people implicitly use touch to communicate (and potentially share) emotions not only in reality, but also in virtual environments and with virtual agents. Indeed, romantic couples have been asked to engage either in a video call or in a video call enriched by the use of a remote massage device. Participants could either send (through the manipulation of a shoulder-like device) or receive (through vibrotactile stimulation) massages. The inclusion of touch increased the perceived emotional and physical connection within the couples (Haritaipan et al., 2018).

Despite all the potential benefits, the implementation of interpersonal tactile devices in VR also raises some risks and ethical issues that should be carefully considered. Introducing tactile stimulation into IVR, the virtual experience tends to connect very closely to the person's perceptual system, thus allowing for high degrees of immersion. This increased realism of multisensory virtual exchanges fosters more intense experiences, which might result in some people beginning to have difficulty differentiating from the offline and online world. Consequently, cognitive, emotional and behavioral disturbances may arouse after re-entry into the real world following the VR experience (Behr et al., 2005). As the perception of one's own body can be manipulated in VR, continued exposure to such embodied experiences enriched by somatosensory stimulation, may cause confusion in people about their real body, impacting the development of oneself identity (Slater et al., 2020). Moreover, social interaction in VR could become more enjoyable and desirable in various ways in comparison to real-life interaction, so that people withdraw from society (Slater et al., 2020). This risk is particularly relevant for children or adolescents, who may not distinguish well between reality and virtual reality as adults do (Maloney et al., 2020; Tychsen and Foeller, 2020), and for vulnerable people, such as those prone to psychosis. Although interpersonal exchanges in VR are based on virtual sense data and virtual actions, they are nevertheless real as first-person experiences, thus they have physical, emotional, and cognitive consequences, which may be beneficial or harmful (Slater et al., 2020). Therefore, careful attention needs to be paid to the introduction of interpersonal touch in virtual environments. As well as emphasizing the positive aspects of increasing social connection, potential negative effects should also be considered, specifically in contexts where touch could be unwanted, unpleasant, improper or felt as a violation. Indeed, researchers must take into account specific low-level properties of tactile devices (e.g., how users can control pressure, speed, temperature, and attrition of tactile interactions) as well as the high-level aspects such as communicative intentions and subjective perception (e.g., touch provided by an avatar or virtual agent, context of social interaction, and pleasant/unpleasant feelings). Different effects of virtual tactile interactions should be experimentally evaluated using suitable neurophysiological and behavioral measures to compare participant socio-emotional and behavioral outcomes before and after a brief period in VR, perhaps comparing two scenarios that elicit contrasting emotions. Scientific support will be essential for developers of VR environments and legal authorities to determine evidence-based regulations and recommendations in order to prevent danger or immoderate use of VR (e.g., clear warnings and minimum age requirements). In addition, developers and users need to be aware about the ethical implications and the potential advantages and dangers that can arise as a consequence of interpersonal exchanges in multisensory VR. In particular, to reduce the risk of harm, developers could build up different multisensory levels of virtual interaction that could be flexibly selected and users' education should also include training of disengagement from VR (e.g., remind users of their right and ability to shut-off the devices and stop the experience at any moment).

USING VIRTUAL REALITIES ON SOCIAL PURPOSE: HOW TO FOSTER SOCIAL CONNECTION AMONG THE MOST DISCONNECTED INDIVIDUALS

A number of clinical conditions entails concurrent distorted connection with the self and the others. Early sensory mechanisms and higher-order cognitive and social difficulties are bound together in shaping how people perceive their own bodies and interact with others (Baum et al., 2015). In this manuscript, we review the extant literature and propose that an altered perception and use of touch during self exploration and social exchanges might be part of the neurocognitive and sensory loneliness that affects the social life of some individuals. Research in this area dramatically neglected to investigate the sensory factors and effects of loneliness across different developmental trajectories, clinical conditions, or other cases of social disconnection. In this section, we discuss these aspects in three example cases: anorexia nervosa, autism, and interpersonal violence. Specifically, we select these examples to disentangle three parties of analysis that characterize the ability to create meaningful social connections: the (bodily) self, self-other interaction, perception of the other (**Figure 2**). Beyond the profound differences among these conditions, a comparative approach allows us to explore how they all include sensory atypia and states of loneliness that impact connection with the self and the others. As the neuroconstructivist approach suggests, early, domain-general, low-level processing deficits might affect several domains but in varying ways and times across different developmental trajectories. Therefore, similar behavioral outcomes may stem from very different cognitive and neural causes, and similar atypicalities may give rise to different manifestations (Karmiloff-Smith, 2009). This gives us some insights into the possibility that sensory mechanisms (i.e., affective touch) across various diagnoses (i.e., Autism Spectrum Disorders and Anorexia Nervosa) and social dynamics (i.e., interpersonal violence) may play a key role in understanding the individual and defining personalized intervention. More specifically, identifying early predictors of loneliness by means of understanding their low-level origins is of great importance to design sensory interventions through careful identification of which level of stimulation is appropriate to promote social connection in different individuals through each sensory modality. This approach would open new perspectives for individuals at heightened risk for or with impairments in social abilities, as well as those experiencing high levels of loneliness, both during development and in adulthood. In this perspective, technologies have unique advantages and potential to manipulate through the senses, the perception that we have of ourselves and others. In the next paragraphs, we will present some applications of these theoretical approaches.

Disconnection From the Bodily Self: Anorexia Nervosa

Anorexia Nervosa (AN) can be considered a clinical example of disconnection from the bodily self which comes with a vicious

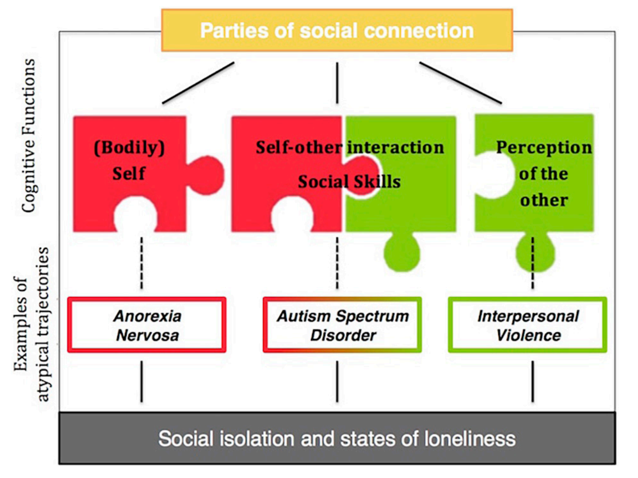

FIGURE 2 | Example cases of atypical connection with the self and the others which may be related to social isolation and states of loneliness. Anorexia Nervosa as a case of disconnection from the bodily self, Autism Spectrum Disorder as atypical self-other interaction and Interpersonal Violence as a result of disconnection from the other.

cycle of social isolation, loneliness, and disconnection from others (Levine, 2012). Patients suffering from this condition not only present low body weight and behaviors to avoid gaining weight (American Psychiatric Association, 2013), but also present a maladaptive need for control, scarce flexibility, low emotional awareness and expression, reduced connection, and intimacy with others (Hempel et al., 2018). Notably, most patients with AN reported that both core symptoms (i.e., eating and weight concerns, drive for physical activity), loneliness and mood conditions increased during COVID-19 pandemic (Schlegl et al., 2020). As a sensory aspect of social disconnection, AN patients frequently report reduced pleasantness of interpersonal affective touch (Crucianelli et al., 2016). These subjective ratings are sustained by reduced response to affective touch in the brain's reward and body image systems (Davidovic et al., 2018). Moreover, the atypical processing of affective touch persists after patients recover from AN (Bischoff-Grethe et al., 2018; Crucianelli et al., 2021), indicating that sensory mechanisms have long lasting effects on people's sense of self and connection with others. On the other hand, preliminary findings support the use of massage and social touch for people with AN, showing that the inclusion of massage therapy in a standard treatment reduces the stress and anxiety levels and decreases the scores of body dissatisfaction (Hart et al., 2001).

Innovative interventions to modulate the individuals' sense of bodily self, which happens to be atypical in AN, are based on virtual body illusions that manipulate multisensory body-related signals. Specifically, synchronous visuo-tactile stroking of the real and virtual body has been used to achieve full body illusions and make people feel embodied in a virtual body that may differ in shape and size from the one's own real body (Petkova and Ehrsson, 2008). Through the illusory sense of ownership over the virtual body, the mind also generates attitudes and behaviors that are congruent with that type of body (Slater and Sanchez-Vives, 2014). Interestingly, it has been found that people with AN are more susceptible to bodily illusions compared to healthy controls, with enhanced sensitivity for visual manipulations of the body self (Crucianelli and Filippetti, 2020). This led researchers to investigate the beneficial use of IVR to treat eating disorders through the full body illusion (Riva et al., 2021). The visuo-tactile stimulation of the real and virtual body is an effective way to make individuals with AN feel as they own the virtual body, thus allowing the assessment and modification of their body image (Serino et al., 2019). Such exposure and embodiment in a virtual body can decrease the overestimation of AN patients' own body size (Keizer et al., 2016). Given the strong connection between the bodily self and social abilities, IVR might be used not only to directly re-shape the patients' body image, but also to leverage such rehabilitative embodiment to engage people in "rehabilitative social interactions." Indeed, recent therapeutic approaches specifically target AN interventions to social connection (Hempel et al., 2018). To this end, integrating interpersonal affective touch in IVR applications for the treatment of AN would provide a sensory framework to simultaneously manipulate the bodily self and connect the bodily self with the others throughout physical contact. Immersive technologies would have the unique possibility to adapt tactile stimulations to the individual's sensory perceptions and feelings of pleasantness, thus allowing patients to receive and deliver affective touch in a safe and controlled environment, discover what type of interpersonal touch they like or dislike, and potentially expand the range of affective tactile sensations perceived as positive. We propose that with this bodily and social experience one can also take care of core symptoms of distorted body image.

Self-Other Disconnection: The Case of Autism

From early childhood, children with NeuroDevelopmental Disorders (NDDs) show early risk markers of atypical sensory processes, which confer cascading effects on child development, potentially marking the onset of neurodevelopmental difficulties and disorders (Hill et al., 2012) and being the very first source of social disconnection. Children with NDDs are the most exposed to social exclusion, interpersonal disconnection, and loneliness, which is a predictor of mental health issues later in life (Kwan et al., 2020). They frequently manifest hypo or hyper-responsiveness to tactile stimulation and avoidance or seeking behaviors toward touch (Smirni et al., 2019), which has the unique power of connecting the self with the others in an indissoluble bond between touching and being touched. In particular, Autism Spectrum Disorders (ASD) are persistent and pervasive deficits in social communication and social interaction, as well as restricted and repetitive patterns of behaviors, interests, or activities (American Psychiatric Association, 2013). In adulthood, loneliness seems to mediate the effects of autism features and social contact on mental health (Schiltz et al., 2021). Looking at the sensory aspect of self-other disconnection, individuals with ASD have unique (and heterogeneous) processing of tactile stimuli (Balasco et al., 2020), such as atypical brain responses to both affective and non-affective touch (Kaiser et al., 2016), delayed or reduced effects of visuo-tactile stimulation on the bodily self (Cascio et al., 2012; Greenfield et al., 2015), reduced subjective pleasantness of affective touch (Voos et al., 2013). Notably, touch deprivation is associated with altered sensory thresholds, depression, and self-aggression (Field, 2005), which are frequent symptoms of ASD. On the other hand, people with ASD seem to benefit from intervention through massage and social touch (Rodrigues et al., 2019). A recent study suggested that 5 months of daily parent-delivered massage and weekly sessions of therapist-delivered massage brought great benefits to preschool children with ASD. When compared to no-treatment controls, children showed more pronounced improvements in sensory responses, self-regulatory abilities and receptive language, as well as reduced symptom severity (Silva et al., 2015). A longitudinal follow-up study confirmed the massage beneficial effects over the long term (Silva and Schalock, 2016).

Technologies such as immersive virtual reality become increasingly popular to reshape sensory and bodily experiences and social connection for clinical goals, with long-lasting effects that generalize to the real world (Riva, 2022). For instance, IVR is largely employed to deliver social skills training in safe, various and ecological situations (i.e., classroom, park, shop, and street), where individuals with ASD can foster their communication (verbal and non-verbal), social cognition (i.e., Theory of Mind – ToM), emotional competences (i.e., emotion recognition and regulation and empathy), as well as learn appropriate social behaviors (Herrero and Lorenzo, 2020). However, results about IVR social training are still preliminary in providing evidence of effectiveness, duration of effects, transfer of skills to real-world contexts. Moreover, the virtual experience is not a perfect replica of the one we have in reality but is rather different in both bottom-up sensory aspects and top-down cognitive mechanisms (Harris et al., 2019; Giesel et al., 2020). This becomes particularly relevant when we talk about people with atypical development and unique sensory functioning. For instance, real and virtual experiences might have distinct sensory implications for people with ASD (Valori et al., 2021). The implicated sensory mechanisms might also affect cognitive and social processes, as suggested by the evidence that people differently adapt their social behaviors (i.e., interpersonal distance) in real or similar IVR environments, but this does not seem the case for people with ASD, who show similar behaviors in the two environments, toward a real partner or virtual avatar (Simões et al., 2020). In addition, it has been suggested that adults with ASD are less susceptible to the full body illusion in IVR, which was associated with more severe autistic traits and social difficulties (Mul et al., 2019). This may indicate a reduced sensitivity to visual manipulations of body self, which would limit the possibility of intervention through the visual channel. On the other hand, people with ASD seem to heavily rely on somatosensory cues (Izawa et al., 2012), of which touch is particularly powerful in connecting the self and the other. The potential of leveraging tactile inputs in IVR to foster the body illusion, shape the bodily self and stimulate social connectedness of people with ASD has yet to be investigated.

In an attempt to integrate touch in applications for ASD, literature describes many prototypes of virtual tactile tools designed for telemedicine (distant therapy) or innovative intervention. The idea here is to develop tools that can deliver tactile stimuli with no role of human partners, or with remotely interacting partners. Vaucelle et al. (2009) designed tools such as Touch Me and Squeeze Me. With the former, caregivers can remotely activate a vibrotactile motor array to deliver tactile inputs to large areas of the patient body. With the latter, both caregivers and patients themselves can use a digital control system to hug the patient who wears a sort of tactile vest. The authors mention that these technologies are also suitable for people with touch aversion, thus allowing them to experience touch without the overwhelming human contact (Vaucelle et al., 2009). Overall, researchers created tactile technologies to help people with ASD experiencing human contact through virtual simulations of being touched (Tang et al., 2014). To the best of our knowledge, these studies rarely go beyond specifying design features, creating prototypes, assessing feasibility, and piloting. A deep understanding of the subjective, behavioral, physiological, and neural responses of people with ASD (also taking their profound interindividual differences into consideration) of such simulated touch has yet to be conquered. Beyond the main barriers imposed by the limitations of technology in integrating touch into IVR, it is important to note that also theoretical hurdles arose from the idea that people with ASD rely on a primarily visual learning style, and this would blend happily with the primarily visual (and auditory) characteristics of virtual worlds (Strickland, 1997). This prevented researchers from wondering whether VR has any unique potential for stimulating touch in individuals with ASD. Future research could explore innovative ways to adapt tactile stimulations to the individual's functioning and needs. In this respect, IVR offers unique options to manipulate the stimulation to re-shape sensory thresholds, bodily perceptions and feelings. Simultaneously, these low-level manipulations could lay the foundations to allow people with ASD to prove themselves in interpersonal interactions that are tailored to the personal needs of each individual, who can be facilitated in his/her discovery of pleasant affective tactile experiences.

Disconnected From the Other: Interpersonal Violence

One of the worst-case scenarios for failure to connect with others is interpersonal violence, which is the violence inflicted by one individual to another (Dahlberg and Krug, 2006). This social dynamic involves two parts, the victim, and the perpetrator of violence, who both may experience forms of loneliness and difficulties in connecting with others. Looking at the victims of interpersonal violence (i.e., bullying), they report higher levels of loneliness compared to controls and offenders, from early in childhood and across cultures (Eslea et al., 2004). The violence suffered frequently results in post-traumatic stress disorders (PTSD) that lead the victims to ambivalent perceptions, feelings and thoughts toward affective exchanges (Eslea et al., 2004). Such trauma profoundly affects the psychological functioning of the victims, beginning with their sensory responses to social stimuli. For instance, victims of interpersonal violence and PTSD show aversion and atypical neural activation for skin-to-skin touch (Strauss et al., 2019). On the perpetrator's side, it has long been suggested that violent behaviors could be modulated by feelings of loneliness (Check et al., 1985). Notably, loneliness affects the perception of others as distant or disconnected and may contribute to the tendency to see them as less fully human than the self (Haslam, 2022). In line with the strong interconnection between social and perceptual mechanisms, recent studies suggested that aggressive behaviors are associated with reduced ability to discriminate emotions in faces (Zeng et al., 2021), with male offenders having difficulties toward female fearful faces (Nyline et al., 2018), and a bias toward classifying fear as happiness (Seinfeld et al., 2018). On a positive note, this dehumanization process might be reduced by promoting social connection, which has been done through sensory stimulation such as embodiment in virtual scenarios and interpersonal affective touch.

The possibility to immerse the senses of one person into the eyes of the other person is a powerful way to fight interpersonal disconnection and the resulting manifestations of violence. To this aim, IVR has been recently used to investigate and train individuals' ability to connect with others from the outgroup. Researchers found that when observing interpersonal violence between virtual humans interacting in IVR, participants intervened physically to help the victim more frequently if the victim was from the same social group. They were also more sensitive to the ingroup victim's gaze for help (Slater et al., 2013). As a perceptual perspective-taking training, IVR has been used to induce a full body illusion that brings men in the female body of a victim of domestic violence. After being embodied in a female victim and exposed to violent scenarios, offenders improved their ability to recognize fearful female faces (Seinfeld et al., 2018).

Scientists have been suggesting for some time that the lack of affective touch in child nurture is leading to an increase in violence against ourselves and others across the lifespan, while placing a high emphasis on touch in childhood results in a lower incidence of violence among adults (Field, 2005). This evidence points to interpersonal affective touch as a promising complement of traditional interventions. Indeed, touch has the potential to shape our perception, emotions, cognition and attitudes toward others, thus reducing self-other boundaries in interpersonal and intergroup interactions (Shamloo et al., 2020). This is particularly powerful when people interact with social partners who are perceived as different from them on salient aspects (i.e., ethnicity, gender and so on), that might be a risk factor for interpersonal violence. A possible application consists in massage therapy, which may promote well-being and reduce aggressive behaviors, through reducing cortisol and increasing serotonin levels (Field, 2005).

In light of these considerations, we can speculate on the potential of including affective touch in IVR interventions for victims and perpetrators of social violence. While interacting with virtual agents (namely computer-controlled characters), the way individuals touch the other seems to mirror their interpersonal attitudes. For instance, by using controllers to hug virtual agents, participants differently modulate touch duration and intensity according to their own gender and attitudes toward their own and others' bodies (Tremblay et al., 2016). The combination of IVR and interpersonal touch may further boost the possibility to foster social connection through embodied self-other experiences. The resulting process of identification, differentiation and comparison between oneself and the others, first takes place in the bodily domain (Meltzoff, 2007; Tsakiris, 2016) and in tune extends to socio-cognitive domain, resulting in reduction of implicit biases against outgroup members and modulation of social cognition processing (Paladino et al., 2010; Farmer et al., 2014). Indeed, during interpersonal interactions, shared sensory experiences may partially modulate the overlap in the brain representation of the self and the other, which underpin the basis of social understanding and social connection (Brozzoli et al., 2013; Courtney and Meyer, 2020). These findings suggest that sensory experiences shape the representation of one's own body as a point of reference for interactions with the external social environment with cascading effects on socio-emotional and cognitive development. Future studies could deepen the role of interpersonal affective touch to assess the modes of interaction and communication deployed by victims and perpetrators of interpersonal violence. This would provide a deeper understanding of the sensory and relational mechanisms related to violence, and open new perspectives on intervention mediated by physical contact and affective touch.

DISCUSSION

The present review offers an innovative and multidisciplinary perspective on the human need for social connection in a world that relies more and more on distant communication. Specifically, we focused on the impact of interpersonal affective touch, as an essential means of social connection that may increase the sense of social presence and emotional support during virtual exchanges, thus preventing possible aversive effects of feeling lonely and disconnected from the others. Indeed, with the extensive diffusion of digital technologies, an increasing amount of social interaction is mediated by communication devices, substituting direct physical contact (Twenge et al., 2019), which on one hand facilitates communication between distant people and on the other may reduce opportunities of physical contact critically impacting the ability to establish emotional and meaningful social bonds. Therefore, one of the most challenging future directions for the IVR field is the integration of interpersonal touch in virtual realities, critically supporting the human need to feel emotional and social connection through physical contact. This would expand the perspectives to manipulate users' perception beyond the possibilities given by visual and audio stimulation. In this perspective, the open debate about the consequences of interactive technologies on social interactions should move from asking whether new technologies connect or disconnect people, to investigating different forms of social connection based on multisensory exchanges through innovative tools.

To date, researchers mainly used IVR and tactile stimulation to achieve body ownership illusions toward the virtual body, thus manipulating individuals' sense of self or attitudes toward others (i.e., members of out-groups; Maister et al., 2015). However, this interactive technology can go far beyond this, and enable different types of interpersonal interactions and connection. For example, haptic interfaces may enable tactile communication between people who are physically apart by providing mediated interpersonal affective touch, which can carry important socio-emotional feedback. Overall, advances in technology are still a long way from offering effective and accessible proposals for integrating touch into the virtual, especially social, experiences. For instance, haptic devices lack physical cues such as temperature, grip, textures, and limit users' emotion discrimination as compared with *in vivo* human touch (Bailenson et al., 2007). However, we are not facing a mere technical challenge. Future research should carefully investigate the behavioral, psychophysiological, and neural responses that are elicited by any future devices that would bring interpersonal affective touch in virtual realities. Although it is still under discussion to what extent mediated affective touch can reproduce real interpersonal tactile interactions, there is preliminary evidence supporting that physiological, behavioral and social reactions to mediated touch resemble the way people experience and react to direct interpersonal touch (Bailenson and Yee, 2008). Interestingly, also the representation of the space surrounding the body (i.g. peripersonal space) has been shown to adapt because of technology-mediated and social interactions (Serino et al., 2018; Serino, 2019).

Besides the fascinating perspective of studying how to invent tactile technologies to simulate interpersonal touch, we also have the intriguing potential of using concomitant immersion in IVR and "real" skin-to-skin contact with others, whereby users share the same physical space and discover completely new means of interaction. The different effects of simulated and real touch remain largely unexplored, as well as the role of contextual factors, such as the identity, intentions and emotional profile of the person who is touching us or touched by us (i.e., AI avatar, remote human partner represented by the avatar). This is particularly powerful when people interact with social partners who are perceived as different from them on salient aspects (i.e., ethnicity, gender and so on), that might be a risk factor for scarce social connection. Interpersonal touch represents a multisensory experience that involves bottom-up processes (the neurophysiological properties of affective touch, mediated by the activations of C-tactile afferents), as well as top-down processes (i.e., the other familiarity, our past experiences and expectations) that modulate the emotional valence of physical contact between individuals. The identity, intent and relationship with the person delivering the touch become part of a complex interplay of many sensory, emotional, and social factors, which ultimately determine the perceptive experience and communicative meaning of tactile interactions. However, to the best of our knowledge, the applicability of interpersonal tactile intervention in VR interactions has never been investigated as a potential driver of social connection.

From a clinical perspective, the use of new technologies that provide additional tactile stimulation could be of high potential in healthcare. More specifically, tactile stimulation, which is frequently used by therapists for patients suffering from various conditions that benefit from massage or manipulative treatment of tissues, can also be beneficial for people who suffer from different forms of social disconnection (e.g., patients in physical isolation or quarantine, lonely people, individuals refusing touch by another person). Indeed, recent evidence suggests that physical contact has beneficial effects on reported feelings of loneliness (Heatley Tejada et al., 2020) as well as positive physiological effects (Jakubiak and Feeney, 2017). In addition, IVR offers unique opportunities to assess and manipulate individual profiles of sensory processing, affective tactile interaction, bodily self, and social abilities. This opens new perspectives to intervene on those cases where atypical functioning of these interrelated mechanisms is associated with clinical conditions or interpersonal disconnection. We have presented evidence about autism and anorexia nervosa, which entails an atypical sense of self and social disconnection, as well as interpersonal violence as a worst-case scenario of social disconnection. We critically reviewed the extant literature and proposed speculations on the way affective touch and IVR can be used for people with such conditions. Beyond the massive differences across these example cases, we believe they all involve multisensory atypia, which affect not only the sense of self but also the difficulty in connecting with others, possibly resulting in feelings of loneliness. Our considerations might also apply to other examples of psychopathology and interpersonal dynamics. In this respect, it is worth mentioning that there is not one unique pattern of affective touch processing by individuals, and researchers and clinicians aiming at the design and implementation of IVR training should be aware of the individual processing styles of the target users to effectively tap their needs, strengths, and weaknesses. Specifically, to address the need of interventions aiming to mitigate the negative effects of sensory deprivation and social isolation, innovative initiative should foster cross-disciplinary collaboration, combining advances in technology with psychophysiological assessment in order to rapidly and efficiently translate knowledge, methodologies and technologies from laboratory experiments to clinical applications. The continuation and extension of this approach is a key factor to help bridging the gap between academic researchers investigating psychological aspects and digital technology developers. Future collaborative research initiatives could lead to better understanding of mechanisms underpinning loneliness and social disconnection, providing the basis to develop efficient and innovative assessment tools and personalized treatment interventions to prevent long-term health consequences of perceived social isolation across different clinical conditions.

CONCLUSION

In conclusion, interpersonal exchanges in IVR are not a mere simulation of real interactions but can rather offer alternative modes of contact with the bodily self and with the others. In particular, the integration of interpersonal affective touch in virtual interactions has the potential for leveraging an innovative way to connect people and create diverse forms of social participation. This challenging perspective would push our possibilities of social connection into a virtual space, thus reshaping our understanding of multisensory interpersonal interactions and offering new opportunities for advances in interactive technology applications and clinical interventions with both developmental and adult populations.

AUTHOR CONTRIBUTIONS

LD provided the conceptualization. LD and IV contributed to discussing and wrote the original draft of the manuscript. LD, IV, and TF reviewed and edited the manuscript and approved the submitted version.

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SUPPLEMENTARY MATERIAL

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Connected Through Mediated Social Touch: "*Better Than a Like on Facebook.*" A Longitudinal Explorative Field Study Among Geographically Separated Romantic Couples

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In recent years, there has been a significant increase in research on mediated communication *via* social touch. Previous studies indicated that mediated social touch (MST) can induce similar positive outcomes to interpersonal touch. However, studies investigating the user experience of MST technology predominantly involve brief experiments that are performed in well-controlled laboratory conditions. Hence, it is still unknown how MST affects the relationship and communication between physically separated partners in a romantic relationship, in a naturalistic setting and over a longer period of time. In a longitudinal explorative field study, the effects of MST on social connectedness and longing for touch among geographically separated romantic couples were investigated in a naturalistic setting. For 2 weeks, 17 couples used haptic bracelets, that were connected *via* the internet, to exchange mediated squeeze-like touch signals. Before and after this period, they reported their feelings of social connectedness and longing for touch through questionnaires. The results show that the use of haptic bracelets (1) enhanced social connectedness among geographically separated couples but (2) did not affect their longing for touch. Interviews conducted at the end of the study were analyzed following the thematic analysis method to generate prominent themes and patterns in using MST technology among participant couples. Two main themes were generated that captured (a) the way the bracelets fostered a positive one-to-one connection between partners and (b) the way in which participants worked around their frustrations with the bracelets. Detailed findings and limitations of this longitudinal field study are further discussed, and suggestions are made for future research.

Keywords: social touch, mediated touch, haptics, social connectedness, longing for touch, haptic bracelets, wearable haptics

INTRODUCTION

Background

Our sense of touch plays an important role in interpersonal and affective communication (Knapp et al., 2013; Eid and Al Osman, 2016), as well as in human development, attachment, and wellbeing (Cascio et al., 2019). The sense of touch is also our primary way to communicate intimate emotions (Field, 2010; App et al., 2011). Social touch can serve to promote human wellbeing by relieving stress (Eckstein et al., 2020), an effect that can be effective at any age (Field, 2019), particularly for people in a romantic relationship (Huisman, 2017). Social touch can also enhance bonding between (romantic) couples (Gulledge et al., 2007) and improve the intimacy and quality of romantic relationships (Debrot et al., 2014).

However, social touch and its benefits are not always readily available. People can be geographically separated from one another for various reasons. Studies on the effects of social distancing on mental health during the COVID-19 related constraints found that deprivation of social touch was associated with higher levels of loneliness and anxiety and poorer overall psychological wellbeing and depression (Heidinger and Richter, 2020; Palgi et al., 2020; von Mohr et al., 2021). According to Beßler et al. (2019), a lack of touch results in longing for touch when the desire for touch outweighs the amount of experienced touch. A persistent lack of interpersonal touch (i.e., touch deprivation) can even cause various negative effects such as anxiety disorders and increased stress levels (Floyd, 2014), and may negatively affect relationships (Alsamarei, 2021). To prevent or counteract the negative consequences of touch deprivation, interpersonal touch should therefore ideally be readily available, even when people are physically separated.

The observation that interpersonal touch is essential for human wellbeing and communication has stimulated the development of mediated social touch (MST) technology, with the aim to enable affective haptic social interaction over a distance (Haans and IJsselsteijn, 2006; van Erp and Toet, 2015; Huisman, 2017; Ipakchian Askari et al., 2020a). Most studies investigating the user experience of MST technology involve brief (ranging from hours to at most a few days) experiments that are performed in well-controlled laboratory conditions (e.g., Rantala et al., 2013; Nakanishi et al., 2014; Erk et al., 2015; Ipakchian Askari et al., 2020b; Sykownik and Masuch, 2020; Price et al., 2022; for a review see Huisman, 2017). Although these studies provide valuable insights into the immediate perception of mediated touch signals, they do not reveal any long-term effects of MST-use, or whether the perception or use of MST changes over time. Two studies that investigated the way that romantic couples use MST technology over a longer period of time in naturalistic settings suggest that mediated touch can be experienced as meaningful (Saadatian et al., 2014) and can enhance feelings of connectedness (Park et al., 2013).

The work reported here covers a 2-week, longitudinal explorative field study into the effects of MST *via* haptic bracelets on the relation and communication between geographically separated romantic couples. The primary goal of this study is to examine whether the use of MST technology in a naturalistic setting and over a longer period of time affects the feeling of connectedness between geographically separated couples. The secondary goal is to explore how couples use the bracelets in a naturalistic setting (i.e., whether they develop certain communication patterns or attribute certain meanings to the signals).

Related Work

Research on MST has culminated in the development of a wide range of prototype systems, such as Huggy Pajama (Teh et al., 2012), InTouch (Brave and Dahley, 1997), POKE (Park et al., 2013), Vibrobod (Dobson et al., 2001), and TaSST (Huisman et al., 2013) (for an extensive survey see Huisman, 2017). Previous research using these prototype systems shows mixed results in terms of replicating findings from unmediated social touch research (Ipakchian Askari et al., 2020b). Hence, it is currently not clear to what degree mediated touch can replicate the effects of unmediated social touch (Toet et al., 2013; van Erp and Toet, 2015). MST is typically not recognized as interpersonal touch (Ipakchian Askari et al., 2020a; Jewitt et al., 2020). It is also highly context dependent (Huisman, 2017; Ipakchian Askari et al., 2020a). Since MST can cause feelings of discomfort between strangers (Smith and MacLean, 2007), a closer (e.g., romantic) relationship may be preferred for this kind of tactile stimulation (Rantala et al., 2013; Suvilehto et al., 2015). Although currently available MST devices do not provide the emotional and contextual complexity of unmediated social touch, previous studies on MST still show some promising results. For instance, Bailenson et al. (2007) found that MST can communicate emotions to a certain degree, while others found that MST can induce increased feelings of intimacy and sympathy (Takahashi et al., 2011) and connectedness toward another person (van Erp and Toet, 2015). Also, a brief MST can induce prosocial behavior to the same degree as a brief unmediated touch (Haans and IJsselsteijn, 2009; Haans et al., 2014).

Current Study

In this study we investigated how using MST technology for 2 weeks in daily life affects social connectedness and longing for touch among geographically separated romantic couples. For 2 weeks, 17 couples used haptic bracelets that were connected *via* the internet to exchange mediated squeeze-like touch signals. Before and after this test period, they reported their feelings of connectedness and longing for touch through questionnaires.

Various researchers emphasize the importance of social connectedness in (mediated) interpersonal communication. Social connectedness is described as "*a short-term experience of belonging and relatedness, based on quantitative and qualitative social appraisals, and relationship salience*" (van Bel et al., 2009, p. 1). According to Janssen et al. (2014), social connectedness is one of the most important needs in interpersonal relationships. A feeling of connectedness increases both physical and psychological wellbeing (Cacioppo and Patrick, 2008), and reduces loneliness (Janssen et al., 2014). Although social connectedness strongly relates to concepts such as loneliness and belonging, it differs from these in the way it is experienced. Social connectedness focusses on short-term experiences, whereas loneliness and belongingness reflect longer-term affective states (Visser et al., 2011). It has also been observed that MST can induce feelings of connectedness toward other persons (Wang et al., 2012; van Erp and Toet, 2015). van Bel et al. (2009) identified two types of social connectedness. At the overall level, social connectedness relates to a persons' entire social network, while it relates to a particular person at the individual level. To measure the effect of MST technology on social connectedness between geographically separated romantic couples in the present study, we focus on social connectedness on the individual level. Based on prior observations that the use of MST can result in increased social connectedness (Visser et al., 2011), our first hypothesis is:

> Hypothesis 1: Geographically separated romantic couples will experience an enhanced feeling of social connectedness after using MST technology, compared to their feeling of social connectedness before using this technology.

The effect of MST on longing for touch was also investigated. Longing for touch can result from touch deprivation, and is described by Beßler et al. (2019) as a gap which is perceived when the frequency with which persons are being touched is lower than their touch wish. When a mediated touch is not recognized as unmediated social touch, MST cannot fulfill the need for touch and potentially alleviate the negative effects of touch deprivation. Moreover, MST could even enhance the desire for social touch if it makes the lack of 'real,' unmediated social touch more salient. Hence, our second hypothesis is:

> Hypothesis 2: After using MST technology, people that experience MST as interpersonal touch will experience less longing for touch, while people that do not experience MST as interpersonal touch will experience more or the same amount of longing for touch, than before using this technology.

In addition, some personal characteristics were measured that are known to influence the way people experience and respond to MST, like touch aversion, extraversion, and affinity with technology. For example, people who are touch aversive may experience relatively more negative consequences (such as anxiety) from MST compared to people who are not aversive to touch (Wilhelm et al., 2001). Another study, that compared mediated touch feedback to visual feedback, showed that more introverted people preferred touch feedback while more extravert people preferred visual feedback (van Erp and Toet, 2015). Lastly, people with low affinity for technology may experience mediated touch *via* MST technology more negatively than people with high affinity for technology (van Erp and Toet, 2015). These factors were taken into account in the design of the questionnaires used in the longitudinal study.

METHODS

Participants

In this explorative study, as many participants as possible were recruited in the time frame of the study. A total of $N = 17$ couples, each consisting of one male and one female (34 participants in total), took part in the study. The age of participants ranged from 21 to 43 years ($M = 26.82$, $SD = 4.96$). The duration of the romantic relationship of the couples in this study varied between 2 and 57 months ($M = 21.26$, $SD = 15.98$). The couples were recruited through various (social) media platforms (Facebook, Instagram, LinkedIn, Proefbunny.nl), as well as the TNO database of volunteers. Inclusion criteria were (1) being in a romantic relationship while (2) not living together with the partner, (3) between 18 and 65 years old, (4) preferably having iPhones, and (5) English proficiency. All participant couples enrolled in this study around the same time of the year, with the last couple starting participation 10 days after the first couple. During the study, there were no (major) differences in COVID-19 related restrictions or other external factors that could influence the convenience or frequency of couples physically interacting with each other. See **Supplementary Material J** for all the inclusion and exclusion criteria for participants. The experimental protocol was reviewed and approved by the TNO Internal Review Board (Approval Ref: 2021-040) and was in accordance with the Helsinki Declaration of 1975, as revised in 2013 (World Medical Association, 2013). Participation was voluntary. All participants received a financial compensation of at least €40 (+ €5 bonus when filling in at least 75% of all questionnaires in the study). All participants gave their (digital) consent and were debriefed at the end of the study about the goal of the study.

Materials

Hey Bracelets

The haptic devices used in this study are commercially available "Hey bracelets" (https://feelhey.com; see **Figure 1**). Hey bracelets are compatible with both Android and iOS devices and come with an app that allows bracelet pairs to be coupled *via* the internet. Users wear a Hey bracelet around their wrist. The bracelet uses internal sensors to detect when its surface is being touched. This touch is sent *via* Bluetooth from the bracelet to the Hey app running on the user's smartphone, which then transmits the touch *via* the internet to the Hey app running on the phone of a connected partner, which in turn activates the partner's bracelet. When activated, a Hey bracelet uses a 100 mA battery to power a small motor to pull part of the wristband into its casing. This contraction creates a squeezing sensation for the user. After the contraction, the motor loosens the wristband again until it has achieved its original position. Each time a 'touch' signal is sent, the sender receives a vibration in the bracelet as a confirmation that the touch was sent.

Before starting the experiment, the authors extensively tested the Hey bracelets with both Samsung (Android) and iPhone (iOS) smartphones. It was found that the haptic bracelets functioned more reliably when paired with smartphones running iOS as an operating system compared to the Android operating system. It appeared that the battery management protocols on Android devices sometimes compromise the connectivity of the Hey bracelets. This finding resulted in the recruitment of participant couples that predominantly used iPhones. To minimize potential technical issues, the bracelets were manually

FIGURE 1 | A pair of Hey bracelets.

updated to the latest firmware and fully charged before sending them to the participants.

Apps

Before using the haptic bracelets, participant couples were asked to install either two or three (depending on the operating system of their smartphones) apps for this study. These apps are described in the next sections.

Hey App

All participants installed the "Hey Bracelet" app on their smartphone (from Google's Play Store for Android phones and from Apple's App Store for iPhones). This app allows the bracelet to be connected to a mobile device *via* Bluetooth. The Hey app also enables two people to connect with each other *via* the internet through accounts with linked email addresses. In the "bracelet" tab of the Hey app, participants can see the status of their bracelet, such as the battery level and connection status. The connection status of a Hey bracelet is indicated by either a green dot (i.e., bracelet is connected to mobile phone *via* Bluetooth) or red dot (i.e., bracelet is not connected) in the upper right corner of the screen. *via* the "timeline" tab of the Hey app, participants can also (retrospectively) see when and from which location their partner sent them a 'touch.' Participants received a personalized password for this app before the start of the study and were asked to login with their personal email address. All these details (e.g., email-addresses, passwords) were deleted at the end of the study.

HowAmI App

All participants installed the "HowAmI" app (an app developed in-house by TNO, available from Google's Play Store and from Apple's App Store). This app allowed participants to fill in questionnaires on their mobile device. The questionnaires used in this study were implemented in the programming language JavaScript Object Notation (JSON; https://www.json.org/json-en.html). The scripts for the questionnaires were uploaded to a secure (GDPR compliant) TNO server, which was connected to the HowAmI app. Each participant received personalized login details (username and password) for this app before the start of the study. All user data was deleted at the end of the study and no other (third) party had access to these data during the study.

DontKillMyApp App

Participants using Android devices were also asked to install the "DontKillMyApp" app, which provides information about battery management protocols. These protocols, which are typically quite persistent on Android devices, can compromise the usability of the Hey and HowAmI apps, as thereby the functionality of the haptic bracelets. The DontKillMyApp app is designed to tackle these battery management protocols on Android phones by showing users how to change their settings. This way, each device was correctly set-up to work with the bracelets and with the apps involved in the current study.

Measures

Demographics

Prior to the experiment participants provided individual information (e.g., age, duration relationship, touch receptivity, personality, affinity for technology) through a first questionnaire that participants could fill in on the HowAmI app prior to receiving the bracelets (*Before Questions*).

Social Connectedness

To investigate whether the use of haptic bracelets enhances social connectedness among geographically separated romantic couples (Hypothesis 1), the individual version of the Social Connectedness Questionnaire (SCQ, van Bel et al., 2009) was applied. This scale contains 18 items that were rated on 7-point Likert scales: (1) *Completely disagree*, (2) *Disagree*, (3) *Somewhat disagree*, (4) *Neither agree nor disagree*, (5) *Somewhat agree*, (6) *Agree*, and (7) *Completely agree*. Social Connectedness is divided into five subscales/dimensions [relationship salience (RS), feelings of closeness (FC), shared understandings (SU), knowing each other's experiences (KE), and (dis)satisfaction with contact quality (CQ)], each with its own score. For this study, the "*X*" in the questions developed by van Bel et al. (2009) was replaced by "*my partner*." All items of the dimension "*dissatisfaction with contact quality*" were reversed before analysis to make a high score contribute to (higher) social connectedness. The reliability (Cronbach's α) of the overall questionnaire was $\alpha = 0.93$. The reliability (Cronbach's α) of the SCQ subscales were: RS, $\alpha = 0.84$; FC, $\alpha = 0.86$; SU, $\alpha = 0.82$; KE, $\alpha = 0.87$; CQ, $\alpha = 0.8$.

Longing for Touch

To investigate whether longing for touch (dependent variable in this study) differs after the use of the bracelets (Hypothesis 2), the Longing for Interpersonal Touch Questionnaire (LITPQ) by Beßler et al. (2019) was used. Although this questionnaire was designed for various types of communication partners, only the specific romantic partner subscale of this questionnaire was used in the current study. Participants filled in the number of touches they experienced over the last 2 weeks, as well as the number of touches they wanted to experience with numbers ranging between 0 and infinity. The LITPQ score was then calculated by dividing the touch wish by the touch frequency, where LITPQ score $> 1 =$ *longing for touch*, and LITPQ score $< 1 =$ *touch satisfied*.

Touch Avoidance

The Touch Avoidance Questionnaire (TAQ) by Ozolins and Sandberg (2009) was used to measure touch avoidance among participants. Only the questions specifically related to a (romantic) partner were used in this study (10 out of 37 questions total). Questions were answered on a 7-point Likert scale where (1) *Fully disagree*, (2) *Disagree*, (3) *Somewhat disagree*, (4) *Neither agree nor disagree*, (5) *Somewhat agree*, (6) *Agree*, and (7) *Fully agree*. Items 1, 5, and 6 were reversed before analysis to make a high score equivalent to a high level of touch avoidance. The reliability (Cronbach's α) of this questionnaire was $\alpha = 0.81$.

Affinity for Technology

The Affinity for Technology Interaction (ATI) by Franke et al. (2019) was used to measure affinity for technology among participants. This questionnaire has recently been assessed through psychometric validation and was shown to be unidimensional, highly reliable, and to have high construct validity (Lezhnina and Kismihók, 2020). The ATI contains nine questions in total and was scored on a 6-point Likert scale: (1) *Completely disagree*, (2) *Largely disagree*, (3) *Slightly disagree*, (4) *Slightly agree*, (5) *Largely agree*, and (6) *Completely agree*. Items 3, 6, and 8 were reversed before analysis since these items were negatively worded. The reliability (Cronbach's α) of this questionnaire was $\alpha = 0.88$.

Extraversion

To measure extraversion in this study, the Extraversion subscale of the International Personality Item Pool (IPIP) by Goldberg et al. (2006) was used. This questionnaire is based on earlier work by Goldberg (1992) and contains 10 questions in total. The questions were rated on a 5-point Likert scale: (1) *Very inaccurate*, (2) *Moderately inaccurate*, (3) *Neither accurate nor inaccurate*, (4) *Moderately accurate*, or (5) *Very accurate*. Items 2, 4, 6, 8, and 10 were reversed before analysis. The reliability (Cronbach's α) of this questionnaire was $\alpha = 0.88$.

Experimental Design

A within-subjects repeated measures design was used to evaluate the effects of the use of haptic bracelets on social connectedness and longing for touch among geographically separated romantic couples. *Social connectedness* and *longing for touch* were the two dependent variables in this study, while *time of measurement* (before/after using MST technology) was the independent variable. Connectedness and longing for touch were measured two times, once before using the bracelets (baseline measurement) and once after using the haptic bracelets. Individual user characteristics (e.g., affinity for technology, touch avoidance and extraversion) were measured as exploratory variables to explore their effect on the difference (post-score–pre-score) score of social connectedness.

Procedure

The questions were presented in a fixed order in this study and were divided into three parts: the *Before Questions*, the *Daily Questions,* and the *After Questions* (see **Table 1**). The *Before* and *After Questions* served to measure the dependent variables (e.g., social connectedness and longing for touch) and the individual characteristics of the study sample, whereas the *Daily Questions* served to stimulate the involvement of participants in the study, and to reveal potential patterns in the use of the bracelets among couples. All questions were answered by participants in the HowAmI app on their own mobile device. Note, that the *Daily Questions* will not be considered further here because they were not directly relevant to the hypotheses, and response rates to these questions varied strongly between couples (see Section Limitations).

Instructions

After signing up for the study, each participant received an email with instructions, an information document, and a digital informed consent form (see **Supplementary Materials L, M**). The instructional email informed participants that the experiment would take 2 weeks and that they could use the bracelets during this period in any way they liked. The primary goal of the study (the effects of haptic bracelets on social connectedness among couples) was not stated explicitly to avoid response bias. Instead, participants were informed that this was an explorative study into the use of haptic bracelets in a naturalistic field setting. Participants were asked to send back a signed version of the informed consent document and to confirm the address to which the bracelets should be mailed.

After returning their signed informed consent form, participants received an email with a confirmation that the bracelets were sent to them and with dedicated instructions for their particular mobile device, along with the bracelet manual, tips for using the bracelets, and login details for the Hey and HowAmI apps. Participants were also instructed to fill in the *Before Questions* before using the bracelets and each couple was given a "couple number" to pseudo-anonymize data before collection. Each couple was instructed to use the bracelets for 2 weeks, in any way (e.g., time and place) they liked, with the only requirement that they should actively use the bracelets during this period. Besides the instructions and information, participants were given the contact details of the experiment leader in case they encountered any problems, or if they had any questions before, during, or after the experiment.

TABLE 1 | Sequence of the three sections of questions as shown to participants in the HowAmI app.

Before questions	Daily questions	After questions
- Demographics - Duration Relationship - Social Connectedness (SCQ) - Longing for Touch (LITPQ) - Touch Avoidance (TAQ) - Affinity for Technology (ATI) - Extraversion (IPIP)	- Questions on use of the bracelet and physical interaction with partner	- Social Connectedness (SCQ) - Longing for Touch (LITPQ) - Explorative questions on the experience with and use of the haptic bracelets

After opening the HowAmI app for the first time, participants were shown an instructional text on the sequence of the questions and were again provided with the contact details of the experiment leader. When continuing, participants were presented with the *Before Questions* in the app and were asked to answer these questions.

Before Questions

The *Before Questions* were the first questions presented in the HowAmI app and contained questions that participants needed to fill in before using the haptic bracelets. The *Before Questions* were comprised of demographic questions and questions on social connectedness (van Bel et al., 2009), LITPQ (Beßler et al., 2019), TAQ (Ozolins and Sandberg, 2009), ATI (Franke et al., 2019), and IPIP (Goldberg et al., 2006). In this section, participants were also asked how long (in months) they had been in a relationship with their partner. The *Before Questions* served partly as a baseline measurement of social connectedness and longing for touch. This section contained a total of 63 questions and took around 9 min to fill in.

During the 2 Weeks of Testing

During the 14 days of the experiment, the participant leader contacted each couple at least once *via* telephone or email to ask if everything worked well (e.g., technical problems, filling in the questionnaires, etc.). This way, any potential technical issues could get tackled and at the same time participants were reminded to fill in the questionnaires. If participants had any questions or experienced any problems during these 2 weeks and reported those, the participant leader contacted them more than once. This applied to nearly half of all participant couples. This contact was done to keep the experienced burden for participants low, while keeping the involvement and response rate high.

After Questions

The *After Questions* were the last set of questions that participants needed to answer in the HowAmI app on their mobile device. These questions appeared 14 days after filling in the *Before Questions*, irrespective of the number of times participants answered the *Daily Questions*. The *After Questions* consisted of the Social Connectedness Questionnaire (van Bel et al., 2009), the Longing for Touch Picture Questionnaire (LITPQ: Beßler et al., 2019), and explorative questions on the experience with and use of the haptic bracelets (see **Supplementary Material G**). This section contained a total of 32 questions which took around 6 min to fill in. See **Table 1** for the order of the three sets of questions in the HowAmI app.

End of the Experiment

After filling in the last questionnaire in the HowAmI app (the *After Questions*) the participants received an email to thank them for their participation. This email also included instructions to send back the bracelets through the return envelope that they had received at the beginning of the study, as well as an invitation for a semi-structured interview about their experience with the bracelets. Out of 36 participants, 32 (16 couples) agreed to take part in the interview. Each interview took approximately 30 min. The interview data were used to gain deeper insight into the way participants had used the bracelets (or potentially would have wanted to use them) and to explore potential patterns in the use of MST technology (secondary goal of the study).

Data Processing and Analysis

Statistical Analysis

The quantitative data collected in this study was analyzed in IBM SPSS Statistics version 28.0 (www.ibm.com). Paired samples *t*-tests were conducted to investigate the effect of the use of MST technology for each couple on both *social connectedness* and *longing for touch*. Overall social connectedness per couple was calculated by averaging the scores of all 18 items per couple. Couples' scores on the subscales of social connectedness were calculated by averaging the aggregated scores of couples for each of the five subscales. Cohen's *d* (Cohen, 1988) was used to determine the magnitude of the effects found in this study. The individual scores for touch avoidance, affinity for technology, and extraversion were used to describe the current study sample, and to explore their relation to the social connectedness scores. Scatterplots and Pearson correlation coefficient (Pearson's *r*) were used to explore this relationship between participants' individual social connectedness scores and individual characteristics.

Thematic Analysis

For the analysis of the interview data, thematic analysis was used. The thematic analysis (TA) approach used here followed recommendations from Braun et al. (2018). The analysis aligns most closely with a 'reflexive thematic analysis' approach (Braun et al., 2018; Braun and Clarke, 2019) where meaning is considered to be contextual and where researcher subjectivity is viewed as an asset in interpreting the data. This is in contrast to approaches that are more aligned with quantitative philosophies of qualitative data analysis (e.g., such as in content analysis or coding reliability TA; see also Braun et al., 2018). In the current analysis, the researchers followed an inductive approach to theme development where the analysis started from the data and where the final themes are the output of the analysis procedures. Where this TA approach deviated from the typical reflexive TA, is in the fact that multiple authors contributed to coding and theme development (though, see Braun et al., 2018, p. 852 and further) discussion of the role of multiple authors in reflexive TA), not to reach consensus, but rather, to build on each other's perspectives to gain greater insight into the data.

Initial coding was done by MvH and codes were further refined independently by AT and GH. Discussions between the researchers served to develop an initial set of themes, which were outlined in a number of thematic maps to further discuss the constructed themes and their connections. Between the construction of subsequent and refined thematic maps, the researchers reread the data to continuously check the salience and fit of the themes with the data, and to check whether the themes captured patterns of meaning across the dataset. This way, an initial set of four themes was reduced to two main themes.

RESULTS

Social Connectedness

Social connectedness among 17 geographically separated couples was measured two times in the current study on a 7-point Likert scale: before and after using haptic bracelets. Potential answers on this scale ranged between 1 (i.e., low social connectedness) and 7 (i.e., high social connectedness). The obtained data was subsequently analyzed through a paired samples *t*-test ($\alpha = 0.05$). This analysis was repeated for each dimension of social connectedness [i.e., relationship salience (dis)satisfaction with contact quality, shared understandings, knowing each other's experiences, and feelings of closeness] to investigate whether some dimensions of social connectedness were more affected by the use of MST technology than others.

Overall Social Connectedness

In the current study, 34 participants (17 couples) rated a total of 18 questions on Social Connectedness. A statistically significant difference was found between couples' social connectedness scores after ($M = 5.67$, $SD = 0.64$) using MST technology than before ($M = 5.38$, $SD = 0.72$) using MST technology, 95% CI [−0.45, −0.13], $t_{(16)} = -3.77$, $p = 0.002$. Cohen's d for this paired samples *t*-test was −0.42, which can be described as a small to medium effect size. This finding supports the first hypothesis of this study: *Social connectedness among geographically separated romantic couples will increase after using MST technology compared to social connectedness before using MST technology.*

Relationship Salience

Seventeen couples rated a total of 4 questions on relationship salience (RS) as dimension of social connectedness. The salience scores obtained after using MST technology ($M = 5.77$, $SD = 0.62$) were significantly higher than the scores obtained before using this technology ($M = 5.29$, $SD = 0.77$), 95% CI [−0.74, −0.21], $t_{(16)} = -3.83$, $p = 0.001$. Cohen's d for this paired samples *t*-test was −0.69, which can be described as a large effect size.

(Dis)Satisfaction With Contact Quality

Thirty-four participants (17 couples) rated a total of 3 questions on dissatisfaction of contact quality (CQ) as a dimension of social connectedness. Before analysis, the scores on all items of this dimension were reversed to make high scores contribute more to overall social connectedness. A statistically significant increase was found in couples' CQ scores after ($M = 6.03$, $SD = 0.82$) compared to before ($M = 5.69$, $SD = 0.8$) using MST technology, 95% CI [−0.57, −0.11]; $t_{(16)} = -3.14$, $p = 0.006$, with a small to medium effect size, $d = -0.42$.

Shared Understandings

Seventeen couples rated a total of 3 questions on shared understandings (SU) as a dimension of social connectedness. No statistically significant difference was found between couples' SU scores before ($M = 5.32$, $SD = 0.76$) and after ($M = 5.51$, $SD = 0.79$) using the haptic bracelets, 95% CI [−0.43, 0.062]; $t_{(16)} = -1.59$, $p = 0.13$.

Knowing Each Other's Experiences

Thirty-four participants (17 couples) rated a total of 4 questions on knowing each other's experiences (KE) as a dimension of social connectedness. No statistically significant difference was found between couples' KE scores before ($M = 4.88$, $SD = 1.01$) and after ($M = 5.09$, $SD = 0.9$) using the haptic bracelets, 95% CI [−0.52, 0.91]; $t_{(16)} = -1.48$, $p = 0.16$.

Feelings of Closeness

Seventeen couples rated a total of 4 questions on feelings of closeness (FC) as a dimension of social connectedness. The couples' salience scores were significantly higher after using the MST technology ($M = 6.01$, $SD = 0.73$) than before ($M = 5.79$, $SD = 0.84$), 95% CI [−0.4, −0.23], $t_{(16)} = -2.38$, $p = 0.03$. Cohen's d for this paired samples *t*-test was −0.27, which can be described as a small effect size. **Figure 2** shows the mean scores of participant couples on overall social connectedness, relationship salience, contact quality, and feelings of closeness, before and after using MST technology.

Longing for Touch

A paired samples *t*-test ($\alpha = 0.05$) was used to compare the 17 couples' longing for touch (LITPQ) scores before and after using the haptic bracelets. All 34 participants were asked to report the number of touches (ranging from 0 to infinity) they received from their partner over a period of 2 weeks (touch frequency), as well as the number of touches they wanted to receive from their partners (touch wish). A LITPQ score was then obtained by dividing the touch wish by the touch frequency. Raw data showed that before using MST technology, 73.53% of all participants in the current study sample had a LITPQ score > 1, which indicates longing for touch. On the other hand, 8.82% of the participants had a LITPQ score < 1 (i.e., touch satisfied) and 17.65% had a LITPQ score of exactly 1 (i.e., touch wish and touch frequency were equal). After using MST technology for 2 weeks, 76.47% of all participants had a LITPQ score > 1, whereas 14.71% of participants had LITPQ scores < 1 and 8.82% had a LITPQ score of 1. Noteworthy was

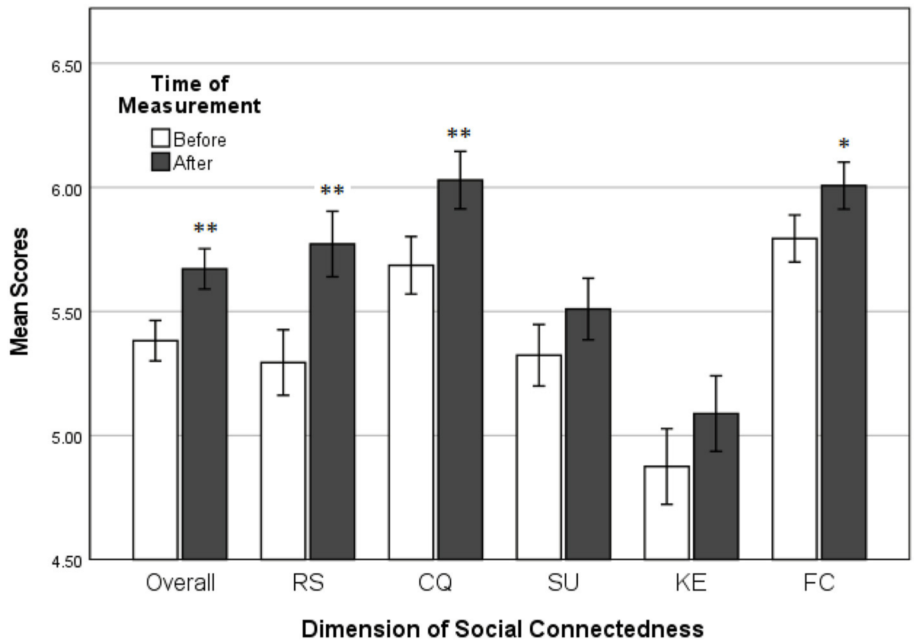

FIGURE 2 | The mean scores of couples on the Social Connectedness Questionnaire, as a function of time of measurement (before and after using MST technology). Answers ranged from 1 (low social connectedness) to 7 (high social connectedness). $\alpha = 0.05$. Couples' scores on all dimensions of the SCQ increased after 2 weeks of using MST technology. Significant increases are indicated by asterisks, where $*p < 0.05$; $**p < 0.01$.

that none of the participants experienced the signal of the Hey bracelet as interpersonal touch.

The Shapiro-Wilk statistic and normal Q-Q plots were used to test the assumption of normality. The assumption for a paired samples *t*-test was violated both these statistics. Moreover, descriptive statistics showed extreme LITPQ score values for four couples (couples 4, 7, 12, 13, all high outliers). First, the data for the LITPQ scores were logarithmically transformed (Log10) to control for these outliers. After the data was transformed, the LITPQ scores were still not normally distributed based on the Shapiro-Wilk statistic ($p < 0.05$) and normal Q-Q plots. After excluding the four couples with extreme LITPQ score values, the LITPQ data was normally distributed based on the Shapiro-Wilk statistic and normal Q-Q plots and there were no further outliers. For this trimmed data set ($N = 13$), there was no significant difference between the mean before ($M = 1.32$, $SD = 0.28$) and after LITPQ scores ($M = 1.57$, $SD = 0.64$), 95% CI [−0.55, 0.51]; $t_{(12)} = -1.807$, $p = 0.096$.

To assess the size and direction of the relationship between couples' social connectedness and longing for touch, Pearson's correlation analysis (Pearson's *r*) was executed. First, the difference scores (couples' post-score–pre-score) of both variables were calculated. Shapiro-Wilk tests suggested that scores were only normally distributed ($p < 0.05$) after excluding five (extreme) outliers (couples 4, 7, 9, 12, 13) from the original dataset of 17 couples. A Pearson's correlation analysis for this reduced dataset indicated that there was a weak, positive correlation between the difference scores of couples' social connectedness and longing for touch, $r_{(12)} = 0.12$, $p = 0.71$, n.s. The (non-significant) correlation is shown in **Supplementary Material P**.

Individual Characteristics

To assess the size and direction of the linear relationship between the individual characteristics and the difference scores of social connectedness (post-score–pre-score), bivariate Pearson correlation coefficients (Pearson's *r*) were calculated. The bivariate correlation between the difference scores of social connectedness and *touch avoidance* was negative and weak, $r_{(32)} = -0.19$, $p = 0.915$, n.s. The bivariate correlation between the difference scores of social connectedness and *affinity for technology* was negative and weak, $r_{(32)} = -0.127$, $p = 0.47$, n.s. The bivariate correlation between the difference scores of social connectedness and *extraversion* was negative and medium, $r_{(32)} = -0.39$, $p = 0.023$. The significant (negative) correlation between social connectedness and extraversion is shown below in **Figure 3**.

Thematic Analysis of Interviews

The two main themes that were generated through the TA are depicted in the final thematic map (see **Figure 4**). The two main themes relate to participants' accounts of their use of the haptic bracelets during the study: (1) *The haptic bracelet fosters a positive one-to-one connection with the partner*; and (2) *Working around frustrations as part of the study*. The first main theme has three subthemes, the second main theme has two subthemes.

The quotes that are used from the data were translated from Dutch into English. All original quotes can be found in the

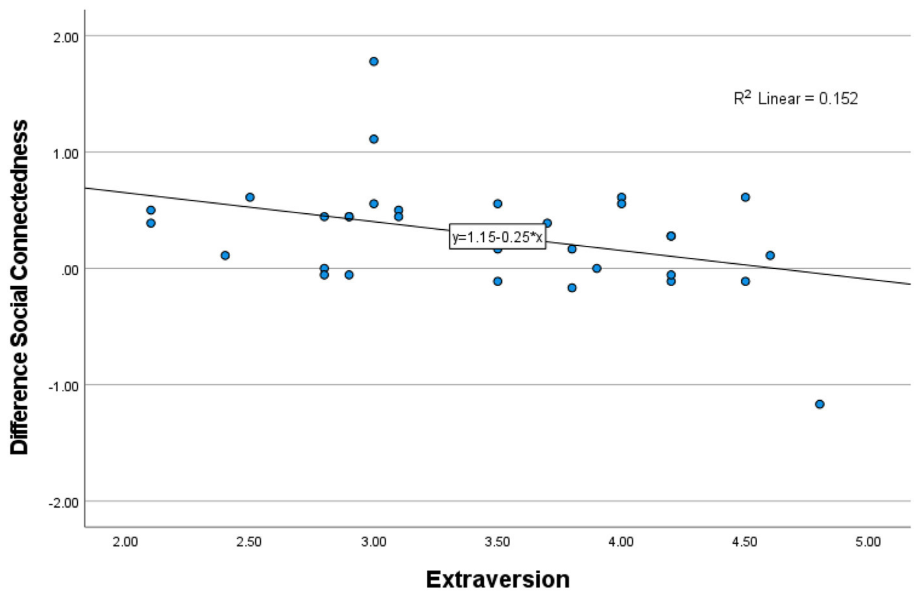

FIGURE 3 | Participants' difference scores of overall Social Connectedness (post-score–pre-score), as a function of extraversion. The bivariate correlation was negative, with a medium effect size, $p = 0.023$.

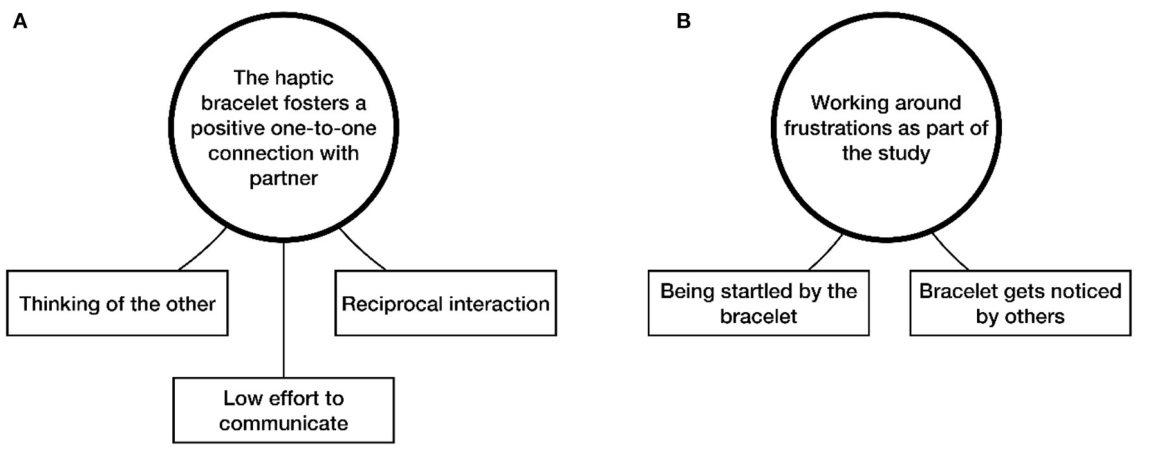

FIGURE 4 | Final thematic map, showing the two main themes derived from thematic analysis. **(A)** The first main theme with its three subthemes and **(B)** the second main theme and its two subthemes.

Supplementary Material R. Names, as well as place names are anonymized ("NAME" and "CITY," respectively) in the quotes. Quotes are labeled per couple number and participant number within the couple (either 1 or 2).

Theme 1: The Haptic Bracelet Fosters a Positive One-to-One Connection With Partner

The first main theme *The haptic bracelet fosters a positive one-to-one connection with partner* captures how participants talked about the use of the haptic bracelet as enabling them to establish a one-to-one connection with their partner. Communication through the bracelets was meaningful for participants because they knew the signal came from their partner, and not because it was a physical signal (i.e., haptic feedback) *per se*. Some participants explicitly described this one-to-one connection in their accounts of the use of the bracelets:

"*I was very aware of wearing the bracelet and what happens at the moment it activates, so I couldn't really compare it to real touch. However, the thought behind it is what makes it nice, that I know that she did it, that she sent it, so it is more the contact that you have. It is what is behind it that makes it nice for me*." (Couple 18, PP2)

"*Yes, I have to say because you know that the touch comes from your partner, that is how you imagine it is a touch*." (Couple 1, PP1)

"*Also, the fact that you know that no-one else does this. Your phone can vibrate because of someone else. Here, you just know for sure that it was NAME. That is a nice feeling*." (Couple 3, PP2)

Here, participants explicitly referred to how they interpreted the received signal and the fact that it represents a direct connection with their partner that makes it meaningful for them. For other participants, this one-to-one connection with their partner was implied in their description of the use of the haptic bracelets. For some, being separated from their partner by physical distance brought this notion of connection more to the surface:

"*Yes, and definitely also because normally during the period that we used the bracelets he was a lot in CITY1 and I was a lot in CITY2, so you really miss each other and you miss being able to hug each other or give each other a kiss every now and again. And this was a way to still feel close. The first time I didn't wear it after the study I was totally like, 'now what'?*" (Couple 11, PP1)

Participants who implicitly or explicitly referred to the one-to-one connection with their partner often saw this as representing a way of 'thinking of the other.' This subtheme had very high prevalence in the data. Virtually all couples at one point or another mentioned that 'thinking of' was what the interaction through the bracelets meant to them:

"*For me, it didn't just mean 'I am here' but especially 'I am thinking of you'. She knows I am thinking of her, that I am preoccupied with her rather than myself. I think that that is very nice. If someone takes the time in between everything else, no matter how busy your day is, to send 'I am thinking of you'. Nothing more. I think that that is very, very nice*." (Couple 18, PP2)

Interestingly, there were no clear mentions of using the bracelets for more complex or elaborate ways of encoding messages (e.g., two squeezes means 'I love you'). With this it would seem the bracelets served as a way to enhance feelings of social connectedness (van Bel et al., 2009), rather than serve as a tactile communication device *per se* (Haans and IJsselsteijn, 2006):

"*In the beginning I was thinking; NAME has sent a touch so I send it back, but of course it is not some kind of Morse code, or visible communication. At one moment you quit doing that and it is more during moments that you think of the other that you send a touch*." (Couple 17, PP2)

"*I don't actually connect it to touch that much. For me it was more, for example, when I woke up and NAME sent me a touch I thought 'my partner is thinking of me, that's nice' and not a touch per se*." (Couple 10, PP1)

In some instances, it was not just the notion that when a touch was received that participants felt that this represented their partner thinking of them. In some cases, they would actively demand or request that their partner think of them by sending a touch signal themselves:

"*I especially appreciated it when I was feeling down that you can ask for attention by sending [a haptic signal], like 'I just need some attention from you right now'*." (Couple 11, PP1)

"*I actually felt like receiving a touch, but I didn't get one. So then I would send one myself and get one back. Kind of like asking for attention*" (Couple 6, PP2)

This idea of 'demanding attention' connects with the fact that in most cases the sending of a haptic signal also resulted in receiving a signal in return, and vice versa. In other words, often, the interaction was reciprocal, involving a back-and-forth of sending and receiving the haptic signals. This was not just the case when participants would 'demand attention,' but also more generally, participants expressed that they felt that it would be strange not to send a haptic signal back when receiving such a signal themselves:

"*Nine out of ten times I would send one back*." (Couple 3, PP1)

"*It felt very weird not to send one back*." (Couple 9, PP1)

Participants actively considered the reciprocal nature of the interaction in the one-to-one connection that the bracelets enabled, and this impacted the way they would use their bracelet. One participant captured the way that the subthemes of 'thinking of' and reciprocity of the interaction relate to each other as follows:

"*Sometimes I wanted to let him know that I was thinking of him and at other times I wanted attention myself. I would wish he would send me something, so then I would send him a touch and then I hoped he would send something back. I noticed that I found it difficult if that did not happen, because I really wanted to receive something back. But perhaps someone is busy at that moment*." (Couple 16, PP1)

The fact that it did not take a lot of effort to communicate with one's partner, was a final element that had high prevalence in the data and that was important to the fostering of a positive one-to-one connection through the haptic bracelets. Many participants described how the haptic bracelets allowed for a simpler or more direct interaction compared to, say, smartphone messaging services or video chat:

"*The moment that you are thinking of someone, you don't have to look at your phone or anything. So that kind of ease-of-use is there*." (Couple 12, PP2)

"*I thought it was quite useful when you don't have the time to write a message, because you have to think more about writing a message. You can just put your hand on the bracelet to let someone know you are thinking of them. I thought that was a really nice added value*." (Couple 16, PP1)

One participant likened this low-effort way of communicating to functionalities on a popular social media platform:

"*Better than a like on Facebook*." (Couple 16, PP2)

The low-effort, simple, and more direct interaction through the haptic bracelets was especially appreciated by participants because it would allow for the one-to-one connection to be maintained even in situations where other forms of mediated communication would be more difficult to use. Examples provided by participants of such situations include being busy at work, or being in the company of other people:

> "*When I don't have time to send a text message, or if I'm busy at work. I work with people, with guests, and so I cannot really pick up my phone then. In those situations, sending a touch is just a little easier than sending a text message*." (Couple 5, PP1)

> "*No, I don't just pick up my phone to send a text message. It is much easier to just put your hand [on the bracelet]. You could also just do that while talking with someone. You could sneakily put your hand on your wrist*." (Couple 3, PP2)

Descriptions of the use of the bracelet in combination with other media, such as text messaging, was also predominant in the data. However, use of other media was most often discussed in such a way that the bracelet served as a low effort way to maintain the one-to-one connection with the partner. Text messaging was then sometimes used to write a more elaborate message, or to check-in with the partner when a touch was not reciprocated.

To summarize, the first main theme captures how participants, implicitly or explicitly, talked about their use of the bracelet as fostering a positive one-to-one connection with their partner. The haptic bracelets were not so much used for haptic messaging, but mainly served as a low-key way to let the other know *'I'm thinking of you'*. Most participants when sending a haptic signal expected to receive a signal back from their partner. Conversely, when receiving a signal, participants described how they felt obligated to respond. The fact that the bracelet could be used without reaching for one's phone was experienced as positive by participants and influenced the way the bracelets were used in situations such as during work or when being with other people.

Theme 2: Working Around Frustrations as Part of the Study

The second main theme *Working around frustrations as part of the study* captures how the use of the haptic bracelets also led to annoyances or frustrations for participants. In the data there was a high prevalence of remarks pertaining to such frustrations with the use of the bracelets. However, while participants expressed their frustrations, in almost all cases they also detailed how they found ways to work around these frustrations. The researchers see this as stemming from the fact that participants were well aware that they were taking part in a study and did not want to drop out or disappoint the researchers. Some participants mentioned this literally:

> "*At one moment it almost become a burden to start using [the bracelet] because we were having issues with the Bluetooth connection. But, of course, we also kind of did it for you. We knew we were part of a study so that lead to the use [of the bracelets] becoming a bit messy*." (Couple 16, PP1)

Not all participants explicitly described being part of the study as the underlying reason for finding solutions to the problems they encountered, despite experiencing frustration. Nearly all participants exhibited an attitude of 'let's make this work.' This attitude was apparent in many descriptions and for many issues that participants encountered, including Bluetooth connectivity issues, issues with the bracelet falling off of participants' wrists, accidentally sent touches, and excessive noise production by the bracelets. While the experienced issues as sources of frustration may have been diverse, the attitude of working around the frustrations was shared by most participants. This attitude also encompassed ways in which participants made sense of the interaction despite issues arising, such as in relation to receiving accidental touches:

> "*I didn't mind [accidental touches] so much. At a certain moment I started taking it into account. Sometimes you receive one [intended] touch and at other times you receive many accidental touches, but do you know what? For me that one [intended] touch still outweighed the other nine that were perhaps accidental because there was contact in that one moment, it's not like the bracelet is on the table sending touches on its own."* (Couple 18, PP2).

One specific frustration with high prevalence in the data that participants described finding ways to deal with, relates to the fact that the activation of the bracelet startled them, in one particular case to the extent that it led to spilling coffee:

> "*Every time [the bracelet] went off it startled me badly. On the first day I spilled a cup of coffee over my keyboard because I was so startled*." (Couple 18, PP1)

Similar remarks of being startled by the bracelet activating were made by other participants. In most cases participants ascribed this to a combination of the sound produced by the bracelet as well as the unexpected nature and unfamiliar feeling of the activation. Here, the novelty of the device and the lack of experience with similar types of haptic communication devices prior to this study, most likely contributed to the startling reactions to the bracelet activating. In all cases, however, participants adopted an attitude of 'dealing with it,' which in this case meant a conscious process of familiarization and acclimatization (i.e., being conscious of the time it takes to get used to the bracelet activating):

> "*There were a few times where [the bracelet] really startled me. It has a kind of silent mode, but it took a few days for me to discover that. I did wear it to work and even during some meetings it really startled me when that thing went off. After a while you get used to it, and you think 'oh, it's that app', but the sound volume and the unexpectedness of it are a bit strange still*." (Couple 17, PP2)

This conscious effort also meant that when being startled by the bracelet, even when only a little, participants were taken out of their concentration or briefly distracted from other things that they were doing. This was described as a related, minor annoyance:

> "*When I'm fully absorbed in something I really want to focus and if that thing [the bracelet] then activates, I'm startled by it. You're all like 'hold on'. It is not for very long, but it does take some time to get back to what you were doing before.*" (Couple 3, PP1)

Related to this discussion of being startled by the bracelet was the fact that participants commented on other people present in the same space noticing the bracelet activating. In a few cases this was in relation to the wearer of the bracelet also being startled, but most often frustration with the bracelet and ways of working around this frustration, related to the notion of others noticing the bracelet. Examples given by participants of how others noticed the bracelet describe the size of the device, and, with high prevalence, the sound produced by the bracelet's activation. Depending on the situation, this led to more or less frustration experienced by participants. A clear way of working around this issue that many participants discussed was strategically deciding when not to wear the bracelet in situations where it could be noticed by others. For example, participants described it as being unprofessional when the bracelet activation would be noticed by others during a meeting, even during online meetings:

> "*I wouldn't wear it during video calls, which is something you now do often for your studies. I wouldn't wear it because it would make a sound. If you're in a professional setting with your teacher and you hear that sound; no, I didn't use it then.*" (Couple 1, PP1)

> "*I would take it off when I was in a meeting. That was more because I was thinking 'if it would go off now that would be awkward'.*" (Couple 4, PP2)

> "*If I'm honest, it was really awkward with some people, some colleagues.*" (Couple 3, PP1)

The sound produced by the bracelet upon activation was a major factor in others noticing the bracelet and in subsequent feelings of unease experienced by participants. One participant expressed this by explaining how they were aware of others staring:

> "*The sound the bracelets produce is not very discrete. When you're in a room with other people, everybody there also knows when you receive a touch. Everyone would be staring.*" (Couple 2, PP1).

From these accounts by participants, it can be seen that the bracelet did not just play a role as a mediating device between both partners, but that it was also a part of other social interactions, although, with more negative connotations. The fact that participants actively worked around the bracelet getting noticed by others shows that it was not properly embedded in existing social structures but that it, instead, had a disruptive effect. Again, the researchers would argue that the willingness of participants to work around this disruption is largely due to the fact that they were aware of being part of a study. The researchers also remark that haptic devices for social communication, such as the haptic bracelets used in this study, should not only be considered from the perspective of remote communication, but should be viewed within a larger context of social interactions that occur during the use of such devices.

To summarize, the second main theme captures how participants described diverse sources of frustration with the bracelets (including frustrations originating from technical issues) but that they, in nearly all cases, exhibited a willingness to work around their frustrations because they were aware of being part of a study. The initial novelty of the device combined with the sound production and unfamiliar squeezing sensation, meant that several participants were startled by the bracelet activating. Here, their remarks show a process of "*getting used to*" the bracelets. In addition, participants shared their frustrations with the bracelet when it was noticed by others and participants would work around this by strategically deciding when and where not to wear the bracelet.

DISCUSSION AND CONCLUSION

The hypotheses of this longitudinal explorative field study were (1) Geographically separated romantic couples will experience an enhanced feeling of social connectedness after using MST technology, compared to their feeling of social connectedness before using this technology, and (2) After using MST technology, people that experience MST as interpersonal touch will experience less longing for touch, while people that do not experience MST as interpersonal touch will experience more or the same amount of longing for touch, than before using this technology. The results show that the use of haptic bracelets (1) enhanced social connectedness among geographically separated couples but (2) did not affect their longing for touch. Interviews conducted at the end of the study were analyzed by way of (reflexive) thematic analysis to generate two main themes (each with their own subthemes), reflecting the way participants talked about their use of MST technology during the study. These themes were (a) The haptic bracelet fostered a positive one-to-one connection with a romantic partner; and (b) Participants were willing to work around frustrations as part of the study. In the rest of this section, the findings and limitations of this study will be discussed in further detail, and suggestions will be made for future research.

Social Connectedness

In agreement with our first hypothesis, the geographically separated romantic couples that participated in this study reported a significant increase of overall social connectedness levels after using the haptic bracelets in daily life for a period of 2 weeks. This result is also in line with similar findings from studies that were performed for a briefer period and in restricted (laboratory) conditions (Visser et al., 2011; Park et al., 2013; van Erp and Toet, 2015; Price et al., 2022).

The effects of the haptic bracelets were investigated on all five dimensions or subscales of social connectedness. This analysis showed that *relationship salience* increased significantly (with a large effect size) after using the haptic bracelets. This finding agrees with the results of Visser et al. (2011), who noticed increased levels of relationship salience after using a social awareness system called SnowGlobe. Relationship salience entails how prominent a relationship is in a persons' mind (Visser et al., 2011). In the current study, communicating 'touches' *via* the haptic bracelets in addition to other ways of communication [e.g., (video-) calling, texting], may have reminded participants more frequently of their mutual relationship (thereby increasing its salience). This explanation aligns well with the first main theme of the TA, which describes the bracelets as fostering a one-to-one connection between the partners. Participants often remarked how they used the bracelets as a way to signal to their partners that they were thinking of them. Conversely, they also often stated that they interpreted the reception of a haptic signal as a sign that their partner was thinking of them.

Furthermore, a significant increase in *feelings of closeness* (as a dimension of social connectedness) was found among couples after using MST technology. Feelings of closeness entails the social presence of another person in one's mind (Visser et al., 2011). Like the increase in salience, this significant increase in closeness is also consistent with prior research (Visser et al., 2011), and may stem from the way the haptic bracelets were used in this study: the use of MST technology in addition to the existing communication channels of couples [such as (video-)calling] may have increased the perceived social presence of a partner (thereby increasing feelings of closeness). Lab-based research by Price et al. (2022) indeed indicates that MST technology can contribute to a feeling of 'tactile presence' where the technology signals that the other 'is there.' Again, this aligns closely with results of the TA, in particular the first main theme.

Although a significant increase in both dimensions after using MST technology was observed, the increase in closeness had a small effect size, whereas the increase in salience had a large effect size. This difference may be related to the baseline levels of the average scores on these two subscales of social connectedness: the average scores on *feelings of closeness* were higher (5.79 on a 7-point Likert scale) than the *relationship salience* scores (5.29) before using MST technology. MST probably does not contribute strongly to *feelings of closeness* between the dyads that already experience high levels of closeness. Future studies should investigate the effect of (similar) MST technology on these dimensions of social connectedness among dyads with other relationships (not romantic; friends or acquaintances).

Satisfaction with contact quality (CQ), as subscale of social connectedness, also showed a significant increase (with a small to medium effect size) after using MST technology. Asking (*After Questions*) the participants how the haptic bracelets fit in their other ways of communication (see **Supplementary Material G**), 75% of all participants rated them as complementary. On the other hand, 21.9% of all participant found the bracelets not adding anything to existing communication, and 3.1% thought the bracelets could replace their existing ways of communication. This illustrates that the majority of participants in this study think this form of MST technology compliments their other ways of communication, instead of seeing this technology as a replacement or that it has no added value. One subtheme in the first main theme from the TA outlines how the bracelets were mainly described as a low-effort way to communicate in comparison to other technologies. Participants described how this enabled them to stay connected in situations where, for example, using their smartphone was more difficult (e.g., while being busy at work). In these situations, as mentioned by participants, the bracelets complemented their use of other technologies and media.

Analyses of the other two subscales of social connectedness, *knowing each other's experience* (KE) and *shared understandings* (SU), showed no significant difference between couples' scores before and after using MST technology. These findings may be explained by the specific MST technology (haptic bracelets) used in this study. This MST technology was tested in isolation, without any other (mediated) sensory input. Moreover, the haptic bracelets only conveyed a single bit of communicative information, which was a mediated touch signal giving a squeezing sensation. As Kaye (2006) argued, a low bandwidth signal (such as produced by the haptic bracelets) leaves a lot of room for interpretation within pre-existing relationships. At the same time, the bracelets' signal does not convey the experiences or understandings of another person. As such, KE and SU may not be affected by MST technology when implemented in an isolated fashion, and perhaps a more multimodal approach of testing this kind of technology (e.g., combined with mediated audio/visual cues) may influence these dimensions of social connectedness. Work by Price et al. (2022) underscores this notion and illustrates how multimodal *haptic* signals (e.g., temperature) could also play a role here. Still, the *thinking of the other* subtheme from the TA illustrates how, even with a low-bandwidth signal, and lack of other (haptic) modalities, participants ascribed specific meaning to receiving a haptic signal through the bracelets and had specific intentions when sending signals.

What can be concluded from this study is that overall social connectedness among geographically separated romantic couples increased after using MST technology, and that the dimensions contributing most to this increase were relationship salience, feelings of closeness, and contact quality. As such, the first hypothesis of this study (*Geographically separated romantic couples will experience an enhanced feeling of social connectedness after using MST technology, compared to their feeling of social connectedness before using this technology*) was supported.

Longing for Touch

Analysis of the scores on the Longing for Touch Picture Questionnaire (LITPQ, Beßler et al., 2019) showed no difference in longing for touch among geographically separated couples before and after using MST technology for 2 weeks. More specifically, after deleting outliers (4 couples) from the total dataset to correct for the violation of normality, no difference was found in the average LITPQ scores among 13 couples before and after using the haptic bracelets. This finding is consistent with the distribution of participants that experienced longing for touch (by having a LITPQ score > 1) across the different times of measurement in this study. Nearly 80% of all participants indicated longing for touch before using the haptic bracelets, as their touch wish outweighed their experienced touch. Although LITPQ scores changed for some participants after using MST technology, the percentage of participants with LITPQ scores > 1 remained nearly identical after using the bracelets (73.5% before vs. 76.5% after), indicating no significant change in longing for touch among participant couples.

What should be noted is that there was high variability across the LITPQ scores of couples, and the distribution of scores was not normally distributed among the 17 participant couples. After deleting the most extreme outliers, the LITPQ was normally distributed. A potential explanation for the high variability in LITPQ data is the way in which the LITPQ is scored by participants: the possible answers that could be given on the amount of wished and experienced touches were between 0 and infinity. Furthermore, the LITPQ is fairly recently developed (in 2020) and thus the instrument has not been elaborately validated yet. However, as prior research indicated, there is only a limited number of validated instruments that aim to measure a lack of touch (Punyanunt-Carter and Wrench, 2009). The Longing For Touch Picture Questionnaire (LITPQ, Beßler et al., 2019) was specifically chosen for this study due to the addition of the specific partner subscale within the questionnaire. Other instruments, such as the Touch Deprivation Scale (Punyanunt-Carter and Wrench, 2009), do not include specific questions or sections relating to measuring touch deprivation among (romantic) dyads. As such, the LITPQ seemed a more viable instrument to utilize in the current study.

Furthermore, questions at the end of the study (*After Questions*) revealed that none of the participants experienced the signal (squeeze) of the haptic bracelets as interpersonal touch. This finding agrees with other recent studies that found that mediated touch is typically not experienced as unmediated social touch (Ipakchian Askari et al., 2020a; Jewitt et al., 2020). Again, this aligns with the first main theme and subthemes of the TA. Participants described the use of the bracelets more as a low-effort way to signal to the other that they are thinking of them. No clear mentions of the bracelets actually being used as a mediated social *touch* device were present in the interview data.

Both the analysis of the LITPQ data and the fact that participants did not recognize the haptic bracelets' signal as interpersonal touch suggest that longing for touch among geographically separated couples is not affected by the use of haptic bracelets as MST technology. Thus, hypothesis 2 (*After using MST technology, people that experience MST as* interpersonal *touch will experience less longing for touch, while people that do not experience MST as* interpersonal *touch will experience more or the same amount of longing for touch, than before using this technology*) was not supported.

Individual Characteristics

Analyses of the individual characteristics data showed that, on average, the current study sample scored relatively low on *touch avoidance* (1.93 on a 7-point Likert scale), high on *affinity for technology* (4.11 on a 6-point Likert scale), and above average on *extraversion* (3.44 on a 5-point Likert scale, indicating more extraverted than introverted characteristics within participants). These findings may be explained by the recruitment protocol of the study, as a specific sample was recruited (e.g., couples not living together and both preferably having iPhones). The recruitment flier (see **Supplementary Material K**) and information document (see **Supplementary Material L**) may have attracted couples that already scored low on touch avoidance (especially related to partner-specific touch) and high on affinity for technology (as the flier and other information indicated working with a new technology for 2 weeks). It seems likely that people with these traits are more inclined to (voluntary) participate in a study that involves touch and technology. The fact that participants scored relatively high on *affinity for technology* could explain the high prevalence of remarks in the interviews that in the TA were taken as an attitude of *working around frustrations* (the second main theme). Their interest in technology could mean that participants were more eager to figure out how to make the bracelets work properly during the study.

Explorative scatterplots and correlations of participants' individual characteristics and social connectedness scores revealed a significant negative correlation between overall social connectedness and extraversion. This may indicate that more introverted participants had a bigger increase in social connectedness after using MST technology, compared to more extraverted participants in the present study. This effect is similar to findings in prior research on MST (Erk et al., 2015). Correlations between participants' overall social connectedness scores and touch avoidance/affinity for technology did not yield significant results. A potential explanation for these results may again be found in the sample of the present study. The effects of MST technology were observed for dyads in a romantic relationship, while non-romantic dyads have not been tested. The interpretation of mediated touch may be less (negatively) affected by high touch avoidance or low levels of affinity for technology among romantic dyads, compared to non-romantic dyads (Rantala et al., 2013; Suvilehto et al., 2015).

Limitations

A major limitation of this study were the technical problems that a majority of participants experienced, to a more or lesser extent, when using the haptic bracelets. Even though the haptic bracelets were elaborately tested before the start of the study, and several instructions and tips were drawn up specifically tailored to the phones of participants, these issues still persisted. Overall, nearly 15% of all participants needed to receive a new bracelet over the course of the study due to technical issues. The problems that participants encountered can largely be divided into two categories: either 'touches' were sent unintentionally (e.g., touches were sent when sitting with arms crossed), or intentionally sent touches were not physically received by the partner. The latter issue was mainly caused by cessation of the Bluetooth connection between the Hey bracelet and mobile phones of participants. See **Supplementary Material O** for a summary of the feedback of participants on the bracelets in the current study.

These technical issues also led to the generation of a main theme in the TA capturing how participants adopted an attitude of working around their frustrations with the bracelets. As outlined in the TA, there were several technical issues that contributed to participants experiencing frustrations and finding ways to deal with those frustrations by changing their use of the bracelets, at least in part, because they were well-aware of being part of an ongoing study. From this, it is clear that the technical issues had a significant impact on the use of the bracelets (e.g., strategically deciding when not to wear the bracelets) within the scope of the study and, thus, the results reported here should be interpreted with this in mind. It could also be that the fact that the bracelets did not function flawlessly resulted in participants having more frequent contact through other means to resolve the issues with the bracelets. Though there was not a high prevalence of remarks to this effect in the interview data, it could still be that this increase in contact could potentially have affected participants' ratings on social connectedness.

Prior research has struggled with reporting quantitative data in longitudinal studies due to high percentages (>30%) of missing data (Visser et al., 2011). This was also the case in the present study. Although the before and after questions were completed by all 17 couples (34 participants), the current study struggled with receiving participants' answers on the daily questionnaires (nearly 40% missing data). While the daily questions were specifically designed to be easy to answer, participants apparently still struggled with answering them consistently. Part of this could be contributed, again, to technical issues experienced by the participants. Open-ended feedback in the explorative questions revealed that some participants did not want to answer the daily questions in the HowAmI app on days when the bracelets did not function properly.

Another limitation of the current study lies in the study sample. Initially, the aim was to recruit 20 couples. However, recruitment was challenging due to the strict recruitment criteria (see **Supplementary Material J**). Ultimately, as many participants were recruited as possible in the time frame of this study. In total, 18 couples participated in this study and analyses were conducted on a sample of 17 couples (one couple withdrew participation halfway through the study). Ideally this sample should be higher in order to increase statistical power, especially when using a between-subjects design to compare an experimental group to a control group. Also, a control group (either wearing passive bands or using a non-tactile communication device with a similar low bandwidth) is needed to confirm that the increase in social connectedness is a result of the use of the MST technology and not a side effect of the study *per se*. Moreover, the specific study sample used in this study (e.g., couples not living together, both with specific mobile devices) makes it harder to generalize the results of this study to a general population.

Lastly, another limitation of this study is related to the Longing for Interpersonal Touch Picture Questionnaire (LITPQ: Beßler et al., 2019). Variability was high in the longing for touch data among participant couples. As stated earlier, this may be explained by the way the questionnaire is scored (between 0 and infinity). Another reason may be that the LITPQ is a fairly new instrument (developed in 2020) and (further) validation of the questionnaire is needed in order to obtain consistent data with less variability.

Future Research

The majority of research in the field of MST technology has been conducted in lab settings (van Erp and Toet, 2015; Eid and Al Osman, 2016; Huisman, 2017). The study reported here is an exception in that it is a longitudinal field study that aimed to provide insights into the actual use of MST and potential effects of extended use of this technology on social connectedness and longing for touch. Despite the limitations of the present study, it is to the best of our knowledge the only one that investigated the use of MST technology in a natural setting over a longer period of time. Participants were free to use the technology as they saw fit. This approaches a more naturalistic setting for the application of MST technology and future studies of this kind may help to shed more light on the use of MST technology. More specifically, future studies may focus on comparing different groups (e.g., homogenic and heterogenic couples, using MST technology or not, etc.) and be longitudinal (i.e., longer than 2 weeks) in nature to control for potential novelty effects when first using new MST devices. Since none of the participants in the current study interpreted the haptic bracelets' signal as interpersonal touch, it may also be interesting to observe whether the effects on connectedness and longing for touch are the same when mediated touch is indeed experienced as interpersonal touch.

Furthermore, replication of the results reported here is needed, given the limitations and scope of the present study. Mediated touch should ideally counteract the negative consequences of touch deprivation (and ultimately convey the advantageous effects of real, unmediated social touch). As van Erp and Toet (2015) suggested: mediated social touch must preferably be understood without diminishment of effectiveness and user gratification. The findings of this study suggest that geographically separated romantic couples feel more socially connected through the use of haptic bracelets in a naturalistic setting. However, it may be interesting to see whether a similar effect can be replicated for non-romantic dyads (e.g., friends, acquaintances, strangers). When these effects can be reproduced and supported by the use of a control group, MST technology can potentially be practically implemented in settings where touch is scarce or particularly beneficial (e.g., nursing homes or therapeutic settings).

In addition, mediated social touch is highly contextual (Eid and Al Osman, 2016; Huisman, 2017). The integration of MST technology in a multimodal way (i.e., combined with other sensory input), as well as the addition of options such as warmth and other forms of touch (e.g., stroking), and the application to different body locations may be promising directions for further MST research. When measuring social connectedness and its dimensions, it may be interesting to see how a multimodal approach influences these measures.

Finally, related to the multimodal context that is relevant to MST technology, the embedding of such technology in existing socio-technical landscapes also deserves further scrutiny. The study of MST in naturalistic settings should not only focus on the technology as it is relevant to the communication between, say, couples, but also needs to consider the fact that such technology is used in a broader spectrum of other technologies and media that are already used. As an example, the TA reported here highlighted how the bracelets were used as a low-effort way to say "*I'm thinking of you*," which complimented the use of other technologies, such as texting. Moreover, MST technologies may also be used during ongoing social interactions in existing social structures, such as meetings in an office. The way MST technologies are situated in such interactions and structures needs to be further investigated. For example, the TA indicated how others noticing the bracelets (e.g., noticing the sound production by the bracelets during a face-to-face meeting) impacted participants' use of the bracelets. Such factors need to be considered in studies of MST technologies in naturalistic settings.

CONCLUSION

In this longitudinal explorative field study, the effects of daily use of MST were investigated during a two-week period on social connectedness and longing for touch among geographically separated romantic couples. The results show that overall social connectedness levels (and specifically the dimensions of *relationship salience*, *feelings of closeness*, and *contact quality*) significantly increased after using MST technology for 2 weeks. Couples' *longing for touch* scores were not significantly different before and after using the bracelets. Furthermore, two main themes were generated from the post-study interview data by way of (reflexive) TA: (a) The haptic bracelet fosters a positive one-to-one connection with partner; (b) Working around frustrations as part of the study. These themes shed further light on the quantitative results. While the increase in social connectedness observed in this study is in line with prior findings in MST research, some caution has to be taken with the interpretation of the results due to technical issues impacting the use of the bracelets. Future research could aim to replicate the findings reported here and also investigate the longitudinal effects of MST technology in different realistic contexts, for different (non-romantic) relationships, and possibly include other sensory modalities like sound, vision or even smell, in line with a multisensory approach. Whether or not this leads to remote interactions that are "*better than a like on Facebook*" remains to be seen.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by TNO Internal Review Board. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

MH conceived the original idea, performed the experiments, analyzed the data, and wrote the initial draft paper. MH, GH, and AT conducted the interviews and performed the thematic analysis. JE critically reviewed the draft manuscript. All authors were actively involved in the revisions of the original drafts and in writing the final version. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

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Understanding the Effect of Speed on Human Emotion Perception in Mediated Social Touch Using Voice Coil Actuators

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Touch as a modality in social communication has been getting more attention with recent developments in wearable technology and an increase in awareness of how limited physical contact can lead to touch starvation and feelings of depression. Although several mediated touch methods have been developed for conveying emotional support, the transfer of emotion through mediated touch has not been widely studied. This work addresses this need by exploring emotional communication through a novel wearable haptic system. The system records physical touch patterns through an array of force sensors, processes the recordings using novel gesture-based algorithms to create actuator control signals, and generates mediated social touch through an array of voice coil actuators. We conducted a human subject study ($N = 20$) to understand the perception and emotional components of this mediated social touch for common social touch gestures, including poking, patting, massaging, squeezing, and stroking. Our results show that the speed of the virtual gesture significantly alters the participants' ratings of valence, arousal, realism, and comfort of these gestures with increased speed producing negative emotions and decreased realism. The findings from the study will allow us to better recognize generic patterns from human mediated touch perception and determine how mediated social touch can be used to convey emotion. Our system design, signal processing methods, and results can provide guidance in future mediated social touch design.

Keywords: mediated social touch, emotion, tactile rendering, wearable haptics, data-driven modeling

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1. INTRODUCTION

Long-distance communication has experienced a tremendous evolution in the past few decades. The invention of phones broke the communication barrier for space-separated individuals (Tillema et al., 2010), and the development of video recording and display technology gives people the ability to explore the colorful world through an electronic screen (Saravanakumar and SuganthaLakshmi, 2012). However, even with the ability to communicate online, over the phone, or through videochat, people can still experience feelings of loneliness or depression due to limited physical contact, especially under the social isolation of the COVID-19 pandemic (Tomova et al., 2020). These negative side-effects of touch starvation, a lack of physical contact with others, have also been observed in elderly individuals, individuals in hospitals, and those who live alone (Tomaka et al., 2006; Klinenberg, 2016).

Social touch is an essential component in human development, cognition, communication, and emotional regulation (Cascio et al., 2019). Although social touch is common in our everyday lives, it is currently not possible for individuals to physically interact with each other when spatially separated.

Although prior work has created haptic devices for displaying virtual social touch (Eichhorn et al., 2008; Tsetserukou, 2010; Nakanishi et al., 2014; Culbertson et al., 2018), there has been limited analysis of the acceptability of these virtual touch sensations or the role they play in mediating social interactions between individuals. The goal of this research is to study individuals' emotional responses to mediated social touch, and determine how the touch gesture and its speed affect the acceptability and emotional perception of the interactions. To achieve this goal, we have designed a system that has the ability to record and reproduce social touch, similar to how phones record and replicate voice. The system consists of two parts: one wearable sleeve that records human gesture data using force sensors, and a second sleeve that generates the mediated social touch to the user (**Figure 1**).

This article evaluates our system's ability to convey emotions using common social touch gestures: poking, patting, massaging, squeezing, and stroking. These gestures were chosen for their ability to express both positive and negative emotions (Hertenstein et al., 2009).

The remainder of the article is organized as follows. In Section 2, we review relevant work in the area of mediated social touch and data-driven methods. Our device design and control methods are explained in Section 3. The study design is introduced in Section 4. The study results are presented in Section 5 and discussed in Section 6.

2. RELATED WORK

Social touch plays an important role in human development and communication, helping individuals maintain relationships (Stafford, 2003) and communicate emotions (Hertenstein et al., 2006), while also directly reflecting physical and psychological closeness between individuals (Andersen, 1998). Research into direct human-human social touch has shown that touch can communicate both positive and negative emotions, including anger, fear, disgust, love, gratitude, and sympathy (Hertenstein et al., 2009). Interpersonal touch is the most commonly used method of providing comfort (Dolin and Booth-Butterfield, 1993), can improve the well-being of older adults in nursing care (Bush, 2001), and reduces patients' stress level during preoperative procedures (Whitcher and Fisher, 1979). Touch as an expressive behavior also plays an important role in building up relationships. Studies have shown that intimate partners benefit from touch on a psychological level (Debrot et al., 2013) and caregiver touch impacts emotion perception in children as a function of relationship quality (Thrasher and Grossmann, 2021). Emotional perception is affected even by gender asymmetries during touch interaction (Hertenstein and Keltner, 2011). Not only can the sense of touch be used to communicate distinct emotions but also elicit (Suk et al., 2009) and modulate human emotion. For example, one can perceive a touch as communicating anger without feeling angry themselves. This profound connection between social touch and emotions opens up a wide range of research areas for haptic researchers to explore.

Social touch can take many forms including shaking hands, hugging, holding hands, and a pat on the back. A major challenge in the field of haptics is how to provide meaningful and realistic sensations similar to what is relayed during social touch interactions (Erp and Toet, 2015). The inability to transmit touch during interpersonal communication leads to a limited feeling of social presence during virtual interactions between people, motivating the design of haptic systems to deliver virtual social touch cues.

Mediated social touch refers to the use of haptic technology to allow people to touch one another over a distance (Haans and Ijsselsteijn, 2006). Researchers have discovered that mediated social touch can compensate for the loss of nonverbal cues that results from the use of current communication methods such as texting and videochat (Tan et al., 2010).

There has been a long history of research on the development of mediated social touch devices to replicate the feelings of social touch through wearable and holdable haptic devices. Most devices have focused on replicating a single form of social touch, such as a handshake (Nakanishi et al., 2014), a hug (Mueller et al., 2005; Cha et al., 2009; Tsetserukou, 2010; Delazio et al., 2018), a high-five (Yarosh et al., 2017), or a stroke on the arm (Eichhorn et al., 2008; Knoop and Rossiter, 2015; Tsalamlal et al., 2015; Culbertson et al., 2018; Israr and Abnousi, 2018; Wu and Culbertson, 2019). Vibration is a commonly adopted modality for social touch rendering, including for conveying specific emotions (Hansson and Skog, 2001) or gestures (Wang et al., 2019). Although these devices are effective at displaying specific touch or motion, they lack the complexity necessary to make clear the intent behind the touch. Social touch signals can be complex and varied, as even a simple stroke can be used to convey a wide range of emotions such as sympathy, sadness, and love (Hertenstein et al., 2009). To create an effective virtual touch system, the signals used to create the gesture are just as important as the device's mechanical design.

Previous research has shown that vibrations (Seifi and Maclean, 2013), thermal feedback (Wilson et al., 2016), and air jets (Tsalamlal et al., 2015) can convey distinct emotions. However, these devices used representational haptic icons that required users to learn associations between the emotion and displayed sensation. The use of icons was intended for the users to focus on emotional content of the signal rather than creating high-fidelity virtual gestures.

Rather than directly playing pre-tuned signals, some researchers have created data-driven social touch systems that measure an input touch signal from a user touching one device and replay that signal to a another user with an output device. These systems have been created for a variety of touch gestures, with varying fidelity and intimacy of touch.

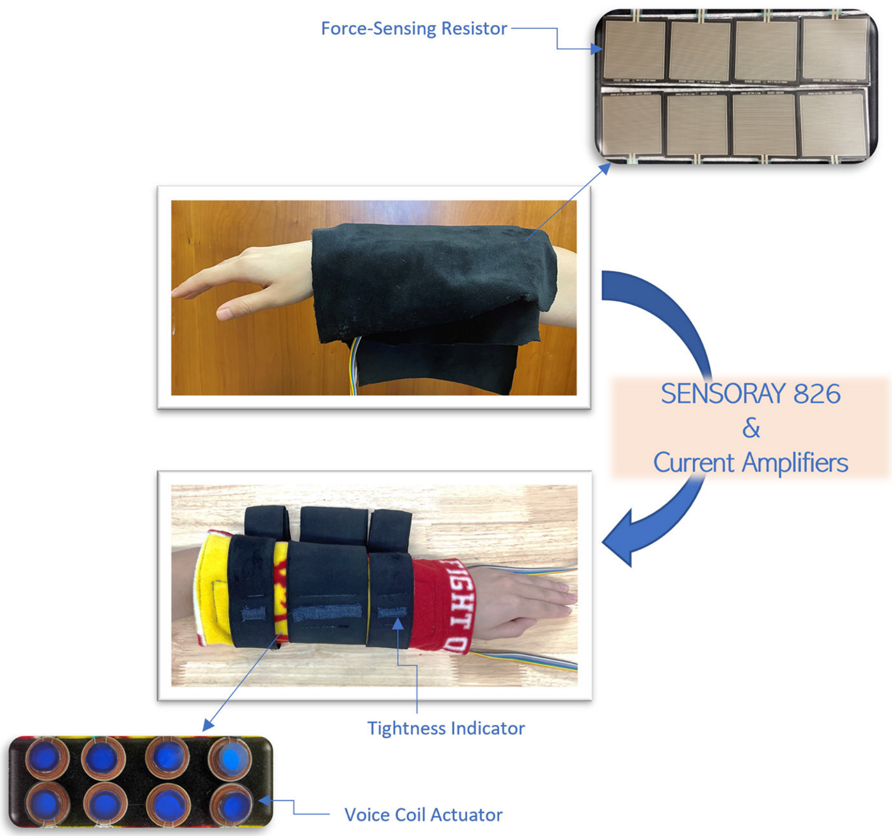

FIGURE 1 | Input device with array of sensors and output device with array of actuators. The output device is controlled by a direct 1-1 mapping of sensor to actuator after gesture-specific data processing.

One common method for measuring touch in these systems is with an array of pressure sensors, with the output varying between pressure (Teh et al., 2012), lateral motion (Eichhorn et al., 2008), vibration (Furukawa et al., 2012; Huisman et al., 2013), and multisensory feedback (Cabibihan and Chauhan, 2015). Researchers have also explored creating higher fidelity input-output systems, for example in kissing display devices for use between family members (Cheok, 2020) and romantic partners (Samani et al., 2012). There has also been work in creating ultra-realistic input devices (Teyssier et al., 2019). Given the complexity of human social touch and the large number of previous devices that have been created, there is a lack of fundamental knowledge of user preferences for realism, touch intimacy, touch location, and interaction method.

Although previous work has shown that both direct (Hauser et al., 2019) and mediated (Salvato et al., 2021) social touch can convey emotion, there has been limited work studying how these emotions are conveyed or recognized. Specifically, research is currently lacking in studying how the actuators signals in mediated social touch devices can be controlled to convey distinct emotions. In this work, we aim to explore how temporal changes to the touch signals can alter perceived emotions. To achieve this, we develop a novel haptic system to examine the relationship between the mediated touch and emotion.

3. SYSTEM DESIGN AND CONTROL

With the goal of realistically replicating human touch, we created a system capable of both recording and displaying human touch patterns. We use a data-driven approach for creating the actuator control signals, recording touch patterns as an array of forces. This section describes the design of our input and output devices, and signal processing methods that make up our lightweight data-driven haptic system.

3.1. Device Hardware

3.1.1. Input Device

Our system consists of two devices: an input device to record the social touch signals as force and an output device for displaying the virtual touch to the user. Both devices were designed as fabric sleeves to be worn on the forearm. As shown in **Figure 1**, the input sleeve has eight force sensing resistors (FSRs) arranged in a 2 × 4 array. The FSRs measure the applied force as a change in resistance. These sensors (Sparkfun SEN-09376) were chosen due to their square shape (1.5 × 1.5 in) that allowed tight packing of sensors, flexible nature that is easily integrated into a wearable device, and ability to measure forces in the range used during human social touch (Wang et al., 2010). A previous study has shown that recorded pressure data is able to generate the control signals that can be used to mimic various gestures with a voice coil device (Salvato et al., 2021). The sensors are embedded in a fabric sleeve. To prevent the sensors from bending and to provide a stiffer material for better force transference when the sleeve is worn on the lower arm, we added a layer of rigid padding as supporting material in between the sensors and skin.

When recording the signals, the sensor sleeve was freely laid on the arm to avoid noise from pre-loading the sensors. We zeroed the sensors before each recording to remove the forces caused by the wearer's motion, bending in the sensors, and the pressure of the sensors resting on the arm. A voltage divider circuit was used to convert the sensors' change in resistance to change in voltage, and the resulting voltage was sampled at 1 kHz as analog inputs through a Sensoray 826 PCI card. The signals were lowpass filtered at 10 Hz to remove high-frequency noise not caused by human motion (Srinivasan, 1995). Further signal processing to convert the recorded signals to actuator control signals is described below.

3.1.2. Output Device

To generate the sensation of different social touch gestures, we created an output device with an array of voice coil actuators (Tectronic Elements TEAX19C01-8). These actuators are driven at low frequencies to provide force normal to the user's arm, This type of actuator has previously been used to create a comfortable and realistic stroking sensation (Culbertson et al., 2018). Salvato et al. (2021) further proved that this actuation hardware is effective at displaying pleasant and realistic social touch cues. Eight voice coil actuators are placed in a 2 × 4 array in a fabric sleeve to simplify mapping from the recorded forces to actuator control signals (**Figure 1**). The actuators signals are output at 1 kHz from the Sensoray 826 PCI card, and are sent through a linear current amplifier with a scaling factor of 1 A/V.

These voice coil actuators are position-controlled, meaning that the control signals specify the amount of actuator motion into the arm, and do not directly control the force that the actuators apply to the arm. Therefore, it is important to ensure the tightness of the sleeve is consistent across users and along the length of the sleeve. We created tightness indicators (TI) at three points along the length of the sleeve. Each TI is a piece of elastic with markings showing the ideal amount of stretch. To create recognizable social touch gestures, the voice coils must be programmed both temporally and spatially. The details of these actuator control signals are discussed below.

3.2. Device Control

This section describes our signal processing algorithms to create actuator control signals from recorded force with the goal of replicating touch gestures as realistically as possible. In Salvato et al. (2021)'s previous study, a similar 2 × 4 voice coil layout was used for generating social touch, and the study showed promising results for generating realistic social touch with this device. Although this previous article used finer resolution in the recording system (1″ × 1″ sensors), the sensing resolution was greater than the actuator resolution, so the increase in resolution helped smooth the gestures both temporally and spatially. In our current system, the individual force sensor we chose covers the same area as the voice coil actuator (1.5″ × 1.5″). We have designed the algorithms that map the sensor data to actuator control signals to include blending between actuators. This blending of the signals produces the same temporal and spatial smoothing as the greater resolution from the previous‘system.

3.2.1. Strategies for Different Gestures

Our system is capable of displaying five social touch gestures: poking, patting, massaging, squeezing, and stroking. These gestures were chosen due to their common appearance in social touch and their ability to convey both positive and negative emotions (Hertenstein et al., 2009). Due to the unique spatial and temporal patterns of the different gestures, the data is processed and smoothed differently for each gesture type. Since the signals directly control the motion of the voice coil actuators, we apply principles of exaggeration to maximize the amount of actuator motion, resulting in more noticeable and salient virtual gestures. Exaggeration is a widely used animation principle to amplify cartoon characters' expression (Lasseter, 1987). **Figure 3** shows the actuator signals for these five gestures. The number of actuators being moved at a single time correspond to the perceived area of contact during the gesture.

3.2.1.1. Poking

Poking involves using a single finger to repeatedly press into the arm. Each poke is made up of a rise in force as the finger presses into the skin, followed by a decrease in force as the finger releases contact. Since each FSR covers an area larger than the size of fingertip, we expect only a single FSR to be activated during poking, but it is still possible that poking happens between two adjacent sensors. During output, we only want to move a single actuator in order to accurately represent the small contact area of a single finger. We first use Touch Point Detection (TPD) to track the number of sensors that have valid contact force with the hand. TPD captures every sensor contact with a cycle (a measure of contact duration) T $\geq$ 0.05 s. This threshold was chosen to ensure only valid contacts are detected, ignoring fluctuations due to noise. We define N_c as the total number of active sensors determined by the TPD. Ideally, TPD for poking would result in $N_c = 1$ active sensor; if the poke occurs between two sensors, $N_c = 2$. When two sensors are activated, we select the more significant sensor (i.e., the sensor with the higher sensed force) and set the second sensor to zero.

To maximize the strength of the poke during actuation, we exaggerate the poke by mapping the sensed force to the full motion range of the actuator. We use a linear mapping where the maximum sensed force corresponds to the largest actuator indentation ($V_{\text{act}} = 0.9V$) and the minimum force corresponds to the actuator's neutral position ($V_{\text{act}} = 0V$). All other actuators' movement is constrained so that only a single actuator moves at a time to ensure the poking sensation is strong and only covers a small contact area.

3.2.1.2. Patting

The main difference between poking and patting is the contact area. Patting uses the entirety or part of the palm to apply a gentle force to the arm. Similar to poking, our first step in processing the signals for patting is to use TPD to determine the number of active sensors. From many recordings, we have determined that N_c = 2–4 sensors for a typical pat. Since the pat has a larger contact area than a poke, we perform a data integrity check on the signals rather than identifying the sensor with the highest significance. This integrity check means we want to make sure the recorded touch signal is reasonable based on the gesture type. For example, if three activated sensors are not adjacent to each other during a pat, it may imply that some sensors are not collecting the data correctly. The integrity check contains two parts. First, it checks to see if all activated sensors are connected using a simple Depth First Search (DFS) to check the graph connectivity, where we set every sensor as a vertex and build an edge for its two or three neighbors depending on where it is located in the 2D layout. Second, we check whether the acceleration of the motion is consistent by taking the derivative of the signals; all values should be either positive or negative. Any signal that does not pass the integrity check is assumed to be an invalid recording and must be collected again. Similar to poking, we linearly map the actuator control signals to the sensor signals by setting the maximum force to the largest actuator indentation and the minimum force to the actuator's neutral position. All actuators corresponding to inactive sensors are set to zero.

3.2.1.3. Squeezing

A squeezing gesture involves movement of multiple fingers during the contact. A typical squeeze on the lower arm is made by having the thumb on the one side of the arm while the other four fingers are on the opposite side; all fingers apply force to a virtual center at the same time. A valid squeezing recording should have the thumb on the one row of the FSRs and the rest of the fingers on the second row, as shown in **Figure 3**. If the fingers are too condensed in a single area, the information loss of the touch gesture will cause the transformed signal to appear ambiguous, and the gesture will likely be incorrectly interpreted as poking. Therefore, we first use TPD to determine if the signals match what we expect from a squeeze, that is N_c = 1–2 active sensors in one row and N_c = 2–4 active sensors in the second row. If our recording does not match this pattern, it is determined to be invalid and must be recorded again.

To increase the saliency of the squeeze, we exaggerate the center of force. If two sensors in the same column are activated at the same time, we scale these signals by setting the maximum sensed force equal to the largest actuator indentation. The rest of the sensors are not exaggerated and simply follow a linear scaling between sensed force and actuator voltage. For a squeeze with a long holding period, we manually identify the start and end of the hold and set the actuator signals equal to the mean of the signals during the entire holding period. This scaling and smoothing exaggerates the squeezing sensation, improving its perceived strength and saliency.

3.2.1.4. Massaging

Massaging shares some similar patterns with squeezing, but they are not exactly the same. For purposes of processing, we can consider massaging as repeated squeezing moving across the arm. However, we do not impose the same restriction on N_c across the two rows as we do for squeezing because it is more common that the entire palm presses on one row and four fingers press on the second row. We exaggerate all sensors by linearly scaling them to the actuator's full range of motion using the maximum force across all sensors. To further improve saliency, we use the same method of stabilizing the hold as for squeezing.

3.2.1.5. Stroking

Stroking refers to moving one's hand with gentle pressure over the lower arm. The recorded signal will show multiple sensors in the same row being activated in a sequence. In order to make the stroking pattern more noticeable, we emphasize the moving center of the stroke (i.e., the middle of the fingers applying the force). First, we must determine the direction of the stroke and the size of the contact area. If two sensors in a row are activated, we exaggerate the signal of the front sensor with a scaling factor of α = 1.25. If three sensors in a row are activated at the same time, then we put an emphasize on the middle sensor, amplifying it also with a scaling factor of α = 1.25. To create a smooth and continuous feeling stroke, we blend the signals of adjacent actuators. First, we collect information about the start, peak, and end time-stamps of each signal to determine the direction of the stroking motion. We then blend the signals of adjacent actuators in the direction of motion by shifting the starting time of the next actuator so that it overlaps the previous actuator in time by a set duration. This overlap maintains the shape of the actuator signals, but increases the continuity of the stroke by providing a smooth transfer of pressure between actuators. Similar overlapping of signals was used in Culbertson et al. (2018) to create a smooth stroking sensation, and that research found that an overlap of 25% of the actuator's total motion duration creates the most continuous sensation. Through pilot testing, we also determined that an overlap of 25% was the best choice for our system.

4. STUDY

Speed plays an important role in human perception. Previous research has shown a correlation between perceived emotion and the speed of speech (Lindquist et al., 2006) and the tempo of music (Rigg, 1940). The high arousal caused by fast-paced music has also been shown to increase the risk of traffic violations (Brodsky, 2001). In this research, we examine how users interpret the emotion of mediated social touch gestures and how these emotions can be manipulated by the speed of the gesture.

Twenty individuals (8 females and 12 male, 18–35 years old) participated in the study. The experimental protocol was approved by the Institutional Review Board at the University of Southern California under protocol number UP-19-00712, and participants gave informed consent. Participants sat at a desk and wore the output device on their left arm. They provided feedback through the GUI shown in **Figure 2** and wore headphones playing white noise to block auditory cues from the actuators. Additionally, the fabric of the sleeve blocked the actuators from view, so participants relied only on the haptic cues in their

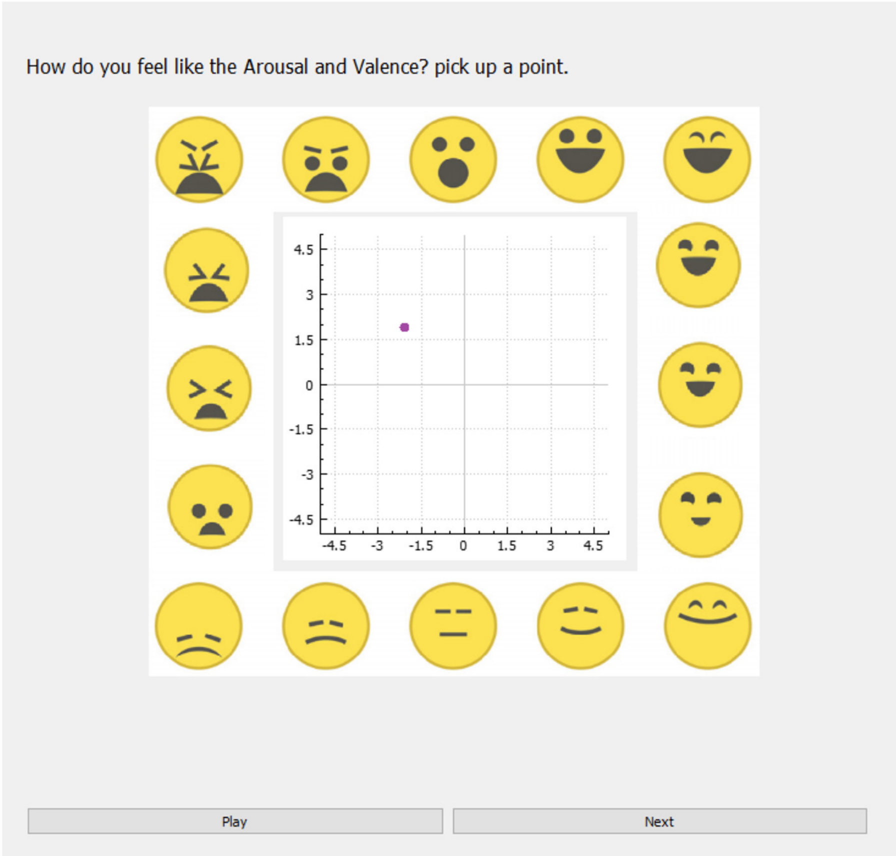

FIGURE 2 | Study GUI, adapted from Toet et al. (2018). Participants rated the valence and arousal of each gesture by selecting a point on the 2D plot.

ratings.The details of the study setup, conditions, and procedure are discussed below.

4.1. Experimental Conditions

The social touch gestures were pre-recorded by the experimenter so that all participants received the same feedback. The experimenter wore the input device on his left arm and made the gestures with his right hand. The data was processed as discussed in Section 3.2 and the actuator control signals were stored in a text file. We created and stored a single recording for each gesture, and empirically determined the ideal speed of each gesture using a pilot study.

In this work, we want to evaluate the effect of gesture speed on user's perception and preference. For consistency, we altered the speed of the five recorded gestures by resampling the original signals, ensuring that the touch pattern in the original waveform was maintained. The signals were downsampled to achieve a faster speed and upsampled to achieve a slower speed. To ensure a smooth signal, spline interpolation was used during resampling. This method preserves the shape of signals and introduces the least amount of noise. We created five levels of speed for each gesture type by both speeding up and slowing down the original gesture recordings: original speed (OS), 4 times slower speed (4S), 2 times slower speed (2S), 4 times faster speed (4F), and 2 times faster speed (2F). Altering the gesture speed only affects the duration and frequency of the gesture signal; the majority of other hyper-parameters for the signal, such as touch intensity and contact area, were preserved by our signal processing algorithm. Five gestures with five speed levels were used in the study to create a total of 25 distinct gestures. The actuator signals used in the study are shown in **Figure 3**.

4.2. Phase 1

In Phase 1, participants were asked to evaluate their emotional response to the mediated touches by rating the perceived valence and arousal of each touch. Valence and arousal are two important dimensions in describing how individuals label their own subjectively experienced affective states (Barrett, 1998). Arousal is an evaluation of emotional intensity, and valence refers to the pleasantness (positive valence) or unpleasantness (negative valence) of an emotional stimulus. Participants rated the valence and arousal of the mediated touch together by selecting a single point on the 2D valence-arousal plot shown in **Figure 2**. This plot was adapted from the EmojiGrid, which was presented and validated in Toet et al. (2018).

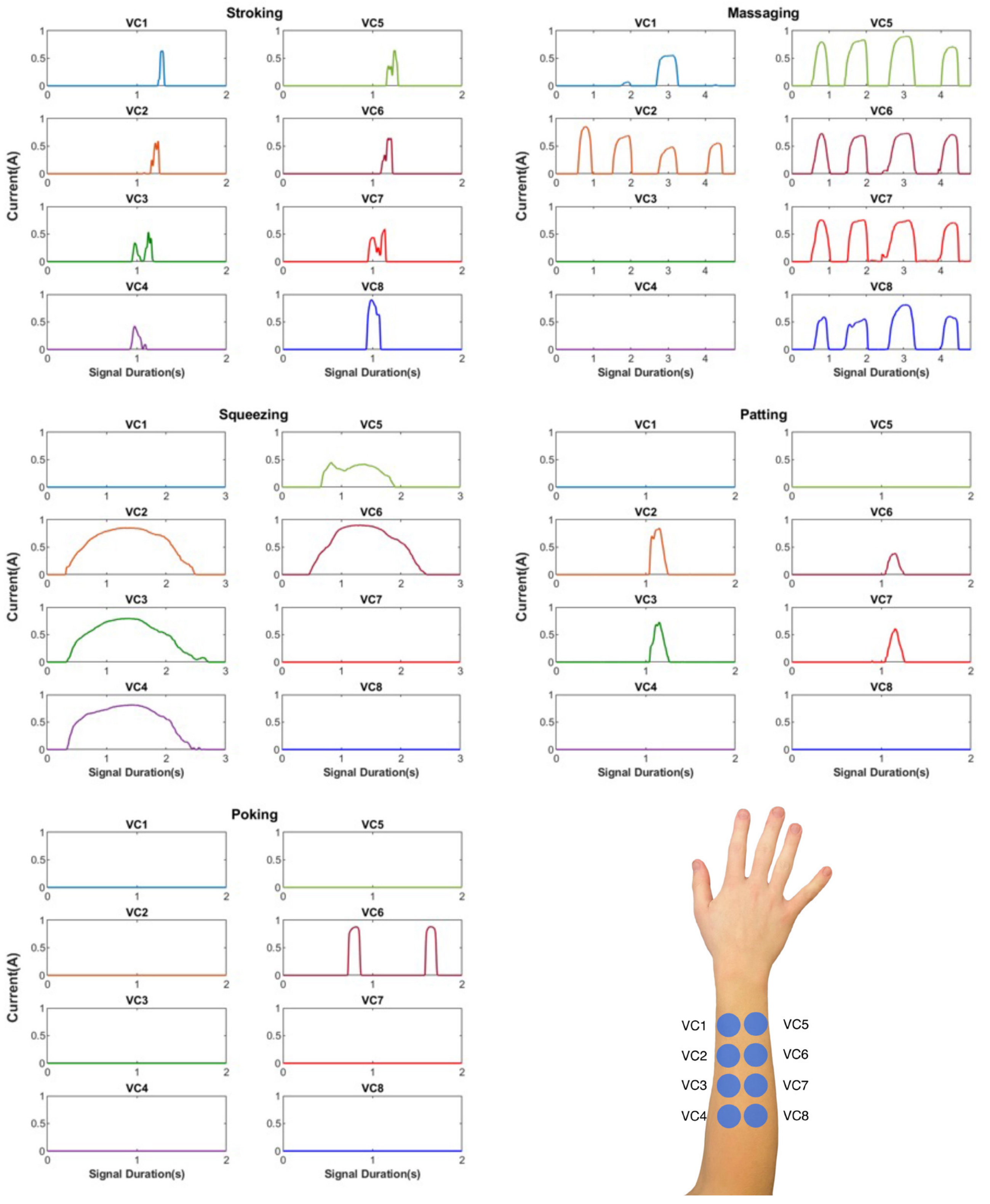

FIGURE 3 | Actuator signals used in the study for speed OS.

Participants rated each mediated touch signal three times for a total of 75 cues, which were presented in randomized order. Participants were presented with a single mediated touch at a time and were are allowed to replay the signal before rating. They were asked to rate the emotion that they felt the gesture was trying to convey. It is worth mentioning that there is a difference between perceived emotion and personal emotion. Perceived emotion is the emotion that is trying to be conveyed through the gesture, while personal emotion is the feeling elicited in the user after receiving the touch. We clarified this concept to each participant to avoid confusion. Signals vary in length from 5 to 20 s, and this phase of the study took about 20–30 min total. After completing all trials, participants were given a 10-minute break before moving on to Phase 2.

4.3. Phase 2

In this phase, we evaluate our system's performance in conveying realistic and pleasant gestures. Additionally, we examine the correlation between the gesture speeds and participants' perception of realism and comfort. We used the same signals from Phase 1, and participants were again asked to rate each mediated gesture three times for a total of 75 trials. Participants were asked "How would you rate the realism of the touch on the following scale?" and provided their answers on a 7-point Likert scale (1 = very unrealistic, 7 = very realistic). The comfort of the touch was similarly rated on a 7-point Likert scale (1 = very uncomfortable, 7 = very comfortable).

5. RESULT

5.1. Phase 1: Effect of Speed on Valence and Arousal

Figure 4 shows the valence ratings for each gesture and speed. We ran a one-way ANOVA on the valence rating for each gesture with the signal speed as factor. This analysis indicated that speed caused a statistically significant difference in the valence rating for stroking [$F_{(4,295)} = 21.81$, $p < 0.001$], massaging [$F_{(4,295)} = 16.26$, $p < 0.001$], squeezing [$F_{(4,295)} = 5.03$, $p < 0.001$], and patting [$F_{(4,295)} = 9.6$, $p < 0.001$]. Speed did not have a significant effect on the valence ratings for poking [$F_{(4,295)} = 1.11$, $p = 0.35$].

We then ran a Tukey's *post-hoc* pairwise comparison test on stroking, massaging, squeezing, and patting to further evaluate the effects of speed on the ratings of valence. The results showed that there was a general trend of decreasing valence with increasing speed. For the stroking gesture: 4F and 2F had significantly lower valence than 2S and 4S, and OS had significantly lower valence than 2S and 4S. For the massaging gesture: 4F and 2F had significantly lower valence than OS, 2S, and 4S. For the squeezing gesture: 4F had significantly lower valence than 4S and 2S. For the patting gesture: 4F had significantly lower valence than OS, 2S, 4S; 2F had significantly lower valence than 4S. There was no significant differences between any other signals.

Figure 5 shows the arousal ratings for each gesture and speed. We ran a one-way ANOVA on the arousal rating for each gesture with the signal speed as factor. This analysis indicated that speed caused a statistically significant difference in the arousal rating for stroking [$F_{(4,295)} = 6.72$, $p < 0.001$], massaging [$F_{(4,295)} = 13.51$, $p < 0.001$], patting [$F_{(4,295)} = 16.4$, $p < 0.001$], and poking [$F_{(4,295)} = 11.48$, $p < 0.001$]. Speed did not have a significant effect on the arousal ratings for squeezing [$F_{(4,295)} = 1.79$, $p = 0.13$].

We also ran a Tukey's *post-hoc* pairwise comparison test on stroking, massaging, patting, and poking to further evaluate the effects of speed on the ratings of arousal. The results showed that there was a general trend of increasing arousal with increasing speed. For the stroking gesture: 4F and 2F had significantly higher arousal than 2S and 4S. For the massaging gesture: signal 4F and 2F had significantly higher arousal than OS, 2S, 4S. For the patting gesture: 4F had significantly higher arousal than OS, 2S, and 4S; 2F has significantly higher arousal than 2S and OS. For the poking gesture: 4F, 2F, OS have significantly higher arousal than 2S and 4S. There was no significant differences between any other signals.

5.2. Phase 2: Effect of Speed Change on Realism and Comfort

Figure 6 shows the realism ratings for each gesture and speed. We ran a one-way ANOVA on the realism rating for each gesture with the signal speed as factor. This analysis indicated that speed caused a statistically significant difference in the realism rating for stroking [$F_{(4,295)} = 15.92$, $p < 0.001$], massaging [$F_{(4,295)} = 17.41$, $p < 0.001$], squeezing [$F_{(4,295)} = 5.46$, $p < 0.001$], and patting [$F_{(4,295)} = 17.53$, $p < 0.001$]. Speed did not have a significant effect on the realism ratings for poking [$F_{(4,295)} = 1.11$, $p = 0.35$].

We then ran a Tukey's *post-hoc* pairwise comparison test on stroking, massaging, squeezing, and patting to further evaluate the effects of speed change on the realism ratings. The results showed that there was a general trend of decreasing realism with increasing speed. For the stroking gesture: 4F and 2F had significantly lower realism ratings than 2S and 4S; 4F was significantly less realistic than OS; OS was significantly less realistic than 4S. For the massaging gesture: 4F, 2F and OS had significantly lower realism than signal 2S and 4S. For the squeezing gesture: 4F had significantly lower realism than signal 2F, OS, 2S, and 4S. For the patting gesture: 4F and 2F had significantly lower realism than 2S and 4S. There was no significant differences between any other signals.

Figure 7 shows the comfort ratings for each gesture and speed. We ran a one-way ANOVA on the comfort rating for each gesture with the signal speed as factor. This analysis indicated that speed caused a statistically significant change in the comfort rating for massaging [$F_{(4,280)}$, $p = 0.002$] and squeezing [$F_{(4,280)} = 6.73$, $p < 0.001$]. Speed did not cause a significant difference in the comfort ratings for stroking [$F_{(4,280)} = 1.47$, $p = 0.21$], patting [$F_{(4,280)} = 1.09$, $p = 0.36$], and poking [$F_{(4,280)} = 1.38$, $p = 0.23$].

We then ran a Tukey's *post-hoc* pairwise comparison test on massaging and squeezing to evaluate the effects of speed change on the ratings of comfort. The results showed that for massaging and squeezing, there was a general trend of decreasing comfort with increasing speed. For the massaging gesture: the comfort for 4F and 2F was significantly lower than for 2S and 4S. For the squeezing gesture: the comfort for 4F was significantly lower than

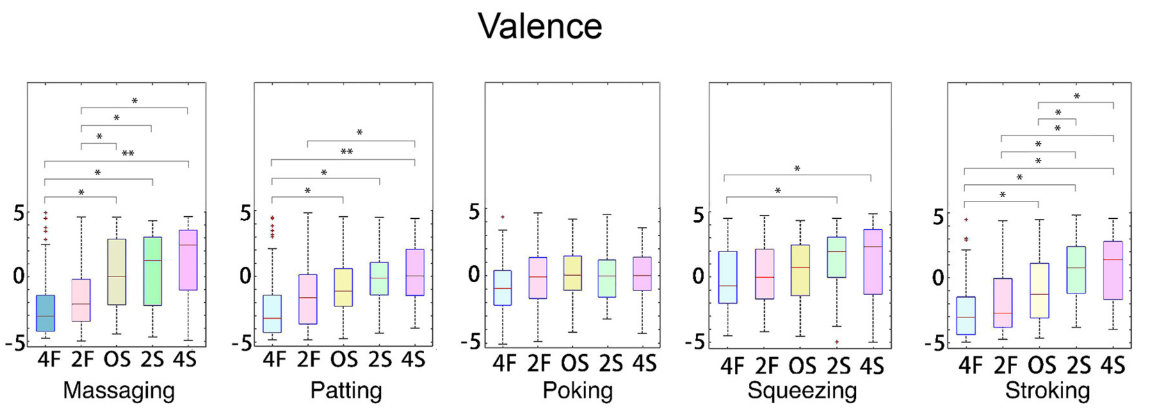

FIGURE 4 | Valence ratings separated by gesture and speed. * $p < 0.05$, ** $p < 0.01$.

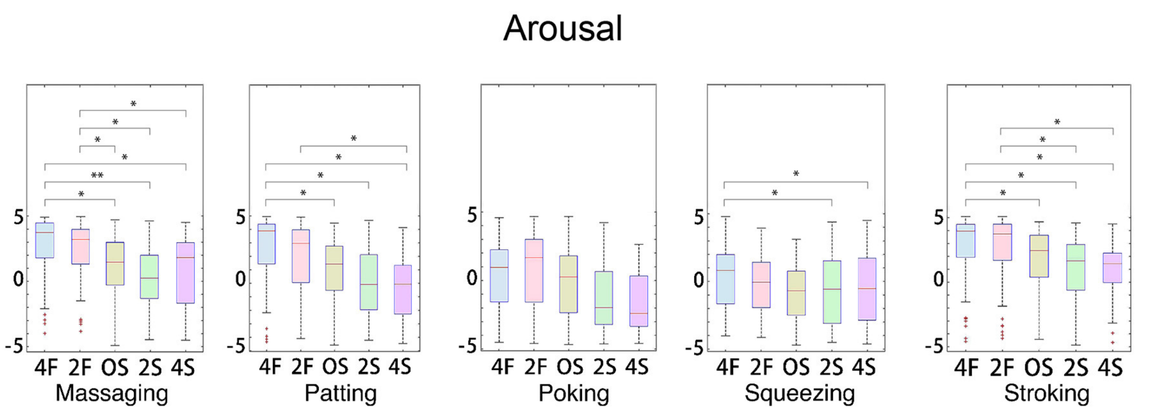

FIGURE 5 | Arousal ratings separated by gesture and speed. *$p < 0.05$, **$p < 0.01$.

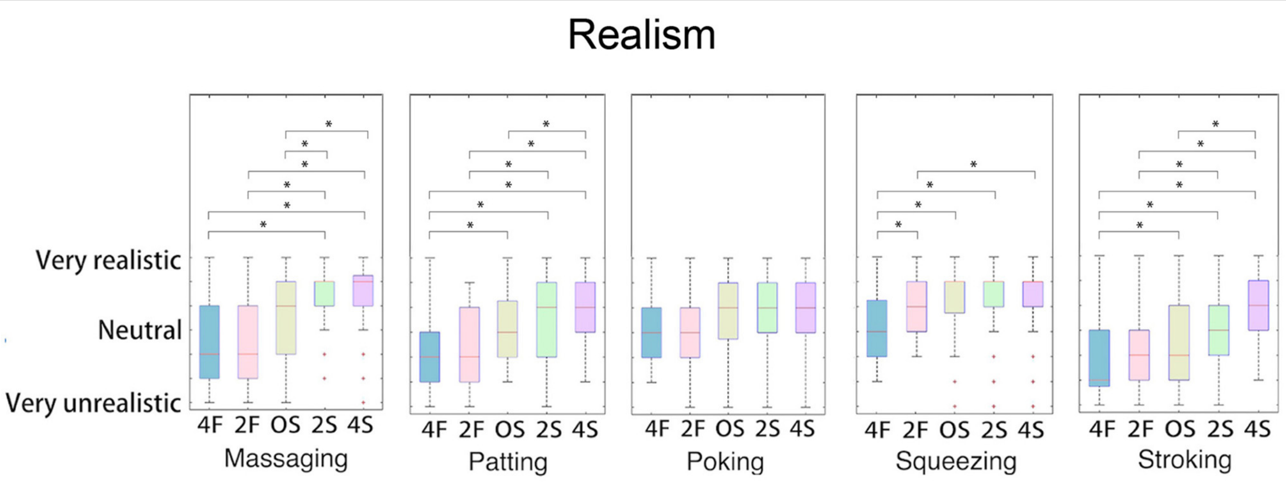

FIGURE 6 | Realism ratings separated by gesture and speed. * $p < 0.05$.

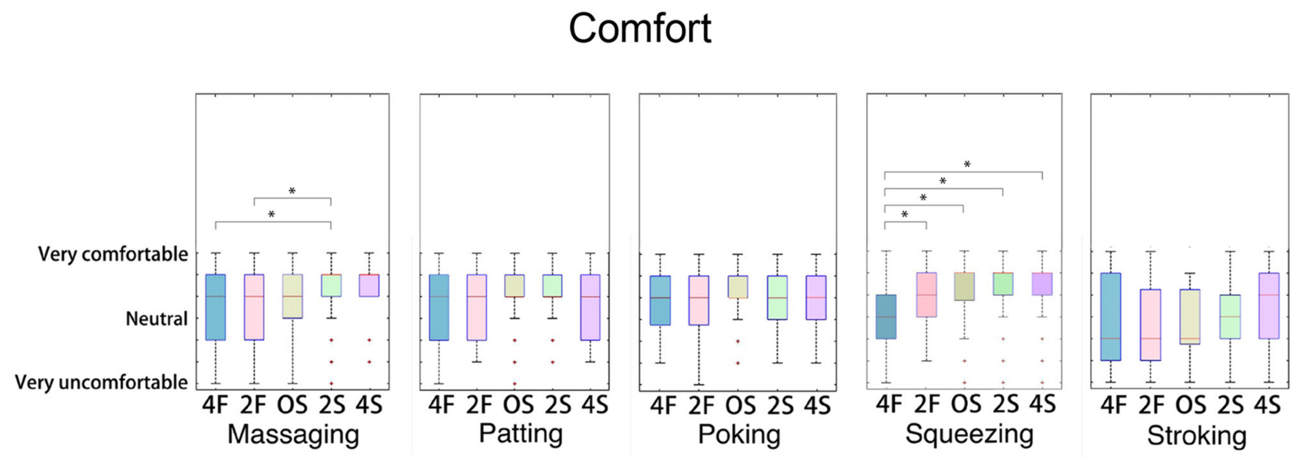

FIGURE 7 | Comfort ratings separated by gesture and speed. * $p < 0.05$.

for the four other speeds. There was no significant differences between any other signals.

6. DISCUSSION

Studies have shown that both visual context (Esposito et al., 2009) and the relationship between toucher and touchee (Thompson and Hampton, 2011) affect the emotional perception of social touch. However, in our study all visual information and context was removed from the interaction. The touches were not presented in the context of any social interaction, and the gestures were recorded by the experimenter who had no social relationship with the participants. Therefore, we expect the participants' ratings to reflect only the emotional content of the gesture itself.

Before expanding the discussion, we summarize the four main findings of our results:

1. The perceived valence of the touch is more positive for slower gestures and negative for faster gestures.
2. The perceived arousal of the touch increases with increasing speed.
3. The realism of the mediated social touch improves with decreasing speed.
4. The mediated touch feels more comfortable when the speed is slow.

The current study provides evidence that the speed of mediated social touch plays a crucial role both on human emotional and personal perception.

Stroking has been shown to strongly activate the CT afferents, which respond maximally to stroking in the range of 1–10 cm/s (Loken et al., 2009). These speeds have also been shown to be the most pleasant range of velocities for stroking on the skin. Research has also shown that people tend to move their hand faster when stroking an artificial arm as compared to stroking their partner's arm (Croy et al., 2016). Therefore, it is expected for their to be an effect of speed on participants' ratings of stroking, with slower speeds being preferred, which our results support. Our study showed that when the speed of the stroking increases, arousal also increases and valence changes from positive to negative. The realism decreases significantly when the speed of the stroke increases, but we did not see a corresponding change in the comfort with speed. The effective speed of the stroke for 4S is 10.9 cm/s and for 4F is 87.0 cm/s, which are both above the CT afferents' preferred speed. It is likely that the low comfort ratings for stroking were partially caused by this mismatch in speeds.

Massaging has been shown to be effective in the application of physical therapy (Field, 1998) and body relaxation (Leivadi et al., 1999). Here, we focus on massaging on the arm, which may not be the ideal location for this specific gesture. Although massaging and stroking likely activate different mechanoreceptors, our results for massaging match those of stroking: increased speed increases the touch's arousal and moves the valence from positive to negative. Slow massaging feels more comfortable and realistic than fast massaging. The ratings of slow massaging signals are in the high comfort range, which also proves our device's ability to generate comfortable touch. The high arousal and negative valence level yielded by fast speed massaging was reported as unrealistic based on the ratings; a similar trend was also observed in gestures like patting and stroking. This finding shows us there seems to be a correlation between realism and the gesture's perceived emotion. However there is not sufficient data to prove that decreased realism causes negative emotions to be perceived in the touch. It remains to be studied in future work the effects between realism and emotion as well as the range of emotional information that a gesture can convey while still being realistic.

Valence goes from positive to negative when speed gets faster with squeezing. Previous studies have shown that squeezing is often related to anger or fear (Hertenstein et al., 2006). However, our analysis shows that even the fastest squeezes indicate a relatively low amount of negativity (median valence = −1) compared to stroking and massaging. This indicates that squeezing might not be an ideal gesture for expressing anger-related emotions, or that another parameter such as signal strength may be more important in altering the valence of this gesture. Similarly, our study also shows that speed did not significantly alter the intensity of the conveyed emotion. In future work we will study how other changes to the squeezing gesture, such as increasing its intensity or the duration of the hold, may alter the perceived emotion. Although the perceived emotion of the squeeze did not change with speed, we did see a decrease in comfort with increased speed, indicating that participants prefer a slower squeeze.

Patting can be used to convey a wide range of emotions, such as anger, happiness, love, gratitude, and sympathy (Hertenstein et al., 2009). Our study results support this idea and show a significant variation in the arousal and valence ratings with speed. However, even though there is no force difference in the gesture, several participants commented that the fast pats felt angry. Patting overall had fairly negative valence ratings, and the ratings decreased even more with increased speed. The arousal of the pat also increases significantly with speed meaning that high-speed pats are perceived as strong emotions. Since the contact duration changes with speed, the pat feel more like a slap when it is very fast.

Poking is consistently neutral in valence, realism, and comfort across all speeds. This result is not particularly surprising since poking is not commonly used to convey emotions (Jones and Yarbrough, 1985). The only factor that changes with speed is arousal, which increases with increasing speed. The reason for this might be that poking is considered an attention-getting gesture rather than an emotional gesture (Baumann et al., 2010).

Our results across the gestures shows that speed consistently has an effect on the human emotional perception during mediated social touch. It is intuitive that the touch's arousal would increase with increased speed. Our results were consistent across participants for a given speed and gesture, meaning that given an emotion we want to convey, we could choose an appropriate speed and gesture to display with our system. One thing to note is that the methods and results we presented apply only to our voice coil system; we plan to confirm this effect in different modalities and actuation methods in future work. An intuitive linking between the valence-arousal ratings and their representative emotions brings up some thoughts for future emotional communication. With a fast motion, massaging, patting, and stroking gestures are rated as low-valence and high-arousal, which can be adopted to convey emotions such as anger or annoyance. Slower-motion gestures are more appropriate for emotions like amused, glad, or pleased. Squeezing is consistent with positive valence and medium arousal, which can represent expressions of relaxed or calm. Poking would be better used for notifications or raising attention rather than conveying emotional information.

This study also provides some insights on factors to consider when designing realistic and comfortable touch signals. Our signals of squeezing, poking, and massaging were rated as highly realistic at slower speed, but stroking and patting showed lower realism overall. For all gestures, the perception of comfort level improves as the speed is decreased. We will explore additional data processing to increase the realism of these gestures.

7. CONCLUSION

In this article, we present a novel data-driven haptic system that can record human touch and output the gestures to a wearable array of actuators. The two sleeves of the system were designed to be lightweight and easy to build, so they are ideal for prototyping mediated social touch research. We designed heuristic algorithms for transforming touch gestures from sensor to actuator. Our signal processing algorithms tune the gestures' hyper-parameters, including moving speed of the motion and contact frequency, and apply additional processing like exaggeration or blending.

More importantly, our study results indicated a clear and consistent effect of speed on human emotion perception through mediated touch. Increased speed increases a touch's arousal and decreases its valence. This result can be used to design mediated touch signals to convey specific emotions. We also gain insights from human perception of mediated touch, knowing that even though slower motion would potentially increase the comfort and realism sensation of a touch, different gesture types still respond to the speed change in a varied way.

In the future, we will continue improving the hardware and signal processing design to create realistic and comfortable touch gestures. Our study showed it is necessary to consider hyper-parameters of gestures when transforming gestures from sensor to actuation signals, parameters such as force and contact area are worthy to explore. We also want to further identify the optimal parameter ranges for generating comfortable and realistic mediated touch signals.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

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

AUTHOR CONTRIBUTIONS

XZ and TF designed and implemented the hardware. XZ and HC contributed to the signal processing methods, study signals, and the study protocol. XZ conducted the user study and data analysis with the guidance from HC. All authors contributed to the drafting of the manuscript, read, and approved the manuscript.

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An Interaction Theory Account of (Mediated) Social Touch

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Research on mediated social touch (MST) has, either implicitly or explicitly, built on theoretical assumptions regarding social interactions that align with "theory theory" or "simulation theory" of social cognition. However, these approaches struggle to explain MST interactions that occur outside of a laboratory setting. I briefly discuss these approaches and will argue in favor of an alternative, "interaction theory" approach to the study of MST. I make three suggestions for future research to focus on.

Keywords: social touch, mediated social touch, interaction theory of social cognition, haptics, enactivism, phenomenology, participatory sense-making

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1. INTRODUCTION

Social touch is a vital form of intersubjective engagement for human beings and plays an essential role in human development (Fotopoulou and Tsakiris, 2017; Cascio et al., 2019). Later in life, social touch is considered important for the communication of affect (Hertenstein et al., 2006), relationship formation and maintenance (Dunbar, 2010), and stress management (Ditzen et al., 2007). Furthermore, it has been suggested that C-Tactile afferent (CT) affective touch receptors, which selectively respond to slow stroking touches, explain sensory effects of touch (McGlone et al., 2014; Schirmer et al., 2022). However, despite substantial progress in social touch research, there remains considerable debate as to how we should conceive of social touch in actual interpersonal interactions. Social touch interactions are often viewed from a sender-receiver perspective (e.g., Fairhurst et al. 2022; see also Schirmer et al. 2022) where the way humans understand each other in social interactions is considered an individual capacity that involves the exchange of signals (see Schirmer et al., 2022). This perspective is in line with two dominant views in social cognition, namely "theory theory" (TT) and "simulation theory" (ST) which entail theorizing about others' mental states or simulating others' mental states, respectively (see Froese and Gallagher, 2012). Despite the relative dominance of these theoretical frameworks, conceptualisations of social touch as a signal in line with TT and ST frameworks do not translate well to interactions outside of the laboratory (see Schirmer et al., 2022).

Moreover, the debate on how to conceive of social touch extends to research into haptic technology that aims to mediate social touch [i.e., mediated social touch (MST); Haans and IJsselsteijn, 2006; Huisman, 2017]. MST research has resulted in many interesting prototypes (for an overview see Huisman, 2017) and there has been a steady increase in empirical studies into the effects of MST (for overviews see Haans and IJsselsteijn, 2006; Van Erp and Toet, 2015; Huisman, 2017). For example, research has investigated the reproduction of CT-like touch through vibrotactile arrays (Huisman et al., 2016), effects of MST on helping behavior (Haans et al., 2014), and on stress reduction (Sumioka et al., 2013). Nevertheless, null findings are also found in the literature (Erk et al., 2015; Willemse et al., 2018), and there have been significant challenges in replicating social touch through technology (Haans et al., 2014; Ipakchian Askari et al., 2020b). Moreover, effects of MST are strongly dependent on contextual factors (Ipakchian Askari et al., 2020a) that make generalisation difficult. Finally, there are arguments to be made for the field of MST to be experiencing a moment of crisis, which calls for rethinking MST in terms of its social and sensory aspects (Jewitt et al., 2021).

To address the issues outlined above we need new ways to conceive of social touch (e.g., Schirmer et al., 2022), which, I argue, requires us to re-examine the theoretical assumptions underlying our understanding of social cognition with respect to social touch. Here, I argue that we should move away from individualistic theories of social cognition that, implicitly or explicitly, underlie thinking about social touch and MST in many cases, and move toward embodied theories that put a strong emphasis on interaction as playing a central and sometimes constitutive role in how humans understand each other (De Jaegher et al., 2010). This theoretical shift in the way we conceive of social touch can help drive forward a more fruitful research agenda for (mediated) social touch. In the conclusions to this article I provide some initial suggestions for how to furnish such an agenda with the aim of opening up new vistas for research to explore.

2. SOCIAL COGNITION AS INTERACTION

Research on social cognition is concerned with the question of how, on a daily basis, humans are able to understand each other, and this question has been mainly approached from TT and ST perspectives (Froese and Gallagher, 2012; Gallagher, 2020). In TT, social cognition is conceived of as an inferential process based on common-sense, “folk” psychology where the outcomes of theorizing about others’ hidden mental states are attributed to the other person (Malle, 2005). In ST, it is supposed that we use our own neural circuitry and mental capacities, including a mirror neuron system (Gallese et al., 2004), as an internal model to simulate the mental states of others. The outcome of this simulation process is then attributed to the other person. Note, that there are different versions of both theories and that hybrid approaches, combining aspects of both TT and ST, also exist (Frith and Frith, 2010).

Taken together, both TT and ST approaches consider social cognition as a reflective, third-person, observation-based process, which is about two (or more) minds, inferring, simulating, or doing a combination of both, to hypothesize about each other’s hidden, internal mental states (Gallagher, 2020, p.72). It is an individual process that is driven by sub-personal mechanisms and is considered to apply universally to how people understand each other in social situations (see Froese and Gallagher, 2012; Gallagher, 2020). Both TT and ST approaches can be characterized by methodological individualism and neuro-reductionism (Froese and Gallagher, 2012). The former refers to the way social cognition is studied mainly from the perspective of individuals and their capacities outside of actual social interactions. The latter indicates that the explanation for social cognition needs to be sought in either neural mechanisms or modules (Leslie et al., 2004), or mirror neurons (Gallese et al., 2004), rather than in first-person experience (Froese and Gallagher, 2012).

Despite the wide-spread application of TT and ST in cognitive science, both theories have been criticized for not offering proper explanations for how we engage with each other socially on a day-to-day basis (De Jaegher et al., 2010; Froese and Gallagher, 2012; Gallagher, 2020, Chapter 4). Discussing these criticisms in-depth is beyond the scope of this article, but the most important aspects of the critique for the current argument relate to a focus on the individual that does not explain social interactive processes well, and a dismissal of first-person phenomenological experiences as important, in favor of a focus on neural mechanisms (De Jaegher et al., 2010; Froese and Gallagher, 2012; Gallagher, 2020, Chapter 4).

An alternative to TT and ST is “interaction theory” (IT; Froese and Gallagher, 2012; Gallagher, 2020). IT posits that social cognition cannot be explained fully by only considering individual participants, but that the dynamical, embodied process of interaction is central (De Jaegher and Di Paolo, 2007; De Jaegher et al., 2010; Froese and Gallagher, 2012; Chemero, 2016; Gallagher, 2020). In IT, minds are conceived of in enactive terms (Varela et al., 2016), and IT incorporates ideas from Gibsonian ecological psychology[1], such as social affordances (Heft, 2020). Minds are not localized in the brain but span brain, body, and environment; they are physically embodied, enacted in interaction, environmentally embedded, and extended (see Newen et al., 2018), and, thus, are not something that is inaccessible and hidden away in the brain or exclusively generated by brain states. IT builds on phenomenology [a detailed overview of the history of phenomenology and its influences on (cognitive) science is provided by Käufer and Chemero (2021)] in arguing that social cognition is dependent on direct perception without mediation by theory or simulation (De Jaegher, 2009; Krueger, 2018). Social understanding depends on, and is sometimes constituted by De Jaegher et al. (2010), immediate real-time interactions with others (Froese and Gallagher, 2012, p.441). In IT, following the definition of De Jaegher and Di Paolo (2007), social interaction is defined as:

[1]Despite the fact that both ecological psychology and the enactive approach build on phenomenological philosophy there are differences between both these theoretical frameworks. One such difference is in the type of explanation offered. Ecological psychology takes an ontological approach by describing the habitat of a species in terms of the opportunities for action for that species (i.e., affordances), whereas the enactive approach employs an epistemic strategy by starting from self-regulating processes of individual organisms (Baggs and Chemero, 2021). Note, that there is an ongoing discussion on how ecological psychology and the enactive approach could complement each other (e.g., McGann, 2016). Travieso et al. (2020) actually argue that the study of dynamic touch could bridge both frameworks, and it is interesting to consider whether dynamic approaches to *social* touch could do the same for enactive and ecological conceptions of social interactions. Importantly, social interactions in both ecological (Chemero, 2016) and enactive (De Jaegher and Di Paolo, 2007) terms are seen as dynamical processes with social understanding resulting from direct interactions, so there is indeed common ground to build on.

> a mutually engaged and co-regulated interaction between at least two autonomous and cognitive agents where the co-regulation and the interactive behaviors mutually affect each other, such that the interaction process constitutes a self-sustaining organization in the domain of relational dynamics (Froese and Gallagher, 2012, p.441).

Our embodied, interactive behaviors (which include movements, facial expressions, vocalisations, as well as touch) are always already situated in a social setting that involves cultural practices, social norms, and social roles (Gallagher, 2020). We do not need to theorize or simulate others' mental states because we can understand others through their embodied, interactive behaviors in context, and we respond with our own behaviors, to which they then respond with their own behaviours, and so forth. This co-regulated process is not reducible to mechanisms within each individual but can only be understood by considering the two (or more) dynamically coupled autonomous agents (De Jaegher and Di Paolo, 2007). Thus, we actively participate in generating shared meaning through embodied interactive behaviors (Froese and Gallagher, 2012; Gallagher, 2020, p.104). Here, interaction is the solution to social understanding, not a problem to be solved through theorizing or simulating (De Jaegher, 2009).

A conception of social cognition in IT terms is better able to explain how we understand each other in day-to-day interactions, aligns better with developmental evidence (e.g., Muir, 2002; Buttelmann et al., 2009), takes phenomenological and enactive research into account (e.g., Varela, 1996; Froese and Fuchs, 2012), and considers the holistic nature of brain-body-environment systems (for a detailed discussion of these points see Froese and Gallagher, 2012). Importantly, IT does not claim universality; in some cases, third-person deliberation about an other's mental state my indeed be how one understands another. However, these are the rare exceptions (De Jaegher and Di Paolo, 2013; Gallagher, 2020).

3. AN INTERACTION THEORY ACCOUNT OF (MEDIATED) SOCIAL TOUCH

Social touch is most often considered from a "sender and receiver" perspective (see Héron et al., 2021), that involves specific roles such as "communicator" and "recipient" (Jones and Yarbrough, 1985, p.20), or indeed "sender" and "receiver" (Fairhurst et al., 2022, p.57). In other words, social touch involves one person encoding a message that is then to be decoded by another person. For example, Hertenstein et al. (2006)'s definition of tactile communication involves transmission of "one's perceptions, thoughts, and feelings to another" (Hertenstein et al., 2006, p.8). On a more recent account, Fairhurst et al. (2022) discuss a signal-based sender and receiver communication model of affective touch, which they argue allows for the separate investigation of factors that impact the "perceived/decoded experience at the level of the receiver" (Fairhurst et al., 2022, p.55). These quotations suggest an observational, third-person stance toward social interaction that aligns with a TT or ST perspective on social cognition. In addition, the central role of the CT system in many conceptualizations of social touch aligns with a more neuro-reductionist perspective where sub-personal processes (i.e., CT afferents "coding for" social touch) are deemed important in explaining social understanding through touch (McGlone et al., 2014; Fairhurst et al., 2022).

Similar observations can be made with regards to MST. In their review paper of MST research, Haans and IJsselsteijn (2006) argue that social touch is symbolic and should be thought of in terms of sender and receiver. Van Erp and Toet (2015) provide a more sub-personal, brain-focused explanation of social touch in saying that "'Social touch' is what the brain makes of these [pressure, vibration, stretch, and temperature] stimulus characteristics (sensations)" (Van Erp and Toet, 2015, p.7). Elsewhere, I have provided a similar explanation of social touch in arguing for "a more cognitively involved process" to derive meaning from social touch (Huisman, 2017, p.393).

At the same time, these works do consider social touch to be bidirectional and reciprocal in nature (Muir, 2002; Hertenstein et al., 2006; Fairhurst et al., 2022), and most researchers agree that the context in which social touch occurs is important (Jones and Yarbrough, 1985; Hertenstein, 2002; Saarinen et al., 2021). In their definition of tactile communication, Hertenstein et al. (2006) remark that social touch is "almost always bidirectional and contingent" (Hertenstein et al. 2006, p.8; see also Muir 2002).

Similarly, Fairhurst et al. (2022) reserve a central role for bidirectionality, reciprocity, and the dynamic nature of touch in their communication model. Note, that these aspects align closely with an IT framework focusing on interaction, and less so with frameworks that focus on individual capacities. Thus, if we consider aspects such as bidirectionality and reciprocity to be important, and I argue we should, an IT framework may be better suited to explain social touch interactions.

On an IT account of (mediated) social touch, social touch is not about a sender "composing" (through a deliberate process of either inference or simulation) and sending a message to a receiver, who then engages in an inferential or simulation process to decode the meaning of a touch. Rather, social touch is a co-regulated process between two (or more) autonomous agents who actively participate in the generation of the meaning of the touch in interaction. This interaction is always already part of a context; even touches in lab studies are situated in a "lab setting" with specific social roles and norms. This context operates as a scaffold for the meaning and significance of actions and their expressive movements (Gallagher, 2020, p.165). We do not need to infer or simulate someone's mental states when hugging them at a funeral or wedding, for example; the meaning of the hug is scaffolded by the respective contexts, and is enacted through co-regulated bodily actions (including verbal and linguistic actions Di Paolo et al., 2018). Importantly, the autonomy of the agents in the interaction needs to be maintained (De Jaegher and Di Paolo, 2007; Froese and Gallagher, 2012), and the interaction process itself can take on an autonomy of its own, such as in the case of a handshake where both "shakers" do not let go of each others' hands, maintaining the interaction perhaps for longer than both interactants would like (see De Jaegher and Di Paolo, 2007, p.496 for an example involving kisses). If the autonomy of one agent is somehow reduced, or removed completely, such as in cases of coercion, we would no longer be speaking of a social interaction (De Jaegher and Di Paolo, 2007; De Jaegher et al., 2010). This would also be the case for, for example, transgressive touches, including physical harassment or in extreme cases assault, where an agent does not have (full) autonomy within the interaction. Such transgressive touches would on most conventional accounts be considered social touch along the same lines as a hug (e.g., "systematic changes in another's perceptions, thoughts, feelings, or behavior as a function of another's touch" Hertenstein et al., 2006, p.8). On an IT account where the autonomy of agents matters, this is not the case. Instead, a co-regulated, dynamical process of enacting meaning by autonomous agents, which inherently involves bidirectionality and reciprocity, is what defines social touch on an IT account.

4. DISCUSSION AND CONCLUSIONS

In this article I have provided an IT alternative to the dominant TT and ST views on social touch and MST. Here, I make three suggestions that could help shape an IT research agenda for (mediated) social touch.

4.1. Active Touch Exploration Rather Than Passive Touch Reception

From an IT perspective (social) touch, is considered as an active, dynamic sense (Carello and Turvey, 2017; Ratcliffe, 2018; Travieso et al., 2020). Suggestions for a stronger focus on the dynamic nature of touch have also been made for haptic technology research, in line with embodied and enactive approaches (Gillespie and O'Modhrain, 2011) and an interactive approach to MST including the use of dynamic haptic feedback (see also Huisman et al., 2021), has been put forth by Héron et al. (2021).

In line with these works, an IT approach to MST should consider the design of tools that enable active exploration through touch, rather than focus on passive touch reception where the recipient of a touch has strongly reduced agency and the focus is mainly on touch sensations (e.g., Huisman et al., 2016). The concept of "augmented sense-making" (Froese et al., 2011b) can be helpful in this regard. Augmented sense-making draws on the enactive approach and refers to devices that are designed to not be the focus of an experience themselves, but that do enable new ways to interactively explore the world. The enactive torch, a haptic navigation device, is an example of an 'enactive interface' that enables augmented sense-making (Froese et al., 2011b). With these types of 'active touch devices' the focus is less on the sensation of touch, but more on the use of touch to actively explore, where a user's actions and perceptions mediated through the device are tightly coupled (see Froese et al., 2011b; Froese and Ortiz-Garin, 2020). MST research and the design of MST devices should focus on this active touch component through approaches such as augmented sense-making, because it aligns with the interactive dynamic nature of (social) touch.

4.2. Social Interactions Rather Than Individual Responses

Social touch takes place, by definition, during social interactions. However, much work on MST not only puts the focus on touch reception, but conceives of interactions in terms of sender-and-receiver (see Héron et al., 2021), where opportunities for real-time co-regulation are diminished. In some cases, MST is studied in settings where the participant only receives touch and thus no opportunity for actual social touch interaction is present at all (e.g., Jung et al., 2013; Haans et al., 2014).

From an IT perspective, approaches where MST interactions are build around direct interaction where there is no clear distinction between sender and receiver are more fruitful as they more closely resemble naturalistic social touch interactions that revolve around co-regulation processes in which bidirectionality and reciprocity are central. Some devices for MST, such as InTouch (Brave and Dahley, 1997), distributed rope-pulling (Beelen et al., 2013), and coupled haptic knobs (Smith and MacLean, 2007), while not designed from an IT perspective, underscore the dynamical, bidirectional, and reciprocal nature of social touch in a technology-mediated setting that allow for co-regulation to take place.

A paradigm that enables the study of co-regulation in touch interactions is found in a study into haptic perceptual crossing by Auvray et al. (2009). In this paradigm, participants are both present in a minimalist 1-dimensional virtual environment. They both are represented by an avatar controlled with a mouse and they receive haptic feedback when their avatars cross each other in the virtual environment. With several distractors in place, only in situations where there is mutual recognition of each other does the interaction result in a stable state of recognizing the presence of the other (Froese et al., 2020). This perceptual crossing paradigm has been used in a number of studies into technology-mediated social interactions (e.g., Froese et al., 2014; Deschamps et al., 2016; Barone et al., 2020; Hermans et al., 2021) and has potential for the study of MST.

4.3. Phenomenological Experience Rather Than Only Outcome Measures

Research on MST has traditionally focused on the effects of MST, and comparatively little attention has been paid to first-person, lived experience in line with the phenomenological foundation of IT (see Froese et al., 2011a). Approaches for studying such lived experience have been developed using haptic interfaces (Froese et al., 2012) and phenomenological interview techniques (Høffding and Martiny, 2016) have already been applied to the study of tactile experiences (Obrist et al., 2013).

With a stronger focus on first-person experiences we also need to recognize that social (touch) interactions take place in context. This necessitates supplementing lab studies with studies taking place in different contexts. Tightly controlled experimental setups might only represent MST as it occurs in the particular situation of a scientific study. Some experimental control may have to be sacrificed in order to provide insights into the lived experience of people using MST devices in diverse contexts (see Saarinen et al., 2021). For example, in a field study by van Hattum et al. (2022), qualitative responses helped shed light on the way MST devices were actually used and experienced by participants over a two-week period of real-world use.

Besides helping understanding of lived experience of MST interactions, a focus on first-person experiences also forces us to consider the fact that lived experiences differ between different people. Rather than focus on sub-personal mechanisms, such as the CT-system (McGlone et al., 2014), a focus on phenomenological experiences would recognize diversity and has the potential to make MST research more sensitive to such diversity in the use of haptic devices for social touch (e.g., see Toro et al., 2020). Different people may enact different meanings through MST; an IT approach to MST would embrace these differences as part of the richness of social interactions.

4.4. Conclusions

In this article, I have argued for an IT perspective on MST that conceptualizes social touch as a co-regulated process between two (or more) autonomous agents who actively participate in the generation of meaning of a touch in interaction. The three suggestions for future MST research I provide build on research in ecological psychology, the enactive approach, and phenomenology (see Froese and Gallagher, 2012; Gallagher, 2020), and represent theories and methods that can aid the further development of a more fleshed-out IT perspective on mediated (social) touch. Such a perspective should help shape the design of and research into MST in a way that does justice to the interactive nature of social touch.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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Linking Haptic Parameters to the Emotional Space for Mediated Social Touch

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Social touch is essential for creating and maintaining strong interpersonal bonds amongst humans. However, when distance separates users, they often rely on voice and video communication technologies to stay connected with each other, and the lack of tactile interactions between users lowers the quality of the social interactions. In this research, we investigated haptic patterns to communicate five tactile messages comprising of four types of social touch (high five, handshake, caress, and asking for attention) and one physiological signal (the pulse of a heartbeat), delivered on the hand through a haptic glove. Since social interactions are highly dependent on their context, we conceived two interaction scenarios for each of the five tactile messages, conveying distinct emotions being spread across the circumplex model of emotions. We conducted two user studies: in the first one participants tuned the parameters of haptic patterns to convey tactile messages in each scenario, and a follow up study tested naïve participants to assess the validity of these patterns. Our results show that all haptic patterns were recognized above chance level, and the well-defined parameter clusters had a higher recognition rate, reinforcing the hypothesis that some social touches have more universal patterns than others. We also observed parallels between the parameters' levels and the type of emotions they conveyed based on their mapping in the circumplex model of emotions.

Keywords: mediated social touch, emotional space, haptics, social interaction, haptic glove, analog control, emotion recognition, pneumatic system

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1. INTRODUCTION

A social touch is a physical interaction that expresses an intent between two or more social agents. Typical examples of social touch include shaking hands with colleagues for greetings, hugging family members for comfort and affection, or patting a friend's shoulder for support and congratulation. Social touch is observed in a wide variety of contexts, not only among humans but also between mammals in general (Harlow and Zimmermann, 1959; Van Erp and Toet, 2015). Such physical interactions give a feeling of mutual awareness and enable to build and strengthen social bonds with other social agents such as other humans, animals, or even artificial intelligence.

Certain emotions such as comfort, love, and sympathy are hard to express in words, such as in written text or with oral speech (Field, 2010; Van Erp and Toet, 2015; Huisman, 2017). Touch is our primary non-verbal communication channel for conveying deeper intimate emotions (Jones and Yarbrough, 1985; Hertenstein et al., 2006; Van Erp and Toet, 2015), and preferred over body gestures and facial expressions for conveying both love and sympathy (App et al., 2011). People want to communicate whilst being physically separated, and although current media such as text messages and video-calls can enable social interactions; they are unable to provide any physical interactions. As a result, these current communication technologies help bring users closer, but the lack of tactile interactions leads to impoverished social interactions between the distant users. To maintain the physical connection, social touch can be conveyed using an intermediate haptic feedback device placed on distant interlocutors known as Mediated Social Touch. Several wearable devices have been investigated for the purposes of social haptic communication, including, shared physical spaces (Dodge, 1997) and objects (Brave and Dahley, 1997), handheld vibrotactile arrays (Chang et al., 2002; Borst and Cavanaugh, 2004), gloves (Singhal et al., 2017), sleeves (Huisman et al., 2013; Cang and Israr, 2020; Simons et al., 2020; Salvato et al., 2021), wristbands (Pezent et al. (2019), HeyBracelet, BondTouch), jackets (Chung et al., 2009; Vaucelle et al., 2009; Teh et al., 2012), and belts (Tsetserukou, 2010). These mediated social touch devices either render canned haptic patterns or directly map the sender's activities to real-time spatiotemporal haptic patterns on the receiver's body, in order to convey expressive touch features associated with user intents and emotions. In the present study, we investigate parametric compositions of haptic patterns to render expressive touch gestures on the hand, and how these parameters vary the affective content of the intended tactile message.

Within literature, there is a need to develop an understanding of the characteristics required to communicate social touch using a shared vocabulary between a sender and a receiver (Gallace and Spence, 2010; Van Erp and Toet, 2015). Recent research has investigated the construction of social touch messages, and if the receiver could interpret the sender's intention and embedded emotions from associated touch gestures on the body. Kirsch et al. (2018) examined touch characteristics to communicate emotions and showed that slow, gentle strokes on the forearm were likely to convey arousal and desire, however, love and supportive intentions were reliably elicited by gentle touch only. McIntyre et al. (2021) investigated social touch gestures associated with six common messages (attention, love, happiness, calming, sadness, and gratitude) conveyed between close relatives on the forearm. They examined primitive elements in touch gestures and developed a standardized set of touch expressions. These expressions were intuitive to their participants, even when the touch was delivered by a stranger with minimal context and training. These studies showed the universality of touch gestures and suggested physical features in interpersonal touch communication between users. Salvato et al. (2021) developed an algorithm to map touch features recorded on a discrete sensor array and rendered on a low degree-of-freedom haptic device on the forearm, and demonstrated above-chance success in communicating six social messages.

In the present study, we construct parametric models for haptic messages associated with high five, handshake, caress, asking for attention, and the pulse of a heartbeat, and render them on a user's hand using a haptic glove. We define two scenarios for each haptic message with different levels of emotional context and examine how model parameters vary with the affective content embedded in these messages. Within this study, we aim to look at building blocks of social touch and how users can tune them to haptically represent emotional content. In addition, we aim to determine how well these parameters can be generalized across participants.

The organization of the article is as follows: the details of the glove, control strategy, social scenarios and haptic parameters are described in Section 2. Section 3 will outline the first user study where participants tune the parameters for 10 different interaction scenarios, and Section 4 will detail the follow up user study where naïve participants attempt to recognize the correct interaction scenario using the tuned parameters from the first user study. Lastly, Section 5 will discuss the results from these two experiments and how modifying haptic parameters can alter the perceived emotional content in social interactions, outline limitations of this study, and paths for future work.

2. EXPERIMENTAL SETUP

2.1. Haptic Glove

The haptic glove is pneumatically actuated as shown in **Figure 1**. It embeds three types of actuators; 15 rounded inflatable bubbles that give normal pressure, four kinesthetic impedance actuators

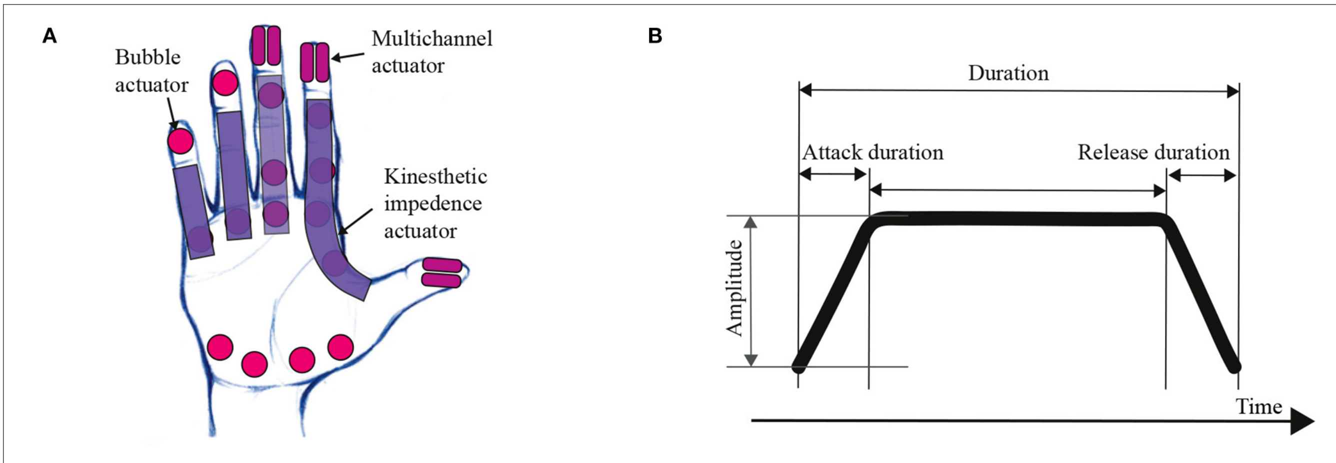


FIGURE 1 | Haptic glove description. **(A)** Description and placement of the haptic actuators and **(B)** illustration of a typical ASR profile for actuation.

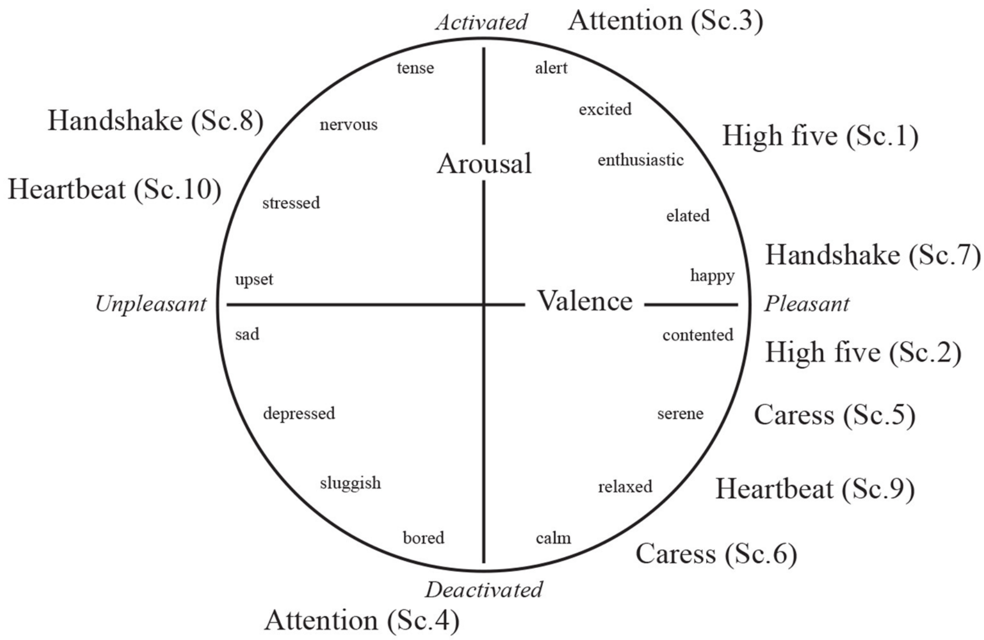


FIGURE 2 | Circumplex model of emotion (adopted from Alexandros and Michalis, 2013) and position of each of the social touch scenario prompts (N.B. valence and arousal placement of the scenarios are speculated by the authors).

TABLE 1 | Scenario prompt for each social touch.

Scenario #	Social touch prompts	Labels
	High five	
Scenario 1	"You just won a game where the score was tight, you are thrilled and you celebrate it with your game partner with a high five. Good job!"	Enthusiastic
Scenario 2	"You are feeling down and your good friend wants to cheer you up with a high five."	Contented
	Asking for attention	
Scenario 3	"Your friend wants to urgently show you something that they are very thrilled about and wants your attention."	Alert
Scenario 4	"A loved one is sorry to disturb you, but they would like your attention."	Bored
	Caress	
Scenario 5	"You have just spent a great day with a loved one and they are showing their affection to you."	Serene
Scenario 6	"You are anxious and a loved one wants to reassure you and help you calm down."	Calm
	Handshake	
Scenario 7	"You are meeting a very good friend that you appreciate a lot and you are happy to see them."	Happy
Scenario 8	"You are meeting a colleague for the first time at the beginning of an important meeting and you are nervous."	Nervous
	Heartbeat	
Scenario 9	"You are receiving the heartbeat of a loved one as they want to show you that they care for you."	Relaxed
Scenario 10	"You are receiving the heartbeat of a loved one as they want to show you that they are stressed."	Stressed

that prevent fingers bending, and three multichannel actuators at the thumb, index and middle fingertips. Depending on the actuation, the multichannel actuator can give shear forces along the lateral plane in any of the four directions or normal pressure when all the channels are inflated simultaneously. The pressures in the pneumatic actuators are controlled through a multichannel pneumatic analog control system (Stephens-Fripp et al., 2021) as this allows for controlling the amplitude of the pressure and the attack and release profiles of the pneumatic waveforms, which are sent to the actuators as time-varying pressure envelopes. Shown in **Figure 1B**, these envelopes have ASR (Attack-Sustain-Release) profiles, consisting of a duration to linearly ramp from zero to a desired maximum pressure level, a duration to sustain that pressure, and a duration to ramp back down to zero.

2.2. Social Touches and Interaction Scenarios

Based on the results of a recent study (Rognon et al., 2021) and on the feasibility of transmitting a social touch *via* a glove, we implemented four social touches, each belonging to a different social touch category according to Jones and Yarbrough (1985). For the social touches, we selected a handshake, which is ritualistic, caress which is a positive affection, asking for attention to represent control, and high five as a playful social touch. We also implemented the physiological signal heartbeat as it is currently the state-of-the-art of personal tactile message that one can send to someone (available on the Apple Watch). In our previous survey (Rognon et al., 2021), we have seen that a social touch can express very different emotions depending on the relationship with the other social agent and the interaction context. Therefore, we designed two scenarios for each of the social touches, which aim at triggering contrasting emotions. To design these scenarios, we built on the circumplex model of emotions (Russell, 1980) and more specifically on its representation proposed by Alexandros and Michalis (2013). This model suggests that emotions are distributed in a two-dimensional circular space, containing arousal and valence dimensions. We have designed the scenarios to be as far apart on the arousal and valence scales as possible, while remaining meaningful. For example, one of the high five scenarios is an "enthusiastic" situation, prompted with "You just won a game where the score was tight, you are thrilled and you celebrate it with your game partner with a high five. Good job!", and the second scenario is a "contented" situation prompted as "You are feeling down and your good friend wants to cheer you up with a high five". The placement of the scenarios in the circumplex model is shown in **Figure 2** and the complete list of the scenario prompts are in **Table 1**. Each scenario prompt includes the relationship with the other social agent and the context of the interaction. As can be seen in **Figure 2**, most scenarios are situated in the positive region of the valence axis and are spread across the arousal axis. This distribution of context scenarios was motivated by the desire to keep the interaction scenarios realistic but also engaging and not distressing the participants.

2.3. Social Touch Haptic Signals

For each of the social touch patterns, we implemented a set of parameters, such as the excitement level and the duration of the haptic cues. These parameters can be varied with sliders to determine the emotional content of the tactile message. For example, a high excitement level and short duration expresses an "enthusiastic" high five. The actuators used to construct the haptic patterns, the haptic signal and the parameters are shown on **Table 2**.

An example of an ASR signal is given in **Figure 1B** showing the amplitude, duration, and attack and release characteristics of the signal. To ensure haptic sensations remained perceivable, the minimum pressure for the amplitude setting was 1.2 psi. The maximum pressure was 15 psi to avoid any potential damage to actuators whilst still ensuring a strong force. During pilot studies, the 15 psi was shown to be stronger than any participant required for any of the interactions; this was confirmed in the study with all participants having settings below the maximum pressure level for all scenarios.

2.3.1. High Five

For the high five, all the actuators trigger synchronously following a trapezoidal signal with symmetrical attack and release duration (see **Table 2**). The multichannel actuators give normal force.

Excitement: when increasing the slider, the user increases the amplitude and decreases the attack and release durations (from 5% of the signal duration to 0%).

Duration: corresponds to the length of the high five and is proportional to the slider position. The duration can be varied between 0.08 and 0.5 s.

2.3.2. Asking for Attention

For asking for attention, five bubble actuators located on the upper palm trigger successive squared signals mimicking pokes (Baumann et al., 2010; McIntyre et al., 2019).

Excitement: this slider modifies the amplitude of a poke, and its length (between 0.04 and 1.2 s). The time between pokes is set to be the same length as the poke itself.

Duration: this slider changes the number of pokes, between one and eight.

2.3.3. Caress

For the caress, only the bubble actuators are triggered, which are divided into four groups along the hand. The group sizing was chosen to minimize complexity whilst maintaining authentic sensation based on initial trials.

Stroke rate: This slider changes the duration of one pulse from 0.2 to 1.5 s. The delay between pulses is set to 10% of the pulse duration and therefore also changes proportionally to the stroke rate. This ratio was chosen following our initial testing on both this glove and other haptic devices, and Stephens-Fripp et al. (2021) demonstrated an enhanced continuity sensation. We set the boundary of the stroke rate to be within the range of pleasant touch, 1 to 10 cm/s (McGlone et al., 2014). The attack and release duration are fixed each to 40% of the pulse duration as our initial testing on both this glove and other haptic devices demonstrated it to be the most pleasant signal (Stephens-Fripp et al., 2021).

Strength: changes the amplitude of the signal and is proportional to the slider position, which can vary between 1.2 and 15 psi.

2.3.4. Handshake

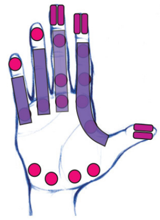
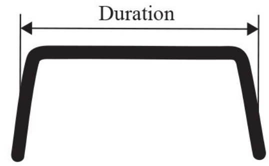
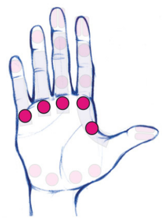
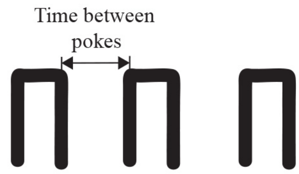
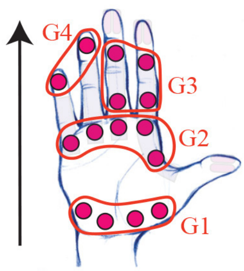
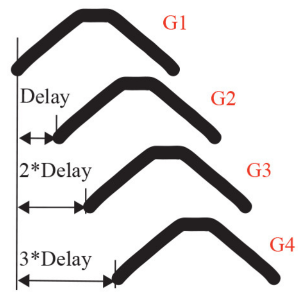
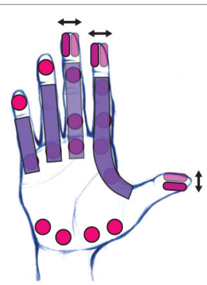
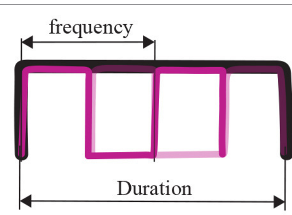
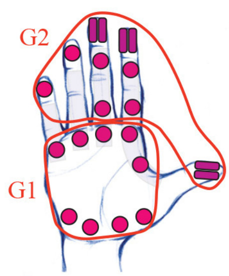
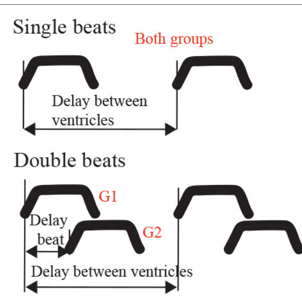
For the handshake, the actuators are triggered with two different signals: the bubble and the kinesthetic impedance actuators receive the black squared signal shown in **Table 2**, mimicking the grip force between hands (Knoop et al., 2017; Orefice et al., 2018). The multichannel actuators alternatively inflate and deflate as shown with the dark and light pink signals, mimicking the up and down movement of the handshake.

Strength: changes the amplitude of the signal and is proportional to the slider position, which can vary between 1.2 and 15 psi.

Excitement: sets the frequency of oscillation, between 1 and 3.33 Hz.

Duration: corresponds to the length of the handshake and is proportional to the slider position. The duration can be varied between 0.4 and 5 s.

TABLE 2 | Description of the social touch haptic signals.

	Actuators triggered	Haptic signal	Parameters
High five			• **Excitement:** amplitude of the signal, and attack and release duration • **Duration:** time length of the high five
Asking for attention			• **Excitement:** amplitude of the signal, length of one poke, and time between pokes • **Duration:** number of pokes
Caress			• **Stroke rate:** duration of one pulse, delay between pulses, attack/release duration • **Strength:** amplitude of the signal
Handshake			• **Strength:** amplitude of the signal • **Excitement:** frequency of the oscillation • **Duration:** time length of the handshake
Heartbeat			• **Number of beats:** single vs double beats • **Heart rate:** delay between ventricles, length of one beat, attack/release duration, delay between the beats • **Intensity:** amplitude of the signal

2.3.5. Heartbeat

Number of beats: to convey heartbeats, participants could choose either "single beats" or "double beats". "Single beats" trigger all the bubbles and the multichannel actuators at the same time, while the "double beats" alternate between two groups (the palm vs. the finger actuators).

Heart rate: this slider sets the heartbeat frequency between 50 and 220 bpm by changing the delay between the ventricles (Benson and Connolly, 2019). One beat length is inversely proportional to the heart rate slider and ranges between 0.6 and 0.1 s. As with the caress signal, the symmetrical attack and release duration are set to 40% of the beat duration.

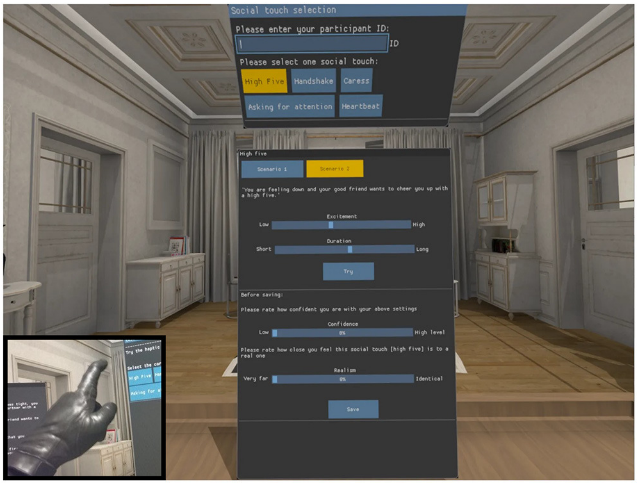


FIGURE 3 | VR environment with the UI presented to the participants for the first user study. The upper panel is used to choose the social touch, and the lower panel to design the haptic patterns and rate them for each scenario. The insert on the lower left shows the glove-like left hand pointing finger used to interact with the UI.

The delay between the two "double beats" is set to 40% of a beat length.

Intensity: changes the amplitude of the signal and is proportional to the slider position, which can vary between 1.2 psi and 15 psi. In the case of "double beats", the second beat, on the finger actuator, is given at half the amplitude for a more realistic sensation.

3. STUDY 1: PARAMETER DEFINITION FOR SOCIAL HAPTIC PATTERNS

3.1. User Study Description

The first user study investigated what should be the parameters of each social touch to convey a tactile message carrying a specific emotional content. 14 participants took part in this first user study (five women, eight men, and one unknown). They have been recruited within our organization and the demographics of 13 participants (one chose not to answer the background questionnaire) can be found in the Appendix 2.1 (**Supplementary Material**). Their task was to tune the parameters using sliders until the haptic patterns fit what they would expect in the presented scenario. Participants were seated, wearing an Oculus head mounted display, with the haptic glove on their right hand, holding the Oculus controller in their left hand to interact with the user interface (UI), and wearing noise canceling headphones playing white noise. We conducted the experiment in a VR environment to control the participants' visual feedback and prevent distractions by the real environment. **Figure 3** displays the VR environment that represents a living room. In this environment, participants were also sitting at a table facing a 2D panel with which they could interact using a glove-like left hand pointing finger. The participants' task was to first select the social touch and scenario to work on. The order was pseudo-randomized and dictated by the experiment facilitator. Then, they tuned the parameter values to fit the scenario prompts (see **Table 1**). The UI in **Figure 3** gives the example of the excitement and duration sliders for a high five. Participants had no time limit and could try the haptic pattern as many times as necessary. When they were satisfied with the resulting haptic pattern, they used the sliders shown below to rate their confidence level in the tuning and how close they thought their tuning was to a real social touch.

Participants also filled out a questionnaire about their demographics, and we measured their extroversion and agreeableness with a personality test (Goldberg, 1990). We also assessed their comfort with physical interaction using the CIT scale (Webb and Peck, 2015). The full background questionnaire can be found in Appendix 1 (**Supplementary Material**).

3.2. Results

To understand how the parametric signal space maps to each contextual social touch communication, we ran a silhouette analysis with a maximum of four clusters, as more clusters would not be meaningful on our 14 data points. Any cluster with less than two data points was defined as outliers according to the silhouette coefficients using the squared Euclidean distance criteria. We reduced the number of clusters until all the clusters (except one that can be treated as an outlier) were composed of at least four participants. We plot the results in the parametric space for each tactile message as shown in **Figure 4**. Each data point represents the data from a single participant. Typically, according to the Euclidean distance criteria more than one cluster emerged, except for the first scenario for high five and asking for attention communications. Using a Gaussian mixture model (GMM), we then calculated the probability with which each data point belonged to one cluster or another, defining the centroids as the mean of the Gaussian distribution(s), and the cluster covariance as the non-orthogonal variance, represented by the colored meshing in **Figure 4**.

For the high five scenario 1, tuning behavior was highly consistent. We found a single clear cluster composed of 12 participant responses (**Figure 4A**, left). The two additional data points were classified as outliers, not as forming an additional cluster. For scenario 2, there was greater variability in parameter tuning results across participants. Two clusters emerged (see **Figure 4A**, right) characterized by opposed duration parameter requirements but similar spread along the excitement axis.

For asking for attention in the context of scenario 3 (**Figure 4B**, left), parameter tuning behavior was highly consistent. We see a distinct cluster (red) emerge, composed of 12 of the 14 participants defined by a high excitement level and a mid-range duration on average. The same outlier criteria as applied to high five was applied here. Higher across participant variability was observed in the tuning behavior for scenario 4 (right) where responses form two clusters (light blue and purple), both characterized by shorter duration signals and excitement on the lower end of the spectrum, however, the two clusters occupy different regions of excitement in the space. The two remaining participants (dark blue) are considered as outliers.

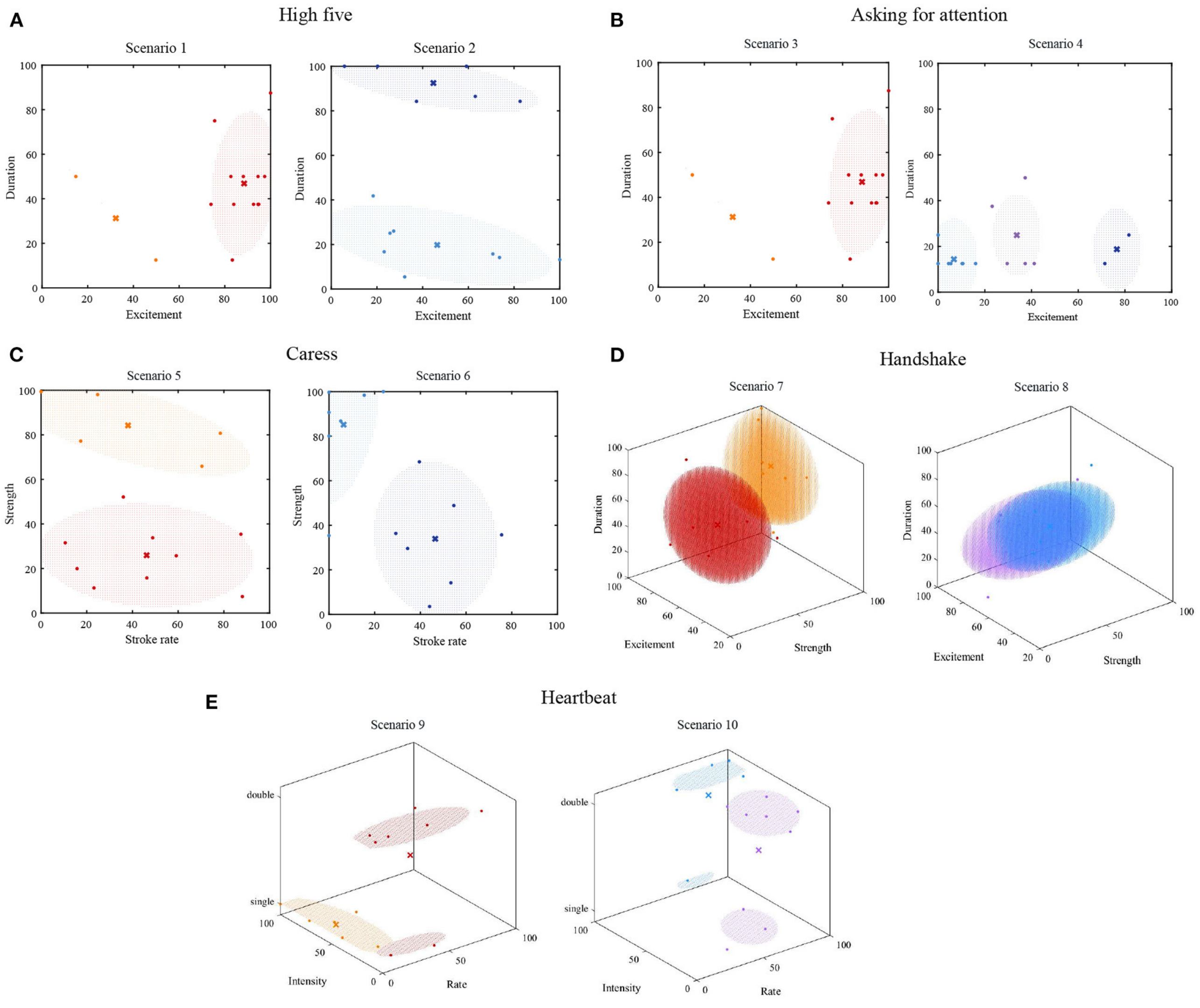


FIGURE 4 | Results of the first user study with the data clustering for each scenario represented in the parametric stimulus spaces. Each data point represents one participant, the crosses the clustering centroids, and the meshing the clusters' covariances for the **(A)** high five, **(B)** asking for attention, **(C)** caress, **(D)** handshake, and **(E)** heartbeat.

The distribution of the participant data for caress scenario 5 is highly spread along the parametric space (**Figure 4C**, left). Indeed, even if data are sorted into two clusters, we can observe that the data don't aggregate in a specific area of the space. One hypothesis is that the scenario prompt "You have just spent a great day with a loved one and they are showing their affection to you" was hard for the participants to identify with, as some participants reported. A second hypothesis is that there is no universal haptic pattern to express such feeling. To validate a hypothesis, more investigation is required. Scenario 6 (right) has a more defined clustering, with the light blue cluster being defined by a slow stroke rate and high strength and the dark blue cluster by mid-range stroke rate and strength. The caress distributions show quite high variance or spread for these clusters as indicated by their covariance $c = [386.57\ 52.67]$ for scenario 5 and $c = [83.79\ 39.18]$ for scenario 6.

As we can see from the size of the ellipses, the handshake clustering (**Figure 4D**) has quite a large covariance. Both clusters of scenario 7 (left) have high excitement and mid-duration, with the red cluster having mid-strength and the orange one high strength. Scenario 8 (right) has one cluster at low excitement and high duration (light blue) while the second one (purple) has high excitement and low duration. Both clusters are spread along the strength axis.

Finally, for the heartbeat (**Figure 4E**), we observe two distinct clusters for each scenario. Scenario 9 (left) is defined either as single beats, low rate and high intensity heartbeat or as double beats, also with low rate, but with low intensity. Scenario 10

TABLE 3 | Results of the centroids for each social touch.

	High five		Asking for attention		Caress	
	Excitement	**Duration**	**Excitement**	**Duration**	**Stroke rate**	**Strength**
Scenario 1a	93.8	10.3	88.5	46.8	38.0	84.2
Scenario 1b					46.2	25.9
Scenario 2a	44.7	92.5	6.7	14.4	6.4	85.2
Scenario 2b	46.4	19.8	33.7	24.9	46.5	33.9

	Handshake			Heartbeat		
	Strength	**Excitement**	**Duration**	**Rate**	**Intensity**	**Beats**
Scenario 1a	38.9	70.5	44.8	8.3	57.2	Single
Scenario 1b	94.4	86.8	61.9	35.1	17.6	Double
Scenario 2a	37.6	51.1	60.2	77.8	93.1	Double
Scenario 2b	56.8	89.5	25.3	69.3	29.0	Double

is defined with double beats and high rate either at low or high intensity.

To understand if there was an influence of participants' background (see Appendix 2.1 in **Supplementary Material**) on the parameter settings selected, confidence and realism ratings, we ran a Spearman's rank correlation analysis between each of these datasets. For none of these 200+ analyses was the participants' background significantly correlated with any parameters of interest, $r_{(11)} = < 0.65$, $p > 0.05$, see Appendix 2.3 in **Supplementary Material** for detailed values.

We also computed the confidence and realism mean and standard deviation per cluster. The visual representation of these can be found in Appendix 2.2 (**Supplementary Material**). We ran t-tests that showed no significant difference between the clusters' ratings, except for the realism of the two clusters for the first heartbeat scenario, $t_{(13)} = 2.5363$, $p = 0.026$.

Results of this first user study found specific data clustering, where the centroids are considered the typical parameters to convey the emotion of the scenario prompted. No rating nor participants' background enables us to determine ideal clusters between the ones found.

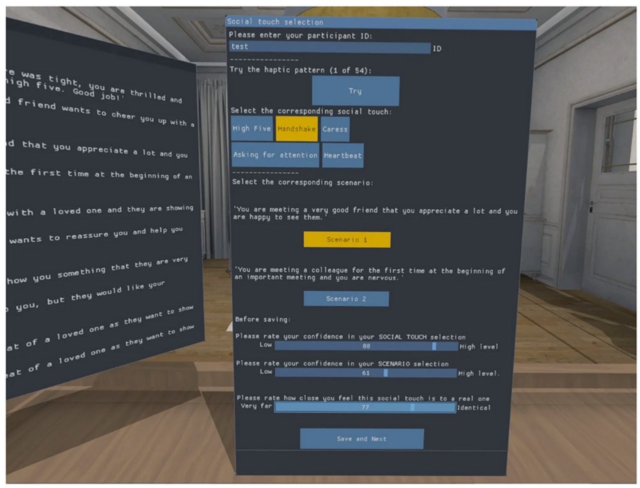


FIGURE 5 | VR environment with the UI presented to the participants for the second user study, where they selected the corresponding social touch and scenario, and they rated the haptic signal. The left panel reminded the social touch scenarios.

4. STUDY 2: VALIDATION OF SOCIAL HAPTIC PATTERNS

4.1. User Study Description

The aim of this second user study is to investigate how the haptic patterns generalize along message types and between users. Using the centroids of the clusters found in the first user study (see **Table 3**), we implemented these 18 haptic patterns and 10 naïve participants (four women, five men, one prefer not to answer, see Appendix 3.1 in **Supplementary Material** for more demographics data) of the second user study had to recognize them as one of the 10 possible tactile messages. One additional participant did not complete the experiment and is not included in the data analysis. Participants were recruited from the same organization pool as in user study 1. The participants used the same setup and environment as in the first user study. As shown in **Figure 5**, the participants tried the haptic pattern, selected the matching social touch (over five choices), and then selected the corresponding scenario (two choices). On their left, a panel reminded them of the social touch scenarios. For each trial, they also rated their confidence in both the social touch selection and the scenario selection, and rated how close they thought this haptic pattern was to a real one. Each of the 18 haptic patterns were presented 3x pseudo-randomly to the participant, and they were able to try the haptic pattern as many times as they wanted. The participants could refer to the panel with the list with the 10 scenario prompts at any time. They did not receive any feedback on their performance. Participants of the second user study also filled the same participant background questionnaire as for the first user study (see Appendix 1 in **Supplementary Material**).

4.2. Results

4.2.1. Haptic Pattern Recognition Rate

Results are represented in confusion tables (see **Figures 6, 7**). On the y-axis is the social touch presented to the participant, also called the true class, and on the x-axis the participant answer, or predicted class. The diagonals are the cases where the participant correctly recognized the type of social touch. We can see that all social touches were recognized well above chance level (20%).

Caress was the most distinct social touch with 91.7% correct recognition, followed by high five with 86.7%. Handshake had a recognition rate of 51.7% and was often mistaken for heartbeat, which also has a "pulsation" pattern. Heartbeat was the least distinctive haptic pattern, often mistaken for asking for attention.

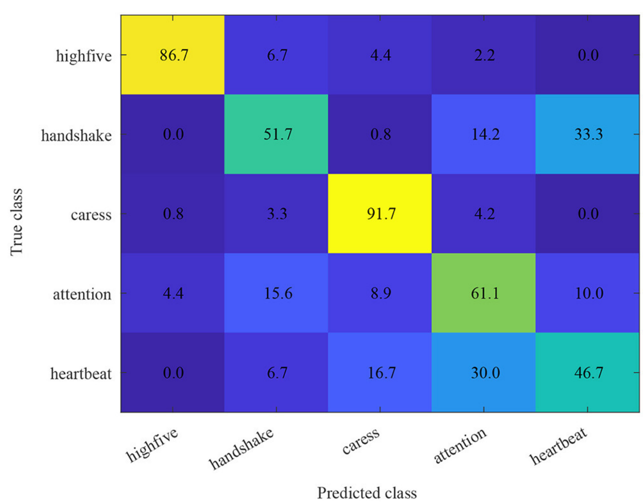


FIGURE 6 | Confusion table presenting the recognition rate of the social touch with the true class, the five social touch, in the y-axis and the predicted class, also the five social touch in the x-axis.

Figure 7 shows the results of the emotional content recognition of the tactile messages. This confusion table shows only the highest correct recognition rate per scenario on the y-axis. On the x-axis, we have the 10 tactile messages, or possible answers. A table representing the full dataset can be found in Appendix 3.2 (**Supplementary Material**). Each of the 18 haptic patterns has been presented three times to the 10 participants. Therefore, each of them has been rated 30x. Accordingly, 3.33% represents one selection of one participant. The cells outlined in gray highlight the correct social touch selection and the one in black, the correct social touch and scenario selection.

We can observe that the "enthusiastic" high five and the "alert" asking for attention patterns have a high recognition rate (see **Table 1** for the scenario prompts), consistent with the human-human communication in McIntyre et al. (2021), who showed higher recognition rates for "happiness" and "attention". Caress had a high recognition rate for the social touch type, but the emotional content is harder to identify. We can see it with the small rating difference between the two scenarios (between the right and left columns outlined in gray). The emotional content of both scenarios of the handshake is also difficult to recognize, and we can also observe that some haptic patterns are often selected as representing the opposite tactile message such as handshake 2a vs. handshake 2b (see Appendix 3.2 in **Supplementary Material**). As shown in **Figure 6**, some haptic patterns are mistaken for another social touch. In **Figure 7**, we can see more in detail which scenarios are more or less distinct. For example, handshake scenario 7 (conveying "happiness") is often mistaken for the heartbeat scenario 10 (conveying "stress").

4.2.2. Confidence and Realism Levels

Results for the confidence and realism levels are presented similarly as for the recognition rate in the confusion tables of **Figures 8, 9**, respectively. To understand whether the users confidence or realism levels could illuminate the recognition rate results (**Figure 7**), we computed the correlation between

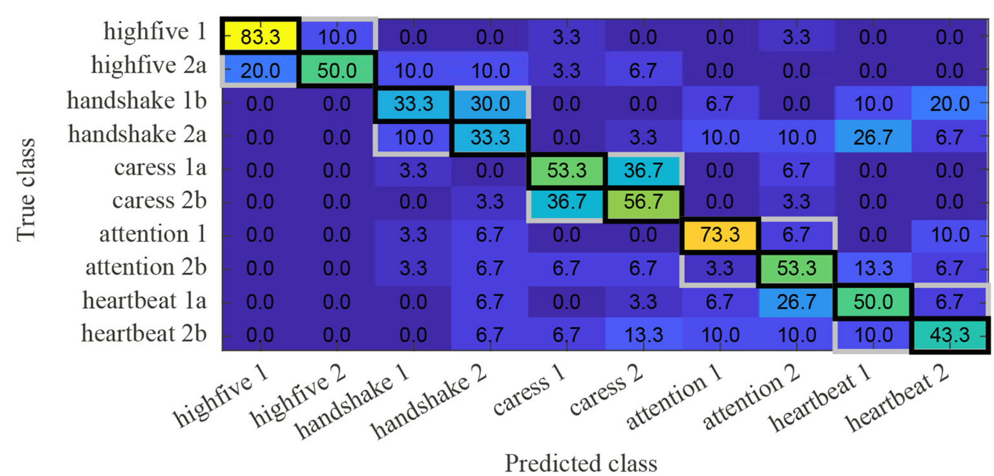


FIGURE 7 | Confusion table presenting the recognition rate of the social touch emotional content. The y-axis displays only the cluster of the haptic patterns (true class) that had the highest correct recognition rate per scenario, and the x-axis displays the 10 possible answers (predicted class). The full dataset can be found in Appendix 3.2 (**Supplementary Material**). The cells outlined in gray highlight the correct social touch selection and the one in black, the correct social touch and scenario selection.

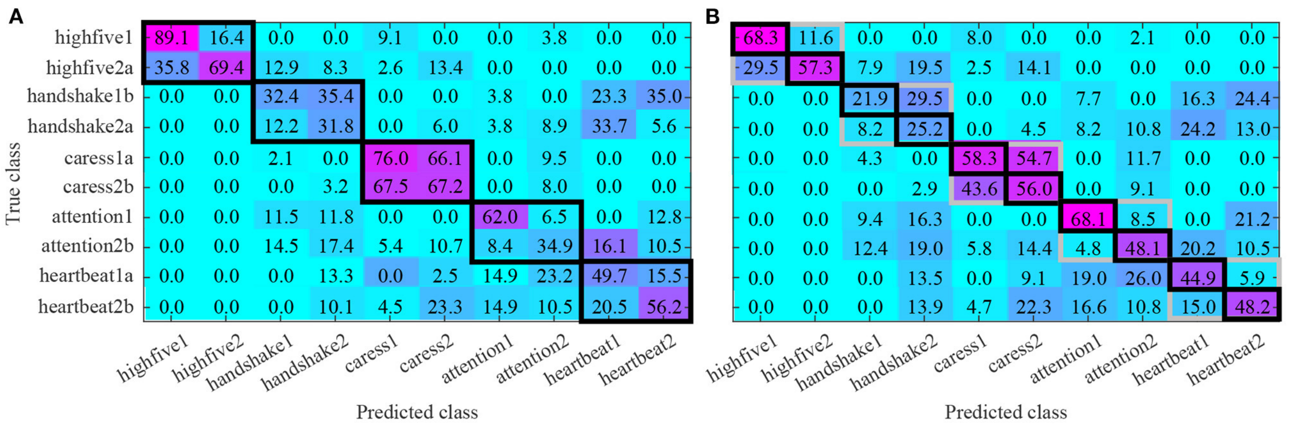


FIGURE 8 | Confusion table presenting the participants' confidence rating in **(A)** their social touch selection and **(B)** their scenario selection. Only the cluster with the highest correct recognition rate per scenario is represented. The full dataset can be found in Appendix 3.2 (**Supplementary Material**). The cells outlined in black highlight the correct selections.

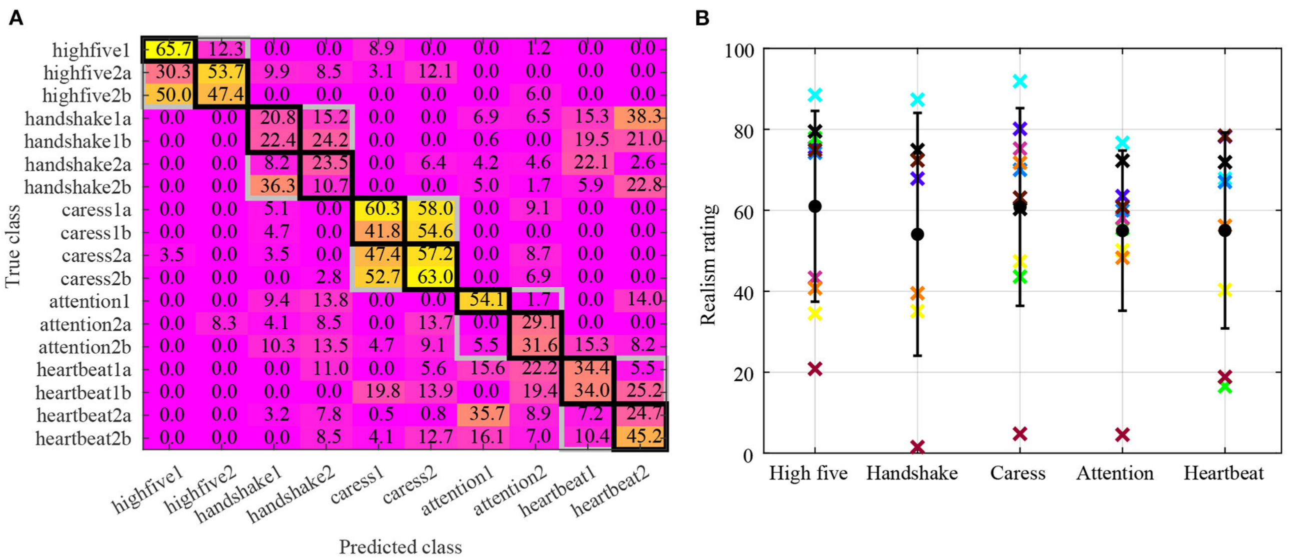


FIGURE 9 | Results of the realism rating. **(A)** Confusion table representing how close to a real social touch participants rated the haptic patterns. Only the clusters with the highest correct recognition rate per scenario are represented. The full dataset can be found in Appendix 3.2 (**Supplementary Material**). The cells outlined in gray highlight the correct social touch selection and the one in black, the correct social touch and scenario selection. **(B)** Realism rating for each social touch. Each colored cross represents one participant, the black circles the mean rating per social touch and the black error bar the standard deviation.

the recognition rates, confidence, and realism level. There is a strong correlation between the three ratings (confidence in the social touch selection, confidence in the scenario selection, and realism), and the recognition rate (Spearman's rank correlation analysis, $r_{(8)} > 0.98$, $p < 0.001$ for all six tests, see Appendix 3.3 in **Supplementary Material** for detailed statistics). This indicated that in the case of an incorrect selection, the participants were relatively confident in their answer and did not choose it randomly. For example, a participant confusing the handshake for the heartbeat was quite confident in their choice and rated realism relatively high.

Figure 9B displays each participant's realism rating (colored crosses), the mean rating (black circles) and the standard deviation (black error bar) of the correct answers for each social touch. We can observe that the average realism is between 54 and 61% of being considered as a real social touch, with very few differences between the social touch type. However, there is a large standard deviation between the participants, with the cyan participant rating the realism to every social touch above 67%, while the dark red participant never rated a social touch above 21%.

4.2.3. Interparticipant Analysis

There were no significant correlation between the participants' background and personality types, and their social touch and

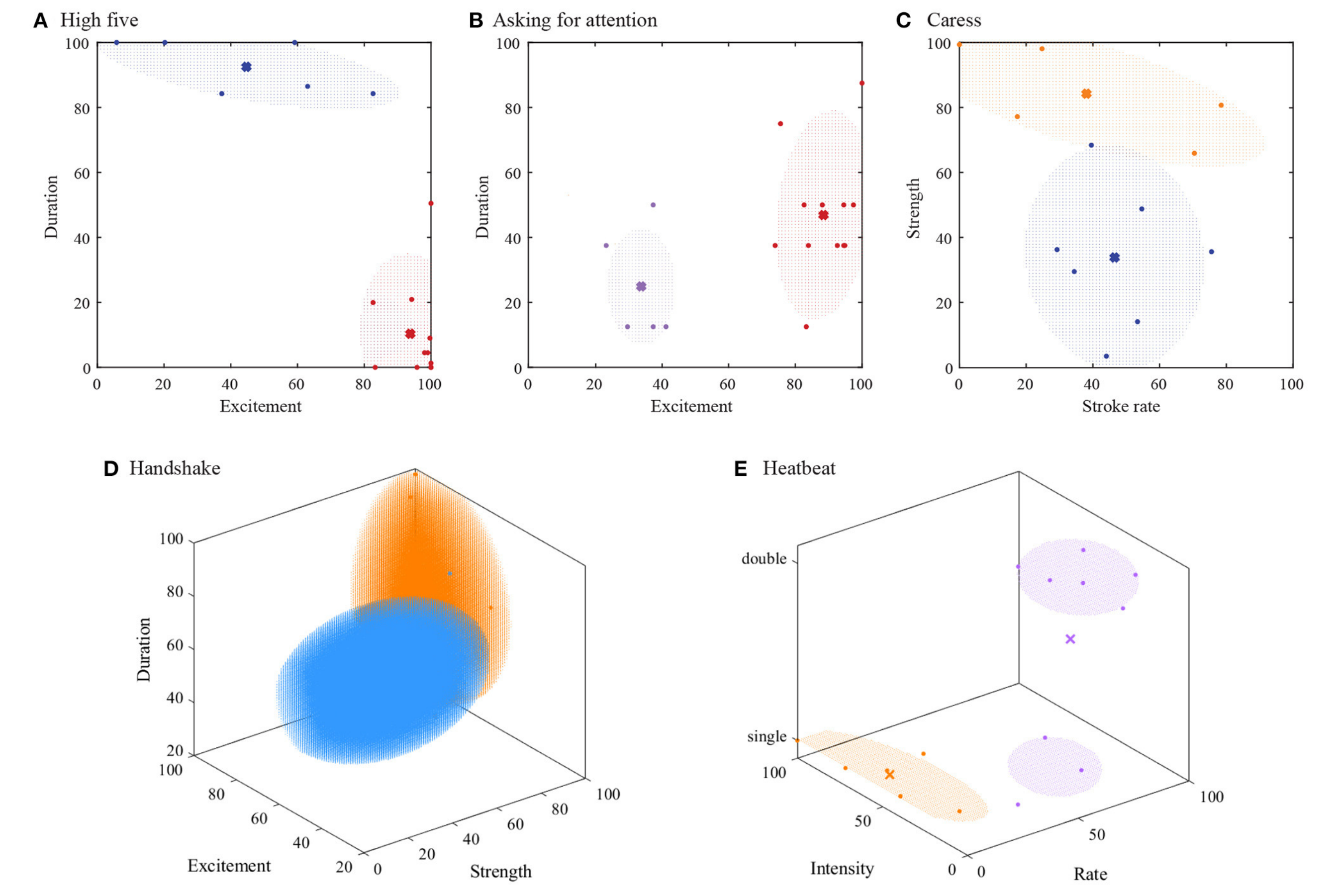


FIGURE 10 | Data of both scenarios represented in the same parametric space for the **(A)** high five, **(B)** asking for attention, **(C)** caress, **(D)** handshake, and **(E)** heartbeat. The dots represent one participant, the crosses the clustering centroids, and the meshing the clusters' covariances.

scenario selection correctness $r_{(8)} < 0.6$, $p > 0.05$, see Appendix 3.3 in **Supplementary Material**.

To check if results were biased due to the novelty of the task, we analyzed whether the participants were learning along the trial and therefore whether their performance was increasing over the trials. We used a general linear mixed model (GLMM) to identify learning at the individual participant and group levels. Our logit link regression function was used to determine whether our binomial data showed a learning effect or not. We performed a single sample test to identify whether the slopes were significantly different than zero, where we hypothesized that a slope greater than zero indicates learning has occurred. We ran the analysis for both the social touch recognition rate and recognition of the scenario to which the social touch belonged. The social touch recognition rate shows no significant effect, $t_{(9)} = 1.4263$, $p = 0.19$. However, the social touch and scenario recognition rate is increasing significantly over time, $t_{(9)} = 2.3940$, $p = 0.04$. We ran a Bayes Factor analysis to understand the effect of this learning, which showed that the evidence is weak/anecdotal (2.08, BF10 < 3) (Jeffreys, 1998).

With this second user study, we demonstrated that the patterns derived from the first user study are generalizable to naïve users. Some of the haptic patterns were easier to recognize than others. Based on the data analysis, we could select the 10 best social touch haptic patterns to represent the scenarios with their emotional content.

5. DISCUSSION

The first user study defined the parameter levels for both scenarios of each social touch (see **Figure 4**) and the second user study validated the results and pointed out which clusters were the most recognizable (see **Figure 7**). When the best haptic pattern is selected and the data of both scenarios are plotted in the same parametric space, we can observe that specific emotions belong to a specific area of the parametric space.

Figure 10 displays the results of the most recognizable cluster of each scenario. For the high five (a), we observe that the clusters representing both scenarios are distinct and belonging to specific areas of the parametric space, with a high excitement and low duration representing an "enthusiastic" high five (scenario 1, red cluster), while a long duration is more representative of cheering someone up (scenario 2, blue cluster). Asking for attention (b) also has distinct clusters, with high excitement and mid-range duration representing "alert" (scenario 3, red cluster) and a low excitement and short duration representing a "bored" touch (scenario 4, purple cluster). The emotional content of the caress (c) is harder to interpret as the clusters are spread and the recognition rate is low between both scenarios (see **Figure 7**). We surmise a high strength may convey "serenity" (scenario 5, orange cluster) while a lower strength represents "calming" (scenario 6, blue cluster). The results of the second user study helped to discern the cluster of the handshake (d). It determined that high strength and high excitement convey a "happy" handshake (scenario 7, orange cluster), while lower strength and excitement convey a more "nervous" one (scenario 8, blue cluster). However, the recognition rate differences were quite low between the clusters (see **Figure 7**) so further investigation is required to build stronger claims. For the heartbeat (e), we observe distinct clustering belonging to a specific area of the parametric space. A low heart rate with single beats conveys a "relaxed" state (scenario 9, orange cluster), while a high heart rate with double beats conveys "stress" (scenario 10, purple cluster).

We see in the previous paragraph that there appears to be a relationship between the parameter levels and the emotional content within each social touch. We can also observe some parallels between the common parameters and our speculated location of each interaction on the circumplex model of emotion. For example, in our scenarios, there is a relationship between the excitement level and the arousal level.The higher excitement levels were often observed for the scenarios that correspond to high-arousal emotions. We can notice, however, that the handshake excitement level does not follow this trend. This may be due to the used interaction scenario, where people may want to project self-confidence and empowerment and therefore give a low excitement level in their handshake despite being nervous, however, we require cognitive interviews to validate this hypothesis. Similarly we observed the scenarios that were representing a higher valence level were tuned by the participants to have a higher strength level. These results are preliminary as we only tested two scenarios for each social touch and further investigations are required looking at multiple points across the emotional space for each touch in order to generalize these relationships for the parameters across the full emotional quadrant. In addition, the mapping of each of these scenarios on the circumplex model of emotion was chosen by the authors with internal piloting, and differences in trends may have arisen from a different interpretation of the anticipated valence and arousal of each interaction scenario. Follow up studies will require participants to map their perceived valence and arousal from the various versions of the social touch received.

Overall, the accuracy to identify correct social touch by naïve participants was 67.6% on the hand using the glove, which is comparable to the human-human communication scores of the standardized touch gestures in McIntyre et al. (2021) on the forearm (73% in experiment 3 and 65% in experiment 4). It is worth noting that these are haptic only cues, without the contextual visual information that comes with interacting with another person which is hypothesized to add to the overall realism experience.

6. CONCLUSION

With this research, we demonstrated that social touch with their specific emotional content can be conveyed using a pneumatic haptic glove. For the four social touches and the physiological signal, we were able to change the emotional mapping with differing valence and arousal levels (represented by a different interaction scenario) by changing the chosen haptic based parameters. To the best of the authors knowledge, this is the first study to link changing haptic based parameters to change the emotional space for mediated social touch. The link between strength and excitement with valence and arousal space respectively was consistent across the different types of social touch (with the exception of handshake's excitement). These results demonstrate the potential of creating haptic building blocks to map a social touch to the emotional spaces. However, further experimentations with more scenarios across the emotional space and run on a larger pool of participants is required to determine generalizability of these parameters. The second user study demonstrated that all the haptic patterns were recognizable by a naïve person well above chance level. Although, it appears that personalization may be required to optimize mediated social touch haptic patterns, our results indicate a level of commonality in different people's social touch language. In addition, since we only speculated the arousal/valence mapping of each scenario, future work should include the receiver's interpretation of arousal/valence mapping.

The results indicated that the emotional content of the caress and the handshake were harder to recognize in some of the trials, shown by a higher spread in the clusters. These social touches may benefit from further context and/or personalization such as tunable haptic patterns or gesture recordings on the sender side. It would be also interesting to investigate if training, or simply more familiarity with the system would further improve the recognition rate of the haptic patterns. In addition, although the studies were performed in a virtual reality environment, there was no visual and auditory information for the person to interact with. Future studies need to be developed to study how a multisensory environment and/or additional context impacts on the interaction realism.

During these two user studies, we limited the experiment to five social interactions in two different scenarios. This gave us an indication of how we can alter the different parameters to change the emotional mapping of the same social interaction in the context of haptic glove. Further studies are needed to determine how well this approach generalizes to other social touches not explored here. In addition, in future work we will explore the development of a model to enable the prediction of the required parameter levels for new interaction scenarios based on its anticipated valence and arousal mapping.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because Meta Platform Inc., has a strict policy about sharing dataset. Requests to access the datasets should be directed to carinerognon@fb.com.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Western Institutional Review Board, Inc. (WIRB), Washington, USA. The participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

CR, BS-F, and AI designed the study. BR made the software for the user studies. CR and BS-F mounted the user studies. CR conducted the data collection. CR and JH-O'B were responsible for data processing and statistical analyses. All authors contributed to the initial piloting study. They also all participated to the manuscript 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/fcomp.2022.826545/full#supplementary-material

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3D Visual Tracking to Quantify Physical Contact Interactions in Human-to-Human Touch

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Across a plethora of social situations, we touch others in natural and intuitive ways to share thoughts and emotions, such as tapping to get one's attention or caressing to soothe one's anxiety. A deeper understanding of these human-to-human interactions will require, in part, the precise measurement of skin-to-skin physical contact. Among prior efforts, each measurement approach exhibits certain constraints, e.g., motion trackers do not capture the precise shape of skin surfaces, while pressure sensors impede skin-to-skin contact. In contrast, this work develops an interference-free 3D visual tracking system using a depth camera to measure the contact attributes between the bare hand of a toucher and the forearm of a receiver. The toucher's hand is tracked as a posed and positioned mesh by fitting a hand model to detected 3D hand joints, whereas a receiver's forearm is extracted as a 3D surface updated upon repeated skin contact. Based on a contact model involving point clouds, the spatiotemporal changes of hand-to-forearm contact are decomposed as six, high-resolution, time-series contact attributes, i.e., contact area, indentation depth, absolute velocity, and three orthogonal velocity components, together with contact duration. To examine the system's capabilities and limitations, two types of experiments were performed. First, to evaluate its ability to discern human touches, one person delivered cued social messages, e.g., happiness, anger, sympathy, to another person using their preferred gestures. The results indicated that messages and gestures, as well as the identities of the touchers, were readily discerned from their contact attributes. Second, the system's spatiotemporal accuracy was validated against measurements from independent devices, including an electromagnetic motion tracker, sensorized pressure mat, and laser displacement sensor. While validated here in the context of social communication, this system is extendable to human touch interactions such as maternal care of infants and massage therapy.

Keywords: touch, social touch, haptics, visual tracking, tactile mechanics, human performance, emotion communication

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INTRODUCTION

Social and emotional communication by touch is important to human development in daily life. It contributes to brain and cognitive development in infancy and childhood (Cascio et al., 2019), and plays a role in providing emotional support (Coan et al., 2006), and forming social bonds (Vallbo et al., 2016). For example, being touched by one's partner mitigates one's reactivity to psychological pressure, as observed in decreased blood pressure, heart rate, and cortisol levels (Gallace and Spence, 2010). Behaviors such as compliance, volunteering, and eating habits are also positively improved (Gallace and Spence, 2010). Moreover, several works now indicate that particular social messages and emotional sentiments can be readily recognized from touch alone (Hertenstein et al., 2006; Hertenstein et al., 2009; Thompson and Hampton, 2011; Hauser et al., 2019a; McIntyre et al., 2021). Despite their importance and ubiquity, we have just begun to quantify the exact nuances in the underlying physical contact interactions used to communicate affective touch.

To decompose how physical contact interactions evoke sensory and behavioral responses, most prior studies employ highly controlled stimuli, which vary a single factor at a time. In particular, mechanical and thermal interactions are typically delivered to a person's skin using robotically driven actuators (Löken et al., 2009; Essick et al., 2010; Ackerley et al., 2014a; Tsalamlal et al., 2014; Bucci et al., 2017; Teyssier et al., 2020; Zheng et al., 2020). For example, brush stimuli swept along an arc have been widely adopted to mimic caress-like stroking, while controlling their velocity, force, surface material, and/or temperature. Using such stimuli, C-tactile afferents are shown to be preferentially activated at stroke velocities around 1–10 cm/s, which align with ratings of pleasantness (Löken et al., 2009; Essick et al., 2010; Ackerley et al., 2014a). Beyond experiments to examine brush stroke, more complex interactions have been delivered via humanoid robots and robot hands (Teyssier et al., 2020; Zheng et al., 2020). However, device-delivered stimuli do not fully express the natural and subtle complexities inherent in human-to-human touch. This can result in disconnect with the everyday, real-world interactions for which our sensory systems are finely tuned.

Measuring and quantifying free and unconstrained human-to-human touch interactions is complex and challenging. In particular, the physical interactions are unscripted, unconstrained, and individualized with rapid and irregular transitions. Indeed, multiple contact attributes often co-vary over time, e.g., lateral velocity, contact area, indentation depth. Therefore, in moving toward quantification, the initial efforts used qualitative, manual annotation to describe touch gestures, and their contact intensity and duration (Hertenstein et al., 2006; Hertenstein et al., 2009; Yohanan and MacLean, 2012; Andreasson et al., 2018). While adaptable to a wide range of touch interactions and settings, qualitative methods are constrained by the time required to analyze the data, the potential subjectivity of human coders, and a courser set of metrics and classification levels. For instance, contact intensity is typically classified in only three levels as light, medium, strong. As a result, automated techniques have been introduced, such as electromagnetic motion trackers (Hauser et al., 2019a; Lo et al., 2021) and sensorized pressure mats (Silvera-Tawil et al., 2014; Jung et al., 2015), with each their own capabilities and limitations. For instance, electromagnetic trackers capture the movement of only a handful of points, thus unable to monitor complex surface geometry, and can emit electromagnetic noise incompatible with sensitive biopotential recording equipment. Pressure sensors and mats inhibit direct skin-to-skin contact, when even thin films are shown to attenuate touch pleasantness (Rezaei et al., 2021). Three-dimensional optical tracking methods have also been employed, such as infrared stereo techniques (Hauser et al., 2019a; Hauser et al., 2019b; McIntyre et al., 2021), motion capture systems (Suresh et al., 2020), and stereo cameras with DeepLabCut (Nath et al., 2019). While these methods are specialized in tracking joint positions of hands and limbs, they do not capture the shape and geometry of body parts, since the infrared cameras lack sufficient accuracy on depth, motion capture systems only track pre-attached markers, and stereo matching of multiple cameras often fail with texture-less surfaces. In contrast, depth cameras can provide high spatial resolution point clouds and allow shape extraction of texture-less body parts, such as a forearm. Depth cameras, as well, are more readily set up without calibration, afford minimum magnetic interference, and can be located at a larger distance from the area of interest. While depth cameras have been used in hand tracking and 3D reconstruction (Rusu and Cousins, 2011; Taylor et al., 2016), they have not been used to measure contact interactions in human-to-human touch.

While defined to a degree, we are still deciphering those physical contact attributes vital to social touch communication. In such settings, human touch interactions tend to include gesture, pressure/depth, velocity, acceleration, location, frequency, area, and duration (Hertenstein, 2002; Hertenstein et al., 2006; Hertenstein et al., 2009; Yohanan and MacLean, 2012; Silvera-Tawil et al., 2014; Jung et al., 2015; Andreasson et al., 2018; Hauser et al., 2019a; Hauser et al., 2019b; Lo et al., 2021; McIntyre et al., 2021). To understand the functional importance of specific movement patterns, certain attributes such as spatial hand velocity have been further decomposed into directions of normal and tangential (Hauser et al., 2019a) or forward-backward and left-right (Lo et al., 2021). Moreover, simultaneous tracking of multiple contact attributes is needed for understanding naturalistic, time-dependent neural output of peripheral afferents. For example, a larger contact area should recruit more afferents, larger force or indentation should generate higher firing frequencies, and optimal velocity in tangential direction should evoke firing of C-tactile afferents (Johnson, 2001; Löken et al., 2009; Hauser et al., 2019b).

Herein, we develop an interference-free 3D visual tracking system to quantify spatiotemporal changes in skin-to-skin contact during human-to-human social touch communication. Human-subjects experiments evaluate its ability to discern unique combinations of contact attributes used to convey distinct social touch messages and gestures, as well as the identities of the touchers. Moreover, the system's spatiotemporal accuracy is validated against measurements from independent devices, including an electromagnetic motion tracker, sensorized pressure mat, and laser displacement sensor.

HUMAN-TO-HUMAN CONTACT TRACKING SYSTEM

This work introduces a 3D visual tracking system and data processing pipeline, which used a high-resolution depth

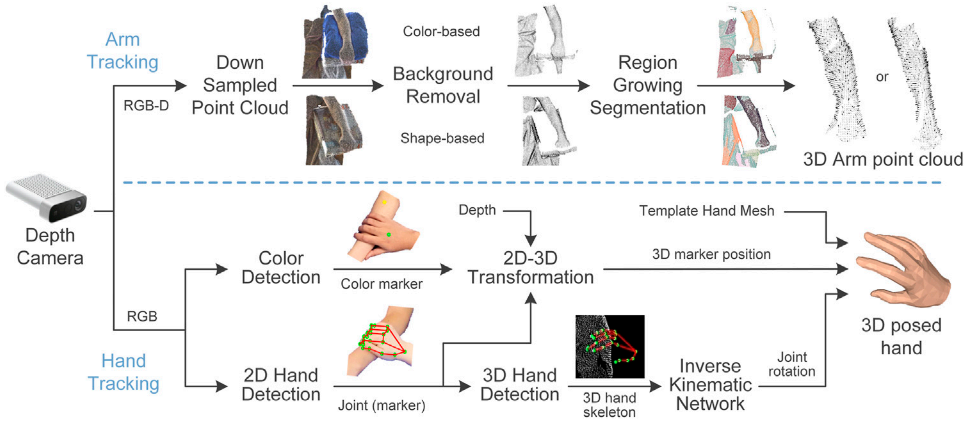

FIGURE 1 | 3D visual tracking setup and data workflow. The toucher's hand and receiver's forearm are tracked using one depth camera (Microsoft Azure Kinect). Forearm shape is extracted as a point cloud while the hand mesh is animated by the gestures and movements of the toucher's hand.

camera to quantify contact attributes between the bare hand of a toucher and the forearm of a receiver. As illustrated in **Figure 1**, the tracking system captured the 3D shape and movements of the toucher's hand and the receiver's forearm independently but simultaneously within the same camera coordinate system. Physical skin contact was detected between the hand and forearm based on interactions of their 3D point clouds. Seven contact attributes were derived over the time course of touch, which were contact area, indentation depth, contact duration, overall contact velocity, and its three orthogonal velocity components.

3D Shape and Motion Tracking With Depth Camera

The tracking procedure extracts the detailed 3D shape of the touch receiver's forearm. By merging the camera's RGB and depth information, an RGB-D image was derived and then converted into a dense point cloud per frame. The point cloud was cropped and downsampled to balance information and computation costs. To obtain a clean point cloud of the forearm without background, neighboring points around the forearm were first removed. Two removal methods were used alternatively based on the experimental setup (**Figure 1**). If the receiver's forearm was placed on a flat surface, such as a table, the points within that flat surface could be removed in a shape-based manner using the plane model segmentation algorithm provided by the Point Cloud Library (PCL) (Rusu and Cousins, 2011). In the second case, if a monochromatic holder was set underneath the forearm, such as a cushion, then the points of that holder could be removed by color-based segmentation in the HSV color space. Next, the 3D region growing segmentation algorithm (Rusu and Cousins, 2011) was applied to separate the rest point cloud into multiple clusters according to the smoothness and distance between points. Since neighboring points around the forearm were removed in advance, points farther away in the background were assigned to separate clusters instead of being blended with the arm. Finally, by setting a relatively large smoothness threshold, all arm points could be grouped into one cluster despite the curvature of the forearm shape.

In human-to-human touch scenarios, the receiver's forearm is frequently occluded by the toucher's hand. Given that a blocked arm region is nearly impossible to capture, only the shape of the forearm prior to the contact was extracted. More specifically, the forearm point cloud was extracted before the beginning of each contact interaction to update its shape and position. During the contact, its position was refreshed in real-time according to the 3D position of the color marker on the arm, though its shape was not updated during the contact. Once the forearm was shape updated, the normal vector $\boldsymbol{n}^i_{arm}$ of each arm point $\boldsymbol{p}^i_{arm}$ was calculated and updated as well to facilitate further contact detection and measurement.

The hand tracking procedure was developed to capture the posture and position of the toucher's hand by combining depth information with a monocular hand motion tracking algorithm (Zhou et al., 2020). The algorithm is robust to occlusions and object interactions, which is advantageous in hand-arm contact. The monocular tracking algorithm contains two neural network modules to predict the 3D location and rotation of all 21 hand joints. In the first module of the hand joint detection network, features extracted from the 2D RGB image were first fed into a 2-layer convolutional neural network (CNN) to detect the probability of the 2D position of all joints. Then, another two 2-layer CNN was used to predict the 3D position of hand joints based on 2D features and 2D joint position estimates. In the second module of the inverse kinematic network, a 7-layer fully connected neural network was designed to derive the 3D rotation of each joint. Finally, the parametric MANO hand model (Romero et al., 2017) was employed to incorporate 3D joint rotations to animate the hand mesh following the shape and pose of the toucher's hand.

The rendered hand mesh was expressed in the local hand coordinate without the spatial information of the hand position. Therefore, depth information is incorporated here to locate the hand mesh in the camera coordinate, according to the movement of any hand joint or the color marker on the back of the hand

(**Figure 1**). Specifically, the 2D position of the color marker was detected in the in the HSV, while the 2D position of the joint was retrieved from the detected 2D hand. The depth value of the hand joint or marker was derived by transforming the depth image to the RGB coordinate, which was then used to obtain its 3D position following the camera projection model. By identifying the corresponding point of that marker or joint in the hand mesh model, the posed hand mesh was moved in real-time following the toucher's hand movements.

Definition of Contact Attributes

Hand-arm contact was measured in a point-based manner (**Figure 2**), which afforded higher resolution compared with a geometry-based method (Hauser et al., 2019a). First, a contact interaction between the hand and forearm was detected when at least one vertex point of the hand mesh was underneath the arm surface. More specifically, for each hand vertex point $\boldsymbol{p}^i_{hand}$, its nearest arm point $\boldsymbol{p}^i_{arm}$ was found first. Then, as detailed in **Eq. 1**, if the angle between the vector $\boldsymbol{p}^i_{hand} - \boldsymbol{p}^i_{arm}$ and the normal vector $\boldsymbol{n}^i_{arm}$ of arm point $\boldsymbol{p}^i_{arm}$ is larger than or equal to 90°, this hand vertex is marked as underneath the arm surface.

$$F_{contact} = \begin{cases} 1 & \forall \left(\boldsymbol{p}^i_{hand} - \boldsymbol{p}^i_{arm}\right) \cdot \boldsymbol{n}^i_{arm} \le 0 \\ 0 & \exists \left(\boldsymbol{p}^i_{hand} - \boldsymbol{p}^i_{arm}\right) \cdot \boldsymbol{n}^i_{arm} > 0 \end{cases} \quad (1)$$

Physical contact attributes were calculated when hand-arm contact was detected. Indentation depth is measured as **Eq. 2**. In particular, N_C is the number of hand vertex points contacted with the forearm. For each contacted hand point $\boldsymbol{p}^i_{hand}$, its indentation depth d^i is approximated as half the distance between $\boldsymbol{p}^i_{hand}$ and its nearest arm point $\boldsymbol{p}^i_{arm}$. The half scale was used because the line between two points might not be perpendicular to the arm surface. The overall indentation d deployed by the hand to the forearm is defined as the average indentation depth of all N_C contacted hand points:

$$Depth = \frac{\sum_{i=1}^{N_C} \left\|\boldsymbol{p}^i_{hand} - \boldsymbol{p}^i_{arm}\right\|_2}{2N_C}. \quad (2)$$

Contact area is measured as the summed area of all contacted arm points. As shown in **Eq. 3**, the unit area S^i for one arm point is calculated as a sphere whose radius is the average neighbor distance, and π is round to 3. Within the arm point cloud of N_{all} points, the average neighbor distance l^i_{nbr} is calculated as the average distance of all points to their nearest neighbor points:

$$Area = 3N_C \left(\frac{\sum_{i=1}^{N_{all}} l^i_{nbr}}{N_{all}}\right)^2. \quad (3)$$

In addition to cutaneous contact attributes, the velocity of hand movement was quantified when contact was detected. The absolute contact velocity V_{abs} is measured as the modulus of the spatial hand velocity $\boldsymbol{v}_{Hand}$:

$$V_{abs} = \left|\frac{\boldsymbol{p}^t_{Hand} - \boldsymbol{p}^{t-1}_{Hand}}{\triangle t}\right|. \quad (4)$$

In **Eq. 4**, hand position $\boldsymbol{p}_{Hand}$ is represented by the position of the middle metacarpophalangeal joint. By defining another coordinate on the receiver's forearm (**Figure 2C**), spatial hand velocity $\boldsymbol{v}_{Hand}$ is further decomposed in the arm coordinate as three velocity components V_{vt}, V_{lg}, V_{lt} parallel with its axis of the arm coordinate (**Figure 2C**). The vertical axis $\boldsymbol{i}_{vt}$ of the arm coordinate is aligned with the vertical direction pointing upright. It could be obtained as the normal vector of a point on a horizontal surface, like a table, or the normal vector of a point on the top of the receiver's forearm. Vertical velocity V_{vt} is the hand velocity component in this direction:

$$V_{vt} = \boldsymbol{v}_{Hand} \cdot \boldsymbol{i}_{vt}. \quad (5)$$

The longitudinal axis $\boldsymbol{i}_{lg}$ is aligned with the direction of the arm bone, pointing from elbow to wrist. To derive this axis, the camera was orientated to display the forearm vertically in the 2D image. Then, the direction of the arm bone in the 2D image was set to be parallel with the y axis of the image coordinate. By projecting the y axis $\boldsymbol{y}$ of the camera coordinate onto the perpendicular plane of the vertical axis $\boldsymbol{n}_{vt}$, the longitudinal axis follows the direction of the projected vector:

$$\boldsymbol{i}_{lg} = \frac{\boldsymbol{y} - (\boldsymbol{y} \cdot \boldsymbol{i}_{vt})\boldsymbol{i}_{vt}}{\left\|\boldsymbol{y} - (\boldsymbol{y} \cdot \boldsymbol{i}_{vt})\boldsymbol{i}_{vt}\right\|_2}. \quad (6)$$

$$V_{lg} = \boldsymbol{v}_{Hand} \cdot \boldsymbol{i}_{lg}. \quad (7)$$

Lastly, the lateral axis $\boldsymbol{i}_{lt}$ is perpendicular to the plane of longitudinal and vertical axis, following the right-hand rule:

$$\boldsymbol{i}_{lt} = \boldsymbol{i}_{lg} \times \boldsymbol{i}_{vt}. \quad (8)$$

$$V_{lt} = \boldsymbol{v}_{Hand} \cdot \boldsymbol{i}_{lt}. \quad (9)$$

Compared with the overall hand velocity, these velocity components can quantify the directional nature of the hand movements.

Moreover, contact duration is measured as a scalar value for each hand-arm touch interaction, which is the sum of time over which contact was detected. Given the recording frequency f of the camera is 30 Hz and N_f is the number of frames per interaction, the contact duration is measured as:

$$Duration = \frac{\sum_{i=1}^{N_f} F_{contact}}{f}. \quad (10)$$

EXPERIMENT 1: HUMAN-TO-HUMAN AFFECTIVE TOUCH COMMUNICATION

The first experiment was designed with the task of human-to-human emotion communication. Touchers was instructed to deliver cued emotional messages, e.g., happiness, sympathy, anger, to the touch receiver at the receiver's forearm using preferred gestures, e.g., tapping, holding, stroking. Recorded contact attributes were then used to differentiate delivered messages, utilized gestures, and individual touchers. Contact analysis was conducted on the platform with the Intel Core i9-9900 CPU, 3.1 GHz, 64 GB RAM, and a NVIDIA GeForce RTX

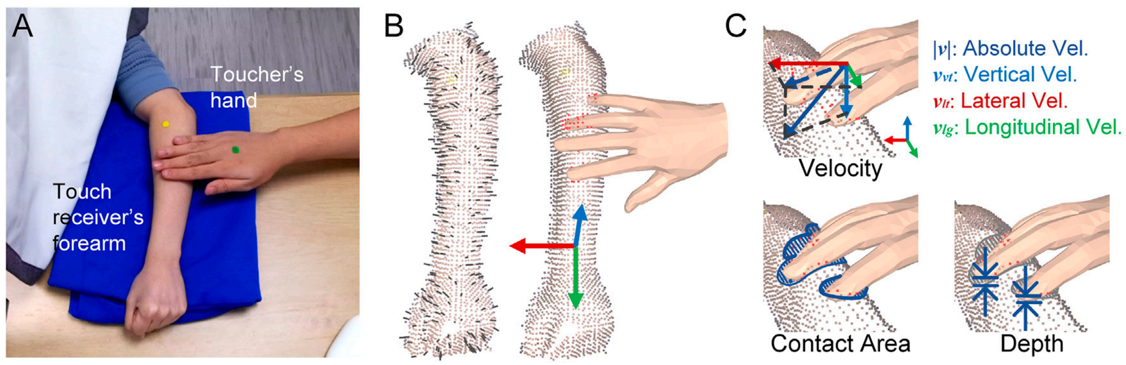

FIGURE 2 | Definition of contact attributes. **(A)** Color image from video recorded by depth camera. Two color markers were placed on the toucher's hand and the receiver's forearm respectively to support motion tracking. **(B)** 3D forearm point cloud and hand mesh. Short black line segments represent the norm vector of arm points; red points on the forearm represent the region contacted by the hand. In the arm coordinate, the vertical axis (blue) is designated along the vertical direction pointing right upward, the longitudinal axis (green) is parallel with the arm direction from elbow to wrist, and the lateral direction is perpendicular to the two axes pointing to the internal side of the forearm. **(C)** Six time-series attributes include absolute velocity, which is the absolute value of spatial contact velocity; three orthogonal velocity components corresponding to the three axes of the arm coordinate; contact area, which is the overall area on the forearm being contact; and the indentation depth as the average depth applied on the forearm by the hand.

TABLE 1 | Available gestures for each cued emotional message in touch communication task.

	Cued emotional messages						
	Anger (Ag)	**Attention (At)**	**Calm (C)**	**Fear (F)**	**Gratitude (G)**	**Happiness (H)**	**Sympathy (S)**
Gestures	Hit/Tap Squeeze/Hold Shake	Tap Shake Squeeze/Hold	Hold/Squeeze Stroke Tap	Squeeze/Hold Shake Tap	Hold/Squeeze Shake Tap	Shake Tap Stroke	Stroke Tap Squeeze/Hold

2080 SUPER GPU. The same platform was used for the second experiment.

Cued Emotional Messages and Gesture Stimuli

Seven emotions of anger, attention, calm, fear, gratitude, happiness, and sympathy were selected as cued messages for touchers to express (**Table 1**). Those messages were adopted from prior studies and have been observed to be recognizable through touch alone (Hertenstein et al., 2006; Hertenstein et al., 2009; Thompson and Hampton, 2011; Hauser et al., 2019a; McIntyre et al., 2021). Among them, gratitude and sympathy are prosocial expressions that are more effectively communicated by touch compared with those self-focused. Anger, happiness, and fear are universal expressions that are commonly communicated by facial, vocal, and touch expressions. Attention and calm are also preferred messages in touch interactions and can be correctly interpreted significantly better than chance. For each of the cued messages, three commonly used gestures were adopted from prior studies (Hertenstein et al., 2006; Thompson and Hampton, 2011; Hauser et al., 2019a; McIntyre et al., 2021) (**Table 1**). Holding and squeezing were combined into one since they share a similar hand gesture and hand motion. Similarly, hitting was combined with the tapping gesture, but only for the message of anger.

Participants

The human-subjects experiments were approved by the Institutional Review Board at the University of Virginia. Ten participants were recruited as touchers, including five males and five females (mean age = 23.8, SD = 5.0). Another five participants were recruited as touch receivers with three males and two females (mean age = 24.0, SD = 4.4). Five experimental groups were randomly assembled, where each group consisted of one male toucher, one female toucher, and one receiver. Each group performed two experimental sessions with one session conducted by the male toucher and another one conducted by the female toucher. Written informed consent was obtained from all participants.

Experimental Setup

To avoid visual distractions during the experiment, touchers and receivers sat at opposing sides of an opaque curtain. They were instructed to not speak to each other. As shown in **Figure 2A**, a cushion was set on the table at the toucher's side upon which the receiver rested her or his left forearm. Cued emotional messages and corresponding gestures were displayed to the toucher on the computer screen. The toucher could select the gesture and proceed to the next message using the computer's mouse. Cued messages and the toucher's selection of gestures were also recorded. As illustrated by a snapshot of the experiment recoding by depth camera (**Figure 2A**), the camera was set in front of the cushion and orientated towards it.

TABLE 2 | Experiment procedure for validating contact velocity.

	Test gesture	Moving direction	Velocity levels	Repeated trials per level	Trials in total
1	Stroking	Longitudinal	Low, Medium, High	3	9
2	Stroking	Lateral	Low, Medium, High	3	9
3	Tapping	Vertical	Low, Medium, High	3	9
4	Holding	None	None	1	1 (long duration)
5	Shaking	Irregular	Irregular	1	1 (long duration)

TABLE 3 | Experiment procedure for validating contact area.

	Test gesture	Force levels	Repeated trials per level	Trials in total
1	Single-finger pressing	Low, Medium, High	3	9
2	Multiple-finger pressing	Low, Medium, High	3	9
3	Holding	Low, Medium, High	3	9
4	Shaking	Irregular	1	1 (long duration)

TABLE 4 | Experiment procedure for validating indentation depth.

	Validation with laser sensor			
	Test gesture	Force levels	Repeated trials per level	Trials in total
1	Multiple-finger tapping	Low, Medium, High	3 (4 taps per trial)	9
2	Palm tapping	Low, Medium, High	3 (4 taps per trial)	9
	Validation with Pressure Mat			
	Test Gesture	**Force Levels**	**Repeated Trials per Level**	**Trials in Total**
1	Single-finger pressing	Low, Medium, High	3	9
2	Multiple-finger pressing	Low, Medium, High	3	9
3	Holding	Low, Medium, High	3	9

Experimental Procedures

In each session, seven cued emotional messages were communicated with each repeated six times. The 42 message instructions were provided in random order. In each trial, one message was displayed on the screen with three gestures listed below. Touchers had 5 s to choose a gesture and report it on the computer display. For each cued message, the three provided gestures were identical but their order was randomized trial by trial. After that, the toucher delivered the message, by touching the receiver's forearm from elbow to wrist, using the right hand. Within each trial, only the chosen gesture was used. The use of other gestures or a combination of gestures was not allowed. For the same cued message across trials, touchers were free to use the same gesture or change to another gesture. A gesture could be deployed in any pattern of contact deemed appropriate by the toucher. No constraints or instructions were given for delivering the gesture, such as its duration, hand region employed, intensity, or repetition. At the end of a trial, by clicking the "Next" button on the bottom of the computer display, the toucher initiated the next trial with a new message word and corresponding three gestures.

Data Analysis

Overall, 420 trials were performed in ten experimental sessions. Twelve trials were excluded from analysis as contact interactions were not properly recorded. Statistical and machine learning analyses were performed to examine the measured contact attributes.

To identify the contact pattern between touch gestures, paired-sample Mann–Whitney U tests were applied across gestures per contact attribute. For time-series attributes, the mean value was used. Since longitudinal velocity, lateral velocity, and vertical velocity are signed variables, the mean was derived from the absolute value of those variables. Contact duration as a scalar variable was directly compared across gestures. To evaluate which of the contact attributes could best identify or describe a certain type of touch gesture, the importance of each attribute in predicting that gesture was identified using a random forest classifier. The mean values of time-series attributes together with the scalar attribute served as inputs. For example, in predicting the stroking gesture, all trials were labeled in a binary fashion as delivering or not delivering this gesture, instead of being labeled as the four gesture types. Seventy-five percent of trials were randomly assigned as the training set and those remaining were assigned as the test set. The permutation method was used to derive the importance of attributes. The value was obtained as the average of 100 repetitions of classification, with 10 permutations per classification.

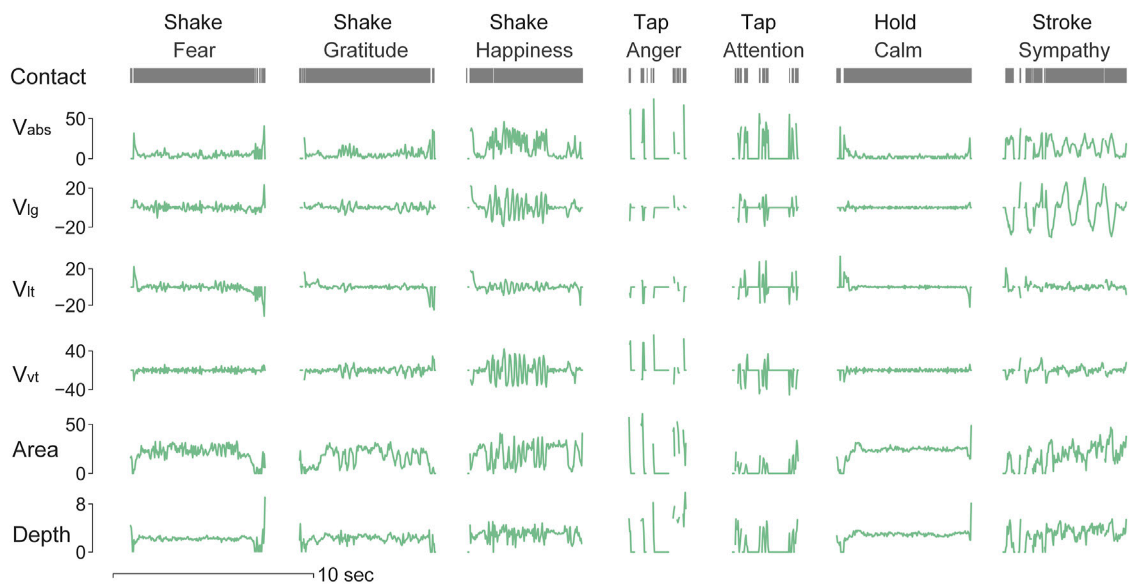

FIGURE 3 | Time-series recordings of each contact attribute across touch gestures and delivered messages. Distinct contact patterns were captured by the spatiotemporal changes of those attributes. The *Contact* variable represents the status of the being contacted or not. V_{abs} denotes the absolute contact velocity (cm/s), V_{lg} denotes the longitudinal velocity (cm/s), V_{lt} denotes the lateral velocity (cm/s), V_{vt} denotes the vertical velocity (cm/s), *Area* denotes the contact area (cm^2), and *Depth* denotes the indentation depth (mm).

Further classification analyses were performed regarding the discrimination of touch gestures, emotional messages, and individual touchers, respectively, using the random forest algorithm. Contact attributes were fed into classifiers in three different formats, including the mean value of each time-series attribute, multiple relevant features extracted from each time-series attribute, and the original time-series attributes. In particular, multiple features were extracted to quantify the amplitude, frequency, and dynamic characteristics of the time-series signal (Christ et al., 2018). For example, time-domain features included mean, maximum, quartiles, standard deviation, trend, skewness, entropy, energy, etc. Frequency domain features included autocorrelations and partial autocorrelations with different lags, coefficients of wavelet and Fourier transformations, mean, variance, skew of Fourier transform spectrum, etc. From all extracted features, relevant ones were selected for classification by significance tests in predicting the classification target and the Benjamini Hochberg multiple test (Christ et al., 2018). When time-series data were used, all attributes were concatenated into one variable as input (Löning et al., 2019). To identify attributes that could better encode social affective touch, the importance of individual attributes was ranked for each classification task. More specifically, based on the mean - value classification, the permutation method was repeated multiple times to derive the average importance values.

Results

Physical Contact Attributes in Human-to-Human Touch

Human-to-human physical contact interactions between social messages, gestures, and individual touchers were quantified by their contact attributes. As shown in **Figure 3**, exemplar data for the four touch gestures (shake, tap, hold, and stroke) exhibit distinct patterns across the contact attributes, consistent with expected hand movements per gesture. In particular, the stroking gesture was characterized by regular patterns in longitudinal velocity, which implies slow and repetitive movements along the direction of the forearm. For the shaking gesture, velocity attributes depicted large changes in frequency and relatively lower amplitude. Meanwhile, velocities in all three directions changed simultaneously, indicating a spatial direction in the movement of the toucher's hand. The tapping gesture was quantified as discontinuous, large-amplitude spikes of short contact duration. Compared with other touch gestures, holding gesture exhibited relatively stable contact with minimal changes. With further inspection into each gesture, contact patterns with subtle differences could also be captured across emotional messages. Such as in the shaking gesture, happiness was delivered with higher velocities compared with the expression of fear. Within the tapping gesture, shorter but more intensive contact was recorded when expressing anger compared with attention.

As shown in **Figure 4A**, the four touch gestures were statistically differentiable according to several of their contact attributes. For instance, absolute contact velocity can differentiate all gesture pairs except for that of stroking and shaking. With the contact attribute of longitudinal velocity, stroking was differentiable from shaking as it afforded higher longitudinal velocity. This also aligns with hand movements during stroking that are typically along the direction of the forearm. Both shaking and tapping gestures exhibited significantly higher longitudinal velocities than the holding gesture. With the lateral velocity, significant differences were derived among all four gestures,

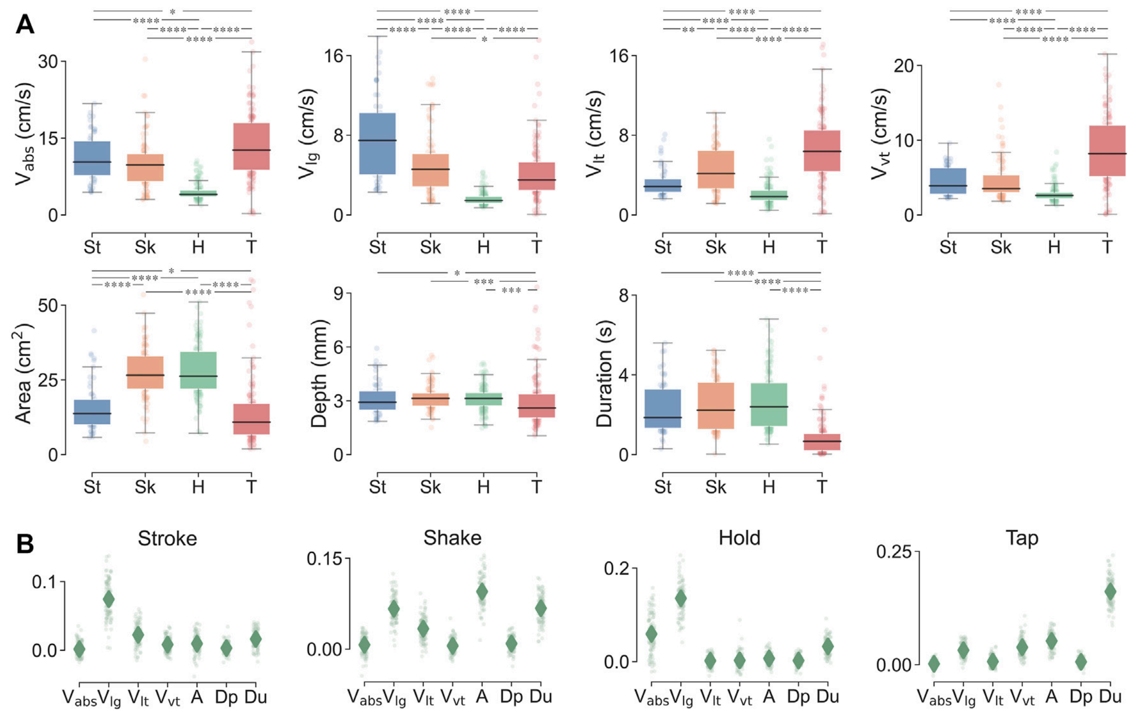

FIGURE 4 | (A) Comparison of contact attributes across the four touch gestures. $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$, $^{****}p < 0.0001$ were derived by paired-sample Mann–Whitney U tests. **(B)** Importance of certain contact attributes in identifying each touch gesture using random forest classification. Diamonds denote means; points denote importance values of 100 repetitions of classification.

where tapping and shaking gestures afforded higher amplitudes than stroking and holding. As for the vertical velocity, the tapping gesture was associated with significantly higher velocities than others, which aligns with its up-down movements. Across all velocity attributes, the holding gesture was significantly distinct from other ones.

For the contact area attribute, shaking and holding gestures exhibited significantly higher values than the stroking gesture, and then tapping. Indeed, participants generally used the whole hand to deliver holding and shaking, while only the finger digits for stroking and the fingertips for tapping. Moreover, with indentation depth and contact duration, tapping was distinct amongst the gestures with significantly lower depth and shorter duration. Note the hand motion with the tapping gesture could be faster than the recording frequency of the camera, where one trial of contact might not be entirely captured and thus lead to a lower estimation of indentation depth.

In **Figure 4B**, the contact attributes that were salient in identifying or describing a specific touch gesture were further analyzed according to their importance in predicting that gesture. From the importance ranking, longitudinal velocity appears to be the most useful attribute in describing the stroking gesture. The shaking gesture did not have a single salient attribute, perhaps because it was delivered from multiple directions and varied velocities. The attributes of contact area, contact duration, and longitudinal velocity were relatively more important. The holding gesture could be identified by longitudinal and absolute velocities with both lower amplitudes. For the tapping gesture, contact duration could be important in identifying it, which should be shorter than other gestures.

Classification Amidst Gestures, Messages, and Individuals

In **Figure 5**, the contact attributes are shown to robustly classify touch gestures, delivered messages, and individual touchers at accuracies better than chance, which is 25%, 14.3%, and 10% respectively. For gesture prediction, the accuracy was 87% when the mean values of contact attributes were used as predictors (**Figure 5A**). The prediction accuracy slightly increased to 92% when all relevant features were used as more information was included, and was around 86% when predicted by the time-series data. In classifying delivered emotional messages, the accuracy was 54%, 57%, and 55%, for the three respective feature classes (**Figure 5C**). Moreover, in classifying the individual touchers, the accuracies were 56%, 72%, and 77%, respectively. For the importance ranking of the contact attributes, those of longitudinal velocity, contact duration, and contact area were typically more important.

EXPERIMENT 2: TECHNICAL VALIDATION ON THE VISUAL TRACKING METHOD

The second experiment was designed to validate the effectiveness of the 3D visual tracking system in measuring controlled human

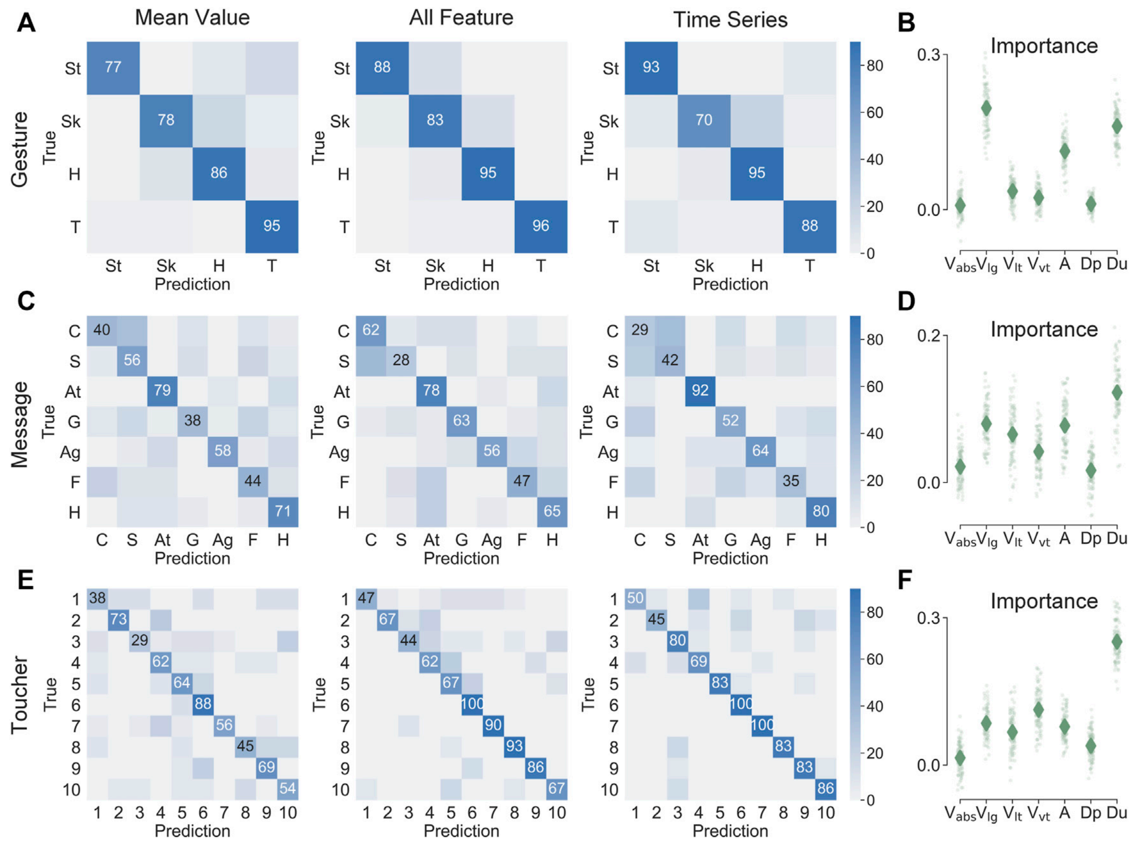

FIGURE 5 | Classification of touch gestures, delivered messages, and toucher individuals using the mean value, all relevant features, and time-series data of contact attributes, respectively. The accuracy in prediction of **(A)** touch gestures, **(C)** delivered messages, **(E)** toucher individual are shown, as well as the importance of particular contact attributes in classifying **(B)** touch gestures, **(D)** delivered messages, **(F)** toucher individual. Numbers and colors in confusion matrices represent the prediction percentage. In the importance plots, the diamonds denote means; points denote importance values from 100 repetitions of classification.

movements against those from independent devices, including an electromagnetic motion tracker, sensorized pressure mat, and laser displacement sensor. These techniques are used commonly in haptics studies (Silvera-Tawil et al., 2014; Jung et al., 2015; Hauser et al., 2019a; Xu et al., 2020; Lo et al., 2021; Xu et al., 2021a). In this experiment, the observed contact attributes were compared within controlled touch conditions, e.g., stroking in different directions at preset velocities, pressing with different parts of the hand varying in contact area, and tapping at different depth magnitudes.

Contact Velocity Validation Using Electromagnetic Tracker

Experimental Setup

Measurements of the directional components of contact velocity, including absolute velocity, longitudinal velocity, lateral velocity, and vertical velocity were validated against those of an electromagnetic (EM) motion tracker (3D Guidance, Northern Digital, Canada. 6 DOF, 20–255 Hz, 1.4 mm RMS position accuracy, 78 cm range; 0.5° RMS orientation accuracy, ±180° azimuth and roll, ±90° elevation range). Both tracking systems were operated simultaneously to capture controlled movements of the human hand touching the forearm. The transmitter of the 3D Guidance EM tracker was oriented to be aligned with the arm coordinate (**Figure 6A**). The sensor of the EM tracker was attached to the toucher's back of the hand near the middle metacarpophalangeal joint.

Experimental Procedures

Given velocity components were defined in different directions, five test gestures were designed in total, as listed in **Table 2**. The first two test gestures were stroking contact along the forearm in longitudinal and lateral directions, respectively. The third test gesture involved tapping vertically to the surface of the forearm. The fourth gesture was holding without movement. The fifth gesture was shaking, which was delivered in an irregular and arbitrary way with different directions and velocities included. For the first three test gestures, each one was performed in three levels of velocities, from low to medium to high. Each velocity level was repeated for three trials. For example, the longitudinal stroking gesture was performed as three trials of stroking in the longitudinal direction with lower velocity, followed by three trials of stroking with medium velocity, and concluded by three trials of stroking with higher velocity. The direction of hand movement and level of velocity were behaviorally controlled by the trained

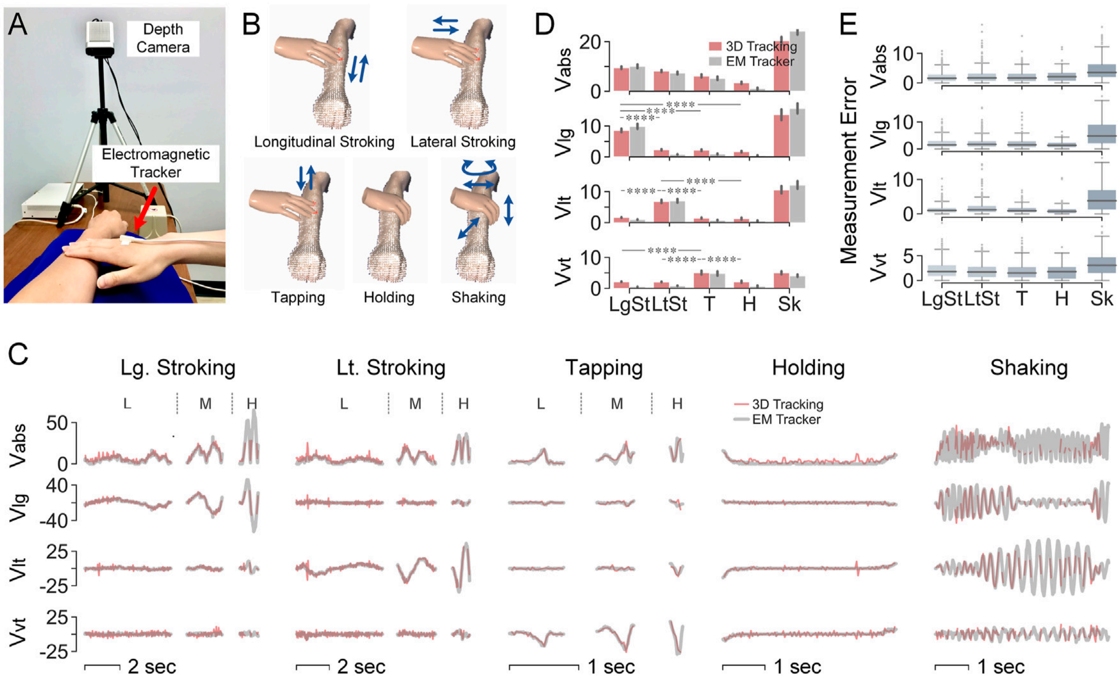

FIGURE 6 | Validation of contact velocity measurements using EM tracker. **(A)** Experimental setup. **(B)** Five test gestures. **(C)**Velocity (cm/s) over time by the two tracking systems. For the first three test gestures, one trial is shown per force level, i.e., low, medium, and high force. **(D)** Mean values of velocities (cm/s) per test gesture. ****p < 0.0001 were derived by paired-sample Mann–Whitney U tests. **(E)** Errors (cm/s) of measured velocities between the two systems for each test gesture.

toucher, who performed all three validation experiments. Shaking and holding gestures were performed only once but lasted for a longer time to collect enough amount of data for validation analysis.

Data Analysis

Similar to the 3D visual tracking system, the four velocity attributes captured by the EM tracker were derived from the original time-series position data. For either tracking system, the absolute mean value of each velocity attribute was calculated per test gesture. Mann–Whitney U tests were conducted across the test gestures based on mean velocity collected by the visual tracking system. Measurement errors between the two tracking systems were derived per attribute and test gesture. Since the sampling rates of the two systems differ, i.e., 30 Hz for the Azure Kinect camera and 60 Hz for the EM tracker, data collected from the EM tracker was resampled to be synchronized. More specifically, the EM tracking data was first interpolated and sampled according to the timestamps of the 3D visual tracking data. Then, the error was calculated for each time point between the velocities from the two systems.

Results

In **Figure 6**, velocities measured by the 3D visual tracking system were accurate when compared with the EM tracker. The time-series data from the two systems well overlaped amidst touch gestures (**Figure 6C**) and the average velocities of the gestures were comparable between the two systems (**Figure 6D**). Shaking delivered high velocities in all three directions, while velocity in a certain direction was significantly higher for hand movements along that direction. All four velocity attributes were significantly lower when the holding gesture was performed. As shown in **Figure 6E**, the measurement error was 1–2 cm/s for the first four gestures and relatively higher at around 5 cm/s for the shaking gesture.

Contact Area Validation Using Sensorized Pressure Mat

Experimental Setup

Contact area was measured simultaneously with the 3D visual tracking system and a sensorized pressure mat (Conformable TactArray SN8880, Pressure Profile Systems, United States, 7 cm × 14 cm, 12 × 27 sensing elements, 0.002 psi pressure resolution, 3.05 psi pressure range, 29.3 Hz). Note that contact was evaluated between the toucher's hand and the surface of the pressure mat which was overlaid on top of the bare forearm, for which it had been custom-designed (**Figure 7A**). Based on pilot tests with the pressure mat, its measurement of contact area could be inaccurate due to the creases caused by pressing when the mat was put on the forearm. To attenuate this effect, a piece of single-face corrugated cardboard was placed between the forearm and the mat to generate a smooth and stiffer curved surface following the shape of the forearm.

Experimental Procedures

Four test gestures were employed, as listed in **Table 3**. The first test gesture was single-finger pressing with the index finger. The second gesture was multiple-finger pressing with all fingers except for the thumb. The third gesture was holding and the fourth

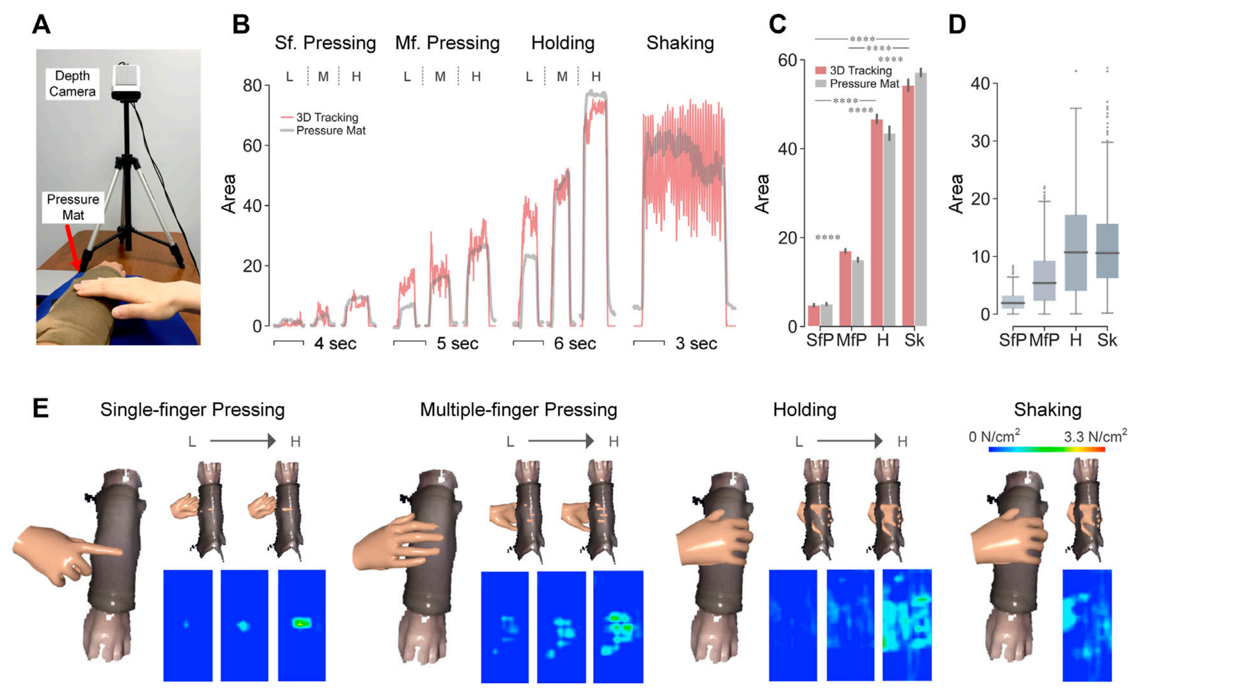

FIGURE 7 | Validation of contact area measurements using sensorized pressure mat. **(A)** Experimental setup. **(B)** Contact area (cm^2) over time by the two systems. For the first three test gestures are shown one trial per force level, i.e., low, medium, and high force. **(C)** Mean values of contact area (cm^2) per test gesture. ****$p < 0.0001$ were derived by paired-sample Mann–Whitney U tests. **(D)** Differences of measured contact area (cm^2) between the two systems per test gesture. **(E)** Visualization of hand-arm contact in top view (left) and bottom view (top right) with heatmaps of contact pressure tracked by sensorized pressure mat across force levels (bottom right).

gesture was shaking. For the first three test gestures, three levels of force were applied from low to medium to high, to generate different levels of contact area within a gesture. Each force level was repeated for three trials. Per trial, the toucher's hand moved downward into the receiver's forearm and maintained pressure/hold at that force level for more than 3 s. For example, the single-finger pressing gesture was conducted for three trials of pressure using the index finger at a low force level, followed by three trials of pressure at a medium force level, and three trials of pressing with a higher force level. The shaking gesture was conducted for one trial with a long duration. Any patterns of shaking could be applied in an irregular and arbitrary manner including different directions, velocities, etc.

Data Analysis

The average contact area per gesture was calculated for both measurement systems. Significance tests were performed across gestures based on average areas from the visual tracking system. The measurement differences between the two systems were derived from time-series recordings per gesture. To overcome the time discrepancy of sampling, data collected by the sensorized pressure mat was resampled to be synchronized with the visual tracking system.

Results

In **Figure 7B**, the time-series contact areas captured by the 3D visual tracking system and the sensorized pressure mat well overlapped with each other across test gestures and force levels. While single-finger pressing (SfP) afforded the smallest contact area, larger multiple-finger pressing (MfP) was significantly smaller than holding (H) and shaking (Sk) (**Figure 7C**). As shown in **Figure 7D**, the measurement differences between the two systems were around 2 and 6 cm^2 for SfP and MfP, while increased to 11 cm^2 for holding and shaking.

Indentation Depth Validation Using Laser Sensor

Experimental Setup

Indentation depth was first validated using a laser displacement sensor (optoNCDT ILD 1402-100, Micro-Epsilon, Germany, 100 mm range, 10 μm resolution, 1.5 kHz). The sensor was mounted on a customized stand with the beam pointing downward. Given its capability of measuring the displacement of one point in only the vertical direction (**Figure 8A**), a limited set of tapping gestures was evaluated in this setting. Other gestures were then tested with a separate validation procedure using the sensorized pressure mat (**Figure 8E**).

Experimental Procedures

Two test gestures were examined with the laser sensor, as listed in **Table 4**. The first gesture was multiple-finger tapping, where the movement of the tip of the middle finger was tracked. The second

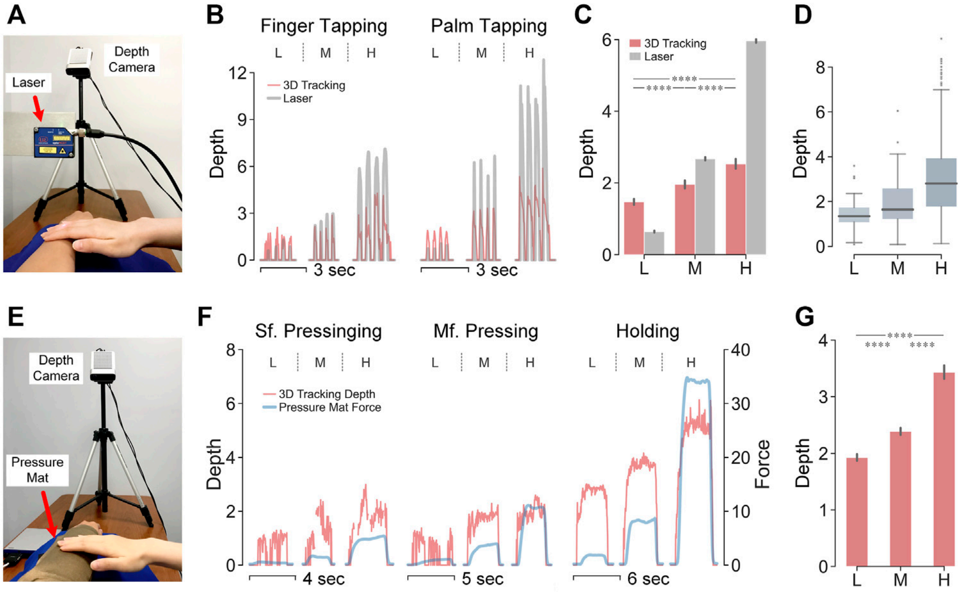

FIGURE 8 | Validation of indentation depth measurements using laser displacement sensor and sensorized pressure mat. **(A)** Experimental setup with laser displacement sensor. **(B)** Indentation depth (mm) over time by the either system. For the two test gestures shown is one trial per force level, i.e., low, medium, and high force. **(C)** Mean values of indentation depth per test gesture. ****$p < 0.0001$ were derived by paired-sample Mann–Whitney U tests across force levels. **(D)** Errors of measured indentation depth between systems per force level. **(E)** Experimental setup with sensorized pressure mat. **(F)** Indentation depth (mm) collected by the 3D visual tracking system overlaps with overall force (N) collected by the sensorized pressure mat. Per test gesture, one trial per force level is shown i.e., low, medium, and high force. **(G)** Mean value of indentation depth per force level recorded by the 3D visual tracking system. ****$p < 0.0001$ were derived by paired-sample Mann–Whitney U tests across force levels.

gesture was tapping with the palm, measured at one point on the back of the hand. Holding, shaking, and stroking gestures were not examined here since these gestures are typically not conducted in the vertical direction. Within each gesture, three force levels were employed, i.e., low, medium, high, and each repeated in three trials. The toucher quickly tapped for four times within one trial. For example, the palm tapping gesture was conducted for three trials of four taps with the palm at a low force level, followed by three trials of four taps at a medium force level, and three trials of four taps at a high force level. The raw data collected by laser sensor contained displacements of both indentations into the skin and movements in the air. Therefore, the toucher conducted a "zero contact" touch to the forearm at a minimally perceptible force prior to each test gesture.

Within the setting of sensorized pressure mat, the three test gestures performed were single-finger pressing, multiple-finger pressing, and holding (**Table 4**). Each gesture was performed in three force levels, where each level was repeated for three trials.

Data Analysis

For the validation with laser sensor, average indentation depth at each force level was obtained by aggregating the two tapping gestures. Significance tests were conducted across force levels based on the average depth collected by the visual tracking system. Measurement errors between the two systems were derived from time-series recordings at each force level. The data from the laser sensor was resampled according to the 3D visual tracking system's results. For quick tapping gestures, slight temporal discrepancies between the two recordings could derive large differences. Therefore, the dynamic time warping method was used to match tracked movements. The measurement errors were obtained by comparing each pair of matched points from the two recordings.

Though no depth data could be captured by the pressure mat, the overall contact force was measured for correlation with indentation depth measured by the visual tracking system. By aggregating all test gestures, the average depth derived per force level was then calculated and compared.

Results

In **Figure 8**, the patterns of indentation depth measured by the two systems were very similar especially for the temporal changes (**Figure 8B**). Though differences could be observed between their overall amplitudes, their increasing trends were maintained across force levels (**Figure 8C**). Therefore, the 3D visual tracking system affords the sensitivity to track slight changes in indentation depth, while the amplitude of changes is proportionally mitigated. Moreover, contact with different force levels could be easily differentiated by indentation depth amongst a variety of touch gestures. (**Figures 8C,G**).

DISCUSSION

To better understand human-to-human touch interactions underlying social emotional communication, an interference-free 3D visual tracking system was developed to precisely measure skin-to-skin physical contact by time-series contact attributes. The system was validated to capture and readily distinguish naturalistic human touches across delivered emotional messages, touch gestures, and individual touchers according to contact attributes. Compared with standard tracking techniques, similar accuracy of spatiotemporal measurements was achieved by this system, while multivariate attributes can be obtained simultaneously within one concise setup.

Deciphering Affective Touch Communication by Contact Attributes

As human affective touch is prone to be impacted by social and individual factors, such contact differences could be readily captured by this system *via* contact attributes. First of all, touch gestures can be differentiated with high accuracy as their contact attributes were significantly different from each other (**Figure 4A**). Measurements of this system also align with prior reports of gesture quantification with similar amplitudes. Such as the velocity for stroking in social touch is around 10 cm/s (Lo et al., 2021), and the average contact area of holding gesture is around 30 cm^2 (Hauser et al., 2019a). In addition, the characterized contact pattern of each gesture align well with the general sense of how we deliver that gesture. For example, tapping is associated with higher vertical velocities, stroking is delivered with higher longitudinal velocities, and holding is commonly applied with lower velocities and larger contact areas (**Figure 4A**).

Moreover, delivered emotional messages can be differentiated by contact attributes much better than chance (**Figure 5C**). The accuracy of 54%, 57%, 55% was achieved when predicted by three different levels of information derived from contact attributes (**Figure 5C**). Note that human receivers only achieve a comparable recognition correctness around 57% when a similar pool of messages were tested (Hauser et al., 2019a; McIntyre et al., 2021). It indicates that some contact information human receivers rely on in identifying emotional messages can be captured by this tracking system. Meanwhile, certain messages that were difficult to be discriminated by contact attributes might indeed be very similar in their social meanings and touch behaviors. Such as sympathy and calm, which are supposed to be close in the terms of contact quantification.

Furthermore, this tracking system can capture individual differences in affective touch as individual touchers were also easily distinguished. Prior studies highlighted that touch behavior in social communication could be influenced by many factors, such as age (Cascio et al., 2019), gender (Hertenstein et al., 2009; Russo et al., 2020), cultural backgrounds (Hertenstein et al., 2006; Suvilehto et al., 2019), relationship (Thompson and Hampton, 2011), or personalities (McIntyre et al., 2021). While the personal information is easy to obtain *via* questionnaires, the uniqueness of their contact performance is always challenging to collect. Prior attempts on individual difference typically focused on contact with engineered stimuli like silicone-elastomers (Xu et al., 2021b), grooved surfaces in grating orientation tasks (Peters et al., 2009), or the contact with robots (Cang et al., 2015). In those settings, contact can be well-recorded by built-in or attached sensors, which in contrast is impractical or interferential for human-to-human touch. As individual difference indeed plays a role in social emotion communication, this system could help bridge the gap by inspecting the differences from the aspect of skin contact quantification.

Improved Skin-to-Skin Contact Measurement by 3D Visual Tracking

The measurement accuracy of this system was validated by several standard tracking techniques. As shown in **Figures 6–8**, time-series recordings of contact attributes aligned well with the data collected from independent devices, i.e., contact velocities from an EM motion tracker, contact area from a sensorized pressure mat, and indentation depth from a laser sensor. Those standard tracking methods typically afford high accuracy or resolution of measurements but are specialized for limited types of contact attributes. Therefore, when different attributes are needed at the same time, a complex combination of multiple devices is usually required. In contrast, the proposed tracking system captures most of those attributes simultaneously with a concise setup without calibration.

Moreover, the proposed 3D visual tracking system is compatible with wider applications as many limitations of standard tracking methods were overcome or avoided. More specifically, compared with the EM tracker, this system is free of electromagnetic interference and provides shape information instead of tracking the position of only few points. Compared with infrared motion trackers like the Leap Motion sensor, it covers a larger range of tracking and captures any 3D shapes in addition to hands and several basic geometric shapes. The motion capture system is superior in tracking movements but is expensive to set up and constrained by pre-attached markers. Sensorized pressure mat and other force sensors always block the direct contact and might not be reliable in area measurement due to spatial resolution constraints and the increasing zero drift over time (**Figure 4B**). While the proposed tracking system is free of those issues mentioned above, limitations still exist. In particular, the attribute of contact force and pressure are unavailable although they contribute to contact interactions (Essick et al., 2010; Huang et al., 2020; Teyssier et al., 2020; Xu et al., 2020). Due to the constraint of recording frequency, fast movements might fail in tracking since the hand image could be blurred. Meanwhile, the forearm needs to be recorded parallel with the y-axis of the color image coordinate. In so doing, the spatial hand velocity can be decomposed into the three orthogonal directions without additional markers to define the arm coordinate.

Further Applications in Human-to-Human Touch Interaction

Human touch each other with different intentions and a wide range of emotional states. In the classic theory of emotion, three dimensions of valence, arousal, and dominance, are typically employed for emotion assessments (Russell and Mehrabian, 1977; Russell, 1980). Indeed, using machine-controlled brush stimuli, the valence rating was reported to be tuned by the tangential stroking velocity (Löken et al., 2009; Essick et al., 2010; Ackerley et al., 2014a; Ackerley et al., 2014b; Croy et al., 2021). In the scenario of naturalistic human touch, our measurements could further facilitate the quantitative analysis regarding other correlates between contact attributes and the three emotional dimensions.

From the perspective of neurophysiology, changes in the skin's mechanics caused by physical contact could elicit different responses of peripheral afferents (Johnson, 2001; Yao and Wang, 2019; Xu et al., 2021a). For example, the firing frequency of C-tactile afferents is associated with the stroking velocity in an inverted-U shape relationship (Löken et al., 2009; Ackerley et al., 2014a; Liljencrantz and Olausson, 2014). Other Aβ afferents are suggested to support the identification of distinct emotional messages delivered by touch (Hauser et al., 2019b). Moving forward into this direction, measurements of naturalistic human contact can aid in uncovering how exactly afferents respond to such contact and contribute to different emotional percepts.

Affective touch is also believed to impact physiological arousal such as blood pressure, heart rate, respiration, ECG, EEG, and hormone level (Gallace and Spence, 2010; Sefidgar et al., 2016). Especially for infants, touch delivered by caregivers contributes to their social, cognitive, and physical development (Hertenstein, 2002; Van Puyvelde et al., 2019), where the underlying contact details would be meaningful to quantify. Additionally, many physical therapies, such as massage, rely on specific manipulation of the muscle and tissue of patients delivered by professional therapists. Those therapies create health benefits including relieving stress and pain, promoting blood circulation, and boosting mental wellness (Moyer et al., 2004). While the underlying mechanism is waiting to be further explored with the aid of physical skin contact tracking.

DATA AVAILABILITY STATEMENT

Data supporting the conclusions of this article can be made available by the authors, without undue reservation. Such requests should be directed to gg7h@virginia.edu.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Institutional Review Board at the University of Virginia. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

SX, CX, SM, HO, and GG conceptualized and designed the study. SX and GG developed the tracking system. SX, CX, and GG performed the experiments. SX, CX, SM, and GG analyzed and interpreted experimental results. SX, CX, and GG drafted the manuscript. All authors edited and approved the manuscript.

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Exploring views on affective haptic devices in times of COVID-19

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Affective haptic devices (AHDs) are communication technologies utilizing the sense of touch, and include mediated social touch (MST), symbolic haptic messaging, and awareness systems that, for example, let one feel another person's heartbeat. The COVID-19 pandemic and consequent social distancing measures have led to a reemphasis of the importance of social touch, and many people have experienced firsthand what it is like to miss touching loved ones. This offers an excellent opportunity to study people's intention to use AHDs. For this purpose, a survey study ($n = 277$) was conducted combining qualitative and quantitative data analysis methods. Touch deprivation, resulting from not being able to touch a loved one, was associated with intention to use AHDs: the more deprived an individual, the higher his or her intention to use AHDs. Technology readiness and touch aversion did not affect intention to use AHDs. AHDs for symbolic messaging gained higher interest than MST and awareness devices, and long-distance relationships were seen as the most likely scenario for using AHDs. Bi-directionality, synchronicity, and symmetry were regarded as important features for providing shared meaning and a sense of connectedness. Reviewability, multimodality, and actuation type were also deemed important. Limitations of the study and implications for the design of AHDs are discussed.

KEYWORDS

mediated social touch, social touch technology, haptic technology, communication characteristics, technology interest, touch deprivation, COVID-19

Introduction

Social touch plays an important role in human development, attachment, bonding, interpersonal communication (Hertenstein et al., 2006a; Gallace and Spence, 2010; Jakubiak and Feeney, 2017; Cascio et al., 2019) and wellbeing (Field, 2014). However, there are circumstances where direct skin-to skin contact is not possible, for example, when in a long-distance relationship, when being isolated from the outside world for longer periods (prisoners or people on expedition), or, as is the case at the time of this writing, during the COVID-19 pandemic. During the current COVID-19 pandemic, social touch has become less accessible for certain people (e.g., people living alone).

It has yet to be investigated what the long-term effects of this lack of touch as a result of lockdown measures are. It has been proposed that social distancing can lead to touch deprivation, also referred to as touch starvation (Pierce, 2020) or touch hunger (Abbate[1]; Durkin et al., 2020). People with touch deprivation experience a strong need for social touch, either because they do not experience sufficient social touch themselves or because they want to touch someone else who is suffering from insufficient social touch (Pierce, 2020). Prior research has shown that touch deprivation can have negative effects on overall wellbeing (Field, 2010). Findings of surveys conducted during the COVID-19 pandemic have provided some early insight into the effects of the COVID-19 regulations on people's social touch interactions and their psychological responses (Field et al., 2020; von Mohr et al., 2021; Burleson et al., 2022). Research by Field et al. (2020) has shown that more people are, indeed, experiencing touch deprivation during the COVID-19 pandemic, resulting in a statistically significant decrease in their wellbeing. As such, touch deprivation occurred in particular among people living alone. The work by von Mohr et al. (2021) shows that people mostly miss intimate forms of touch (e.g., hugs or kisses). Moreover, touch deprivation of intimate touch acts led to higher levels of anxiety and loneliness. Research by Burleson et al. (2022) showed that people who experienced less affectionate touch during the pandemic reported more psychological distress. Researchers have been calling for efforts to minimize these negative consequences (Venkatesh and Edirappuli, 2020). Among the suggestions, it has been proposed that communication tools need to be improved in order to compensate for the lack of touch (Durkin et al., 2020).

Unsurprisingly, given the importance of touch, people came up with creative solutions to safely engage in social touch interactions during this pandemic, such as to bump elbows (Katila et al., 2020) or the heels of their shoes (McKeever[2]) as an alternative for shaking hands. Similarly, people have been designing low-tech and low-cost solutions to enable social touch for vulnerable populations, such as the elderly, for example, in the form of "cuddle screens" that allow for hugging a loved one through a physical barrier designed to prevent infections (Push[3]).

Digital communication technologies that, in some form or another, utilize the sense of touch might also provide a solution to combat touch deprivation during social distancing measures. Mediated social touch (MST) devices, for example, aim to facilitate physical contact over a distance—simulating, for example, a hug (Teh et al., 2012) or handshake (Nakanishi et al., 2014)—by means of haptic and tactile displays (Haans and IJsselsteijn, 2006).

In addition to MST, of which the main aim is to simulate social touches, designers have also created other devices offering other forms of communication through a haptic channel (e.g., warmth, force or vibration, see Figure 1). One category of devices facilitates the communication of abstract messages (e.g., RingU; Pradana et al., 2015), representing affectional messages such as "I'm thinking of you" or "I love you." Furthermore, one's own emotions can be communicated by means of such a symbolic tactile or haptic message (e.g., Huisman et al., 2013). Another category is aimed at creating awareness of each other's activities, context or status (e.g., Iwaki et al., 2008; Markopoulos et al., 2009). As all these three types of haptic devices have been aimed at supporting communication of affective messages using haptic or tactile displays, they can subsequently be placed under the umbrella term "affective haptic devices" (AHDs). The difference between the three categories of AHDs lies in the type of message that can be communicated.

Most work to date has focused on the creation of AHDs, with research into the effects of the use of such devices lagging behind somewhat (Huisman, 2017). In other words, most work to date has focused on exploring designs possibilities through the development of prototypical AHDs. Nevertheless, a body of work is steadily building, showing the potential of AHDs as communication tools. Research has been conducted on testing the affective and behavioral responses toward haptic stimulation (e.g., Haans et al., 2014; Erk et al., 2015; Harjunen et al., 2017; Ipakchian Askari et al., 2019) and has explored the possibility of using touch devices for communicating emotions [e.g., Hertenstein et al., 2006b; Huisman and Darriba Frederiks, 2013; Teyssier et al., 2020]. However, research investigating people's interest in and perceptions toward AHDs has been rare (but see Rognon et al., 2021). Some of the design research has included user evaluations of AHD prototypes [e.g., Kowalski et al., 2013; Park et al., 2013], but the majority of this work has been conducted rather unsystematically and with very small samples.

Eid and Al Osman (2016) have argued that it is important to take into account people's perceptions toward AHDs when designing AHDs, in particular with respect to how comfortable people feel with using touch technology and sharing intimate data. Technology acceptance models, such as TAM and UTAUT2 (Davis, 1989; Venkatesh et al., 2012), propose that *a priori* perceptions (e.g., attitude, perceived usefulness or performance expectancy) can influence technology acceptance. Gaining a better understanding of people's *a priori* perceptions and beliefs thus is beneficial for designing, evaluating, and predicting user responses toward AHDs (Taherdoost, 2019).

Therefore, it is important to complement existing research, which focuses predominantly on the creation of AHDs and testing how these may affect affective and behavioral interaction outcomes, with work focusing more systematically

1 Abbate. Available online at https://www.self.com/story/craving-physical-touch.

2 McKeever. Available online at: https://www.cnbc.com/2020/03/05/the-coronavirus-is-seeing-the-footshake-replace-the-handshake.html.

3 Push. Available online at: https://beverwijk.nieuws.nl/.

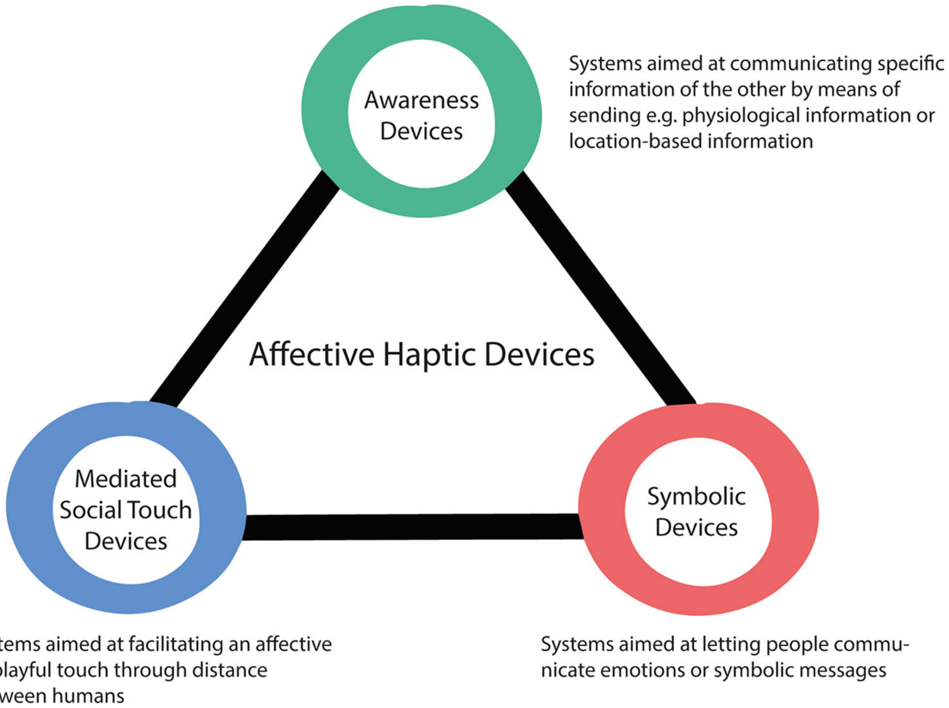

FIGURE 1
An overview of the three categories of affective haptic devices.

on understanding (*a priori*) perceptions of and attitudes toward AHDs. As AHDs are a novel technology, not much is known yet about people's interest and perceptions toward AHDs (Rognon et al., 2021).

It has been proposed that affective responses toward AHDs should be tested in a context where one experiences a need for touch (Willemse, 2018). The current COVID-19 pandemic, hence, provides an interesting opportunity to conduct research on the people's interests and perceptions toward AHDs in a time where more people are exposed to touch deprivation.

To our knowledge, there has been only one other study exploring people's interests and perceptions toward AHDs during this time of pandemic. In this survey study by Rognon et al. (2021), a sample of 258 participants were asked to report on what kind of social touch they missed out most, on what lacks in current mediated communication, and on which interactions they wanted to have with AHDs. The aim of the study was to gain insight into which device features are needed for a meaningful MST communication. Results showed the type of social touch preferred for MST communication to depend on relation type (e.g., a friend or a romantic partner). Moreover, the results showed mixed findings regarding the perception of people toward AHDs, with some people being positive while others were more skeptical on communication through touch.

Although, Rognon et al. (2021) asked participants to report on what social touch they missed most, it is a missed opportunity that the authors did not investigate how experienced touch deprivation related to people's intentions to use MST. Moreover, in their work, the authors have focused solely on MST, thereby lacking insights into other categories of AHDs, such as symbolic and awareness type of AHDs.

Besides touch deprivation, there are two other factors worth investigating when explaining individual differences in people's intention to use AHDs. Prior work in the field of AHDs has suggested technology readiness to influence intention to use (Wiedau et al., 2015). With AHDs being a rather new technology, most people will be unfamiliar with it. Hence technology readiness, that is, the extent to which people embrace new technologies, may be an important factor behind individual differences in people's intention to use AHDs (Parasuraman, 2000). A possible second factor that may explain individual differences in people's intention to use AHDs could be the personal characteristic of touch aversion, which refers to a general dislike of being touched by others. More touch averse individuals generally have less touch interactions and/or struggle to communicate *via* touch (Johansson, 2013). Touch aversion is a rather complex concept, and the extent to which people experience touch avoidance can depend on the relational context (Johansson, 2013; Strauss et al., 2019). On the one hand, one may expect more touch aversive individuals to have less need and thus less intention to use AHDs. On the other hand, AHDs might offer a controllable and/or less intimate type of touch that may be appreciated by some touch aversive individuals. Prior research has shown that for children with autism—who, in general, dislike social touch interactions—providing touch in the right format and through training had positive effects (Cullen et al., 2005). As no prior work has investigated the role of touch aversion in people's perceptions of and interests in AHDs, this relation will be explored in the current study.

Research aims

The aim of this paper is to investigate people's intention to use different types of AHDs (i.e., MST, Symbolic, and Awareness), and the various circumstances (or use cases) in which they would see themselves use AHDs. In addition, we explored what people consider to be the most important system characteristics of AHDs (e.g., synchronicity or reviewability). Finally, we examined how people's intention to use AHDs is related to individual differences in touch deprivation, touch aversion, and technology readiness. For this purpose, we conducted an online survey during a COVID-19 lock-down in the Netherlands in April 2020. Social interactions with people outside of the household were severely restricted during this lockdown. The survey consisted of a combination of closed- (e.g., rating scales) and open-format questions, which were analyzed using both quantitative and qualitative methods. In contrast to the work by Rognon et al. (2021), we did not focus only on MST but on AHDs in general, including also symbolic and awareness devices. Moreover, we included a measure of touch avoidance.

Although most of this survey research was exploratory in nature, we had three *a priori* hypotheses we wanted to test. First, it is to be expected that intention to use AHDs increases when people have a concrete need for social touch, such as when they experience some level of touch deprivation. Thus, our first hypothesis (H1) is that the extent of experienced touch deprivation during the lockdown is positively correlated with a person's intention to use AHDs. Second, based on Wiedau et al. (2015), we expect people that are, in general, more interested in, and willing to use new technology, will also have a stronger intention to use AHDs. Thus, our second hypothesis (H2) is that there is a positive correlation between self-reported technological readiness and general intention to use AHDs. We also expected the relation between touch deprivation and intention to use AHDs to depend on a person's technology readiness (i.e., the extent to which people embrace and use new technologies; Parasuraman, 2000). Therefore, our third hypothesis (H3) states that the relation between touch deprivation and intention to use AHDs is moderated by technology readiness. We expect that the effect of touch deprivation on intention use will be more pronounced if people also have higher levels of technology readiness, Since AHDs are new technologies, we expect early adopters or people who are tech savvy to also have a stronger interest in using AHDs when touch deprived. In addition to this, we also conducted an exploratory analysis to test if touch aversion may moderate the relation between touch deprivation and intention to use AHDs.

Method

Participants

The majority of the participants were recruited through the JF Schouten participant database of TU/e. Other participants were recruited through the personal networks of the authors. When we closed the survey, a total of 277 participants had started the questionnaire of whom 258 completed it. Data from non-completed questionnaires were maintained for analysis, where empty responses were indicated as missing values. From the 258 participants, only 147 participants indicated to have missed touch from a person during the lockdown. There were about 138 participants out of the 258 who had filled in the open-ended questions. However, a couple of entries were very short or not descriptive (e.g., just reporting "no" as the answer).

Participants' mean age was 27 years (SD = 10.24), with a minimum age of 18 and maximum age of 70. The majority of our sample consisted of students, with 56.3% being female, 43% male, 0.4% non-binary, and 0.4% preferred not to disclose their gender. The participants were born in the Netherlands (74.1%), Germany (0.4%), UK (1.1%), India (6.9%), China (2.2%) and other countries (15.3%). For additional information on demographics, see the Supplementary materials. An online questionnaire was sent out to the participants during the period between April 24 and April 30, 2020. During this period, regulations in The Netherlands were to have social distance, to avoid physical contact with people outside of their household, and to work primarily from home if possible. The participants who completed the survey could participate in a lottery with a 10% chance to win 30 euros as compensation for their participation.

Measures

The questionnaire contained a broad set of measurements, of which not all directly addressing our research question (e.g., questions regarding the social distancing regulations, technologies used to stay in contact). Here, we discuss only those measurements that are used in the analysis in this paper. The entire questionnaire, as well as the results pertaining to the other measurements, can be found in the Supplementary materials.

The questionnaire started with several demographic questions regarding age, gender, country of birth, and country of residence. To measure the extent to which people adopt or embrace novel technology, we used the technology readiness index [TRI; Parasuraman, 2000]. The original scale was adapted by choosing only one of the four constructs: innovativeness, which consisted of seven items (e.g., "Other people come to you for advice on new technologies."). The items were measured on a 5-point scale, ranging from 1 (labeled with "strongly disagree"), through 5 (labeled with "strongly agree"). For measuring touch aversion, we used a scale similar to the one used in Ipakchian Askari et al. (2020), which was, in turn, adapted from Wilhelm et al. (2001). This instrument consists of 6 statements (e.g., "I prefer to avoid shaking the hands of strangers.") that were answered on a 5-point scale, ranging from 1 (labeled with "not at all") through 5 (labeled with "very much").

To measure the extent of touch deprivation, an adaptation of the scale by Punyanunt-Carter (2016) was used. Prior to answering the touch deprivation questions, the participants indicated whom they missed having physical contact with the most as a consequence of the regulations around the COVID-19 pandemic, and what kind of touch interaction they missed most with this person. The participants were asked to keep this person in mind while answering the remaining questions, including the touch deprivation questions. The participants who indicated that they did not have a person they missed having physical contact with did not need to fill out the touch deprivation questions. The touch deprivation scale was adapted to measure both participants' experienced need for touch, as well as the participants' consideration for others' need for touch (i.e., experiencing a need to touch the other person, not because of lacking social touch themselves *per se*, but because the other experiences a lack of social touch). Moreover, the instrument was adapted to make it more explicitly focused on measuring touch deprivation in the current context (i.e., missing social touch from a specific person in times of COVID-19). The adapted touch deprivation scale consisted of eight items on a 5-point scale, ranging from 1 (labeled with "strongly disagree") through 5 (labeled with "strongly agree"), to measure the participants' own need for social touch (e.g., "I do not receive enough skin-to-skin contact from this person."). Additionally, there were three items on a 5-point scale, ranging from 1 (labeled with "strongly disagree") through 5 (labeled with "strongly agree"), measuring the participants' need for social touch, considering the other person's need (e.g., "I am currently longing to touch this person"). From the factor analysis, we did not find two separate constructs for measuring touch deprivation. Therefore, we decided to combine the items of the two constructs in one singe variable of touch deprivation.

To measure the intention to use AHDs, we included a list of descriptions of nine different AHDs (see Table 1 for the complete list). As the term "affective haptic devices" could be confusing for the participants (as it is a rather unfamiliar term), we decided to use the term "touch technology" in the questionnaire when referring to AHDs. The participants were asked to indicate on a 5-point scale, ranging from 1 (labeled "I would not at all use this device") through 5 (labeled "I will definitely use this device") to which extent they would use each of the devices if it had been available to them. The participants were asked to answer these questions with the person in mind whom they indicated earlier to miss physical contact with the most. The participants who indicated that they did not have a person they missed having physical contact with did not complete this part of the questionnaire. The nine AHDs in the list consisted of three devices for each category of AHDs (i.e., MST, Symbolic, and Awareness). For the category MST, we selected devices facilitating shaking hands (inspired by Nakanishi et al., 2014), kissing (inspired by Zhang et al., 2016), and hugging (inspired by Teh et al., 2012). The symbolic devices consisted of a device for instant messaging through a haptic channel (inspired by Mullenbach et al., 2014), communication of mood through haptics (inspired by Rantala et al., 2013), and a device communicating "thinking of someone" (inspired by Feelhey[4]). For the awareness category, we selected devices allowing the feeling of someone else's heartbeat *via* haptics (inspired by HB Ring[5], someone else's movement activity (e.g., their walking speed, inspired by Blum and Cooperstock, 2016), and devices that enable the feeling of someone else lying on their pillows (inspired by Iwaki et al., 2008). From these responses, two additional variables were constructed by aggregating (i.e., averaging) the responses of each person in different ways: A person's overall intention to use AHDs (averaging across all nine items), and the intention to use MST, symbolic AHDs, and awareness AHDs (averaging across items per AHD type). After the participants rated their intent to use these AHDs, they were asked to explain the choices they made by means of an open-ended question.

Next, the participants were asked to choose which three characteristics they found most important for touch technology. They were not asked to further prioritize between the three selected criteria. We provided a list of 12 characteristics (see Table 2). The list was composed of characteristics from general communication technologies (e.g., synchronicity, modalities; Dennis and Valacich, 1999), supplemented with haptic-specific characteristics (e.g., actuation technology, touch location on the body). After the participants indicated the three characteristics they deemed most important in AHDs, they were asked to explain their choices by means of an open-ended question. Again, only the participants who indicated missing physical contact with another person were asked to fill in these questions.

In the last part of the survey, the participants were asked to read five different situations (see Table 3 for the complete list) and to indicate for each situation how likely it would be for them to use touch technology in that situation. Their answers were measured on a 5-point scale, ranging from 1 (labeled "I would not at all use touch technologies in this situation") through 5

4 Feelhey. Available online at: https://feelhey.com/.

5 HB Ring. Available online at: https://thetouchx.com.

TABLE 1 A list of AHD devices used in the survey.

MST1: A device that would allow you to shake hands remotely.
MST2: A device that would allow you to give a kiss remotely.
MST3: A device that would allow you to give a hug remotely.
SYM1: A device that would allow you to send someone an instant message through a haptic channel (e.g., warmth, vibration, or pressure).
SYM2: A device that would allow you to communicate your mood *via* a haptic channel (e.g., warmth, vibration, or pressure).
SYM3: A device that would allow you to let someone know you're thinking of them *via* a haptic channel (e.g., warmth, vibration, or pressure).
AWA1: A device that would allow you to feel someone's heartbeat *via* haptic channel (e.g., warmth, vibration, or pressure).
AWA2: A device that would allow you to feel someone's movement activity (e.g., their walking speed) *via* a haptic channel (e.g., warmth, vibration, or pressure).
AWA3: A device that would allow you to feel someone is lying on their pillow *via* a haptic channel (e.g., warmth, vibration, or pressure).

TABLE 2 A list with characteristics of AHDs.

1. The ability to revise a touch message prior to sending it [Revisability]
2. The ability to re-play a touch message after receiving it [Reviewability]
3. The ability to receive the touch message in real time without a delay [Synchronicity]
4. The number of people to which you can send a message and receive a message from [Reach]
5. The ability to both receive and send a touch message [Bi-directionality]
6. The ability to have additional channels next to the touch experience (e.g., sound or video) [Modalities]
7. Both users have the same modalities (i.e., touch, sound, or video) at their disposal [Symmetry]
8. The way in which you have to send a touch [Input Type]
9. The ability to easily take the touch device along with you [Portability]
10. The ability to wear the touch device on your skin (e.g., as bracelet or t-shirt) [Wearability]
11. The physical sensation that is provided through the touch device (i.e., the quality of the touch) [Actuation]
12. The ability to send a touch message on various body locations [Body location]

The labels of these characteristic, here shown in brackets, were not presented to the participants in the survey.

(labeled "I will definitely use touch technology in this situation"). After each scenario, people were asked to explain their choices by means of an open-ended question. Only the participants who had indicated missing physical contact with a person were asked to fill in these questions. The scenarios were selected to reflect different circumstances in which communication through touch devices could be beneficial, including being in a long-distance relationship in quarantine due to the spread of dangerous virus, or if your parents are in a caring home (see Table 3 for the complete list). Throughout all the mentioned measurements, the participants were able to indicate to select the option "I don't know" or to skip a question if they were not able to answer it.

TABLE 3 An overview of the scenarios.

1. If you and your romantic partner would be in a long-distance relationship.
2. If a dangerous virus would be spreading and regulations are withholding you to go out of the house and visit your loved ones.
3. If your parents were staying in a caring home far away from where you live.
4. If one of your loved ones was lying in the hospital.
5. To stay in contact with your loved ones (e.g., partner, family, or friends).

Data analytic strategy

Before data collection, an *a priori* power analysis using the application G*Power[6] was conducted to determine the minimal number of participants. Since our statistical analysis mainly involved correlations (i.e., for H1 and H2), we determined the number of participants to have a power of 90% to detect a correlation of at least $\rho = 0.30$ at $\alpha = 0.05$ (two sided). Given the, by and large, exploratory nature of this study, and no clear indication of what size of population correlations between variables to expect, we chose a minimal effect size of interest of $\rho = 0.30$ to be able to uncover the most interesting relationships between variables. Based on this power analysis, a minimum sample size of $n = 109$ participants was required. A sensitivity analysis (Perugini et al., 2018) revealed that, with $n = 109$ participants, we had 90% power to detect a reasonable small to medium effect size of $f^2 = 0.10$ for individual regression estimates for our moderated regression model. Note that, for interaction terms, as for example for testing H3, the sensitivity may be overestimated. Since we expected not all participants to have experienced touch deprivation during the pandemic, we opted for 200 participants in total.

As a first step in our data preparation, we performed a series of factor analysis on each set of items intended to measure technology readiness, touch aversion, touch deprivation, and intention to use AHDs (Hair, 2009). These factor analyses were performed on the polychoric correlation matrix of the responses. We used principal (axis) factoring as extraction, and oblique oblimin as the rotation method. Prior to the analysis, items were inspected for missing values, low inter-item correlations, and low KMO values. To determine the number of factors, we used parallel analysis (Dinno, 2009) and the estimated correlation between factor scores, where we corrected for measurement

6 G*Power. Available online at: https://www.psychologie.hhu.de/arbeitsgruppen/allgemeine-psychologie-und-arbeitspsychologie/gpower.

error attenuation (Charles, 2005). Based on the final factor solution (see the Supplementary materials), factor scores were calculated using the summated scale method. The Cronbach's alpha values were $\alpha = 0.87$ for technology readiness, $\alpha = 0.84$ for touch aversion, $\alpha = 0.88$ for touch deprivation, and $\alpha = 0.92$ for intention to use AHDs.

Next, we checked the normality of the four obtained measures. Here and elsewhere in our analysis where normality was tested, we relied on the Shapiro–Wilk's test, using $\omega \geq 0.97$ as our criteria for sufficient normality. Intention to use AHDs was found to be normally distributed, but technology readiness, touch aversion, and touch deprivation were not. In general, non-parametric analyses were performed with the latter three variables. When this was not possible, for example, for the moderated regression, transformations were applied: for technology readiness, we used a square transformation, for touch aversion, the inverse, and for touch deprivation, the square root transformation. After this procedure, all factors were normally distributed.

Finally, we examined outliers on the intention to use AHDs, and on the transformed technology readiness, touch aversion, and touch deprivation variables. Here and elsewhere in the analysis where outliers were examined, we relied on Z-scores using the $|Z| > 3$ criterion to identify an outlier. We did not find any outliers in the data.

The analysis of the data was performed as follows, described here in the same order as presented in the results section. First, we summarized and provided descriptives of the various touch deprivation questions (e.g., from whom they missed touch most, and the participants' self-reported touch deprivation).

Second, we investigated the participants' intention to use AHDs in their interactions with the person they indicated to have missed most. People who did not indicate to have missed touch from a person did not answer the intention to use questions and, hence, were not included in the analysis. After estimating descriptive statistics of each of the nine included AHDs, we tested whether use intention was different for the three AHD types using the Friedman test, and follow-up Wilcoxon signed rank tests. For these and all other analysis we performed, significance levels were set to $\alpha = 0.05$, and any exceptions (e.g., to correct for multiple tests) are explicitly mentioned in the relevant Section of the Results.

Third, we analyzed our participants' responses to the open-ended question, asking to them to explain their ratings of their intention to use the nine AHDs. These were analyzed qualitatively using thematic analysis (Braun and Clarke, 2006, 2019), with each extracted (sub-)theme providing an answer to the question of what is behind people's intention to use AHDs.

Fourth, we investigated the relationships between touch deprivation, technology readiness, touch aversion, and overall intention to use AHDs. As a first step, we examined whether the participants that reported not to have missed physical contact from a specific person had higher self-reported touch avoidance than those that did indicate to have missed physical contact. For this, the Mann-Whitney U test was used. Next, we estimated the pairwise non-parametric Spearman correlations between the four variables. The correlation between touch deprivation and intention to use AHDs, and between technology readiness and intention to use AHDs tested H1 and H2, respectively. A measurement error attenuation correction was applied to the correlations following Charles (2005). To further explore the relationship between touch deprivation and the intention to use AHDs, and to test H3, we performed a moderated regression with overall intention to use AHDs as a dependent variable, touch deprivation as a predictor, and touch aversion and technology readiness as moderators. For this analysis, we used the transformed variables, and predictors and moderators were mean centered. Residuals were found to have a normal distribution, but the homoscedasticity assumption was not met (based on visual inspection of the residual against the predicted scores plot), Therefore, we used heterogeneity consistent SEs using the HC3 method. The SPSS add-on PROCESS (Hayes, 2020) was used with SPSS version 25 for conducting the moderation analysis.

Fifth, we investigated what our participants envisioned to be the most likely use cases for AHDs. Difference between the use cases was examined using the Friedman test, and follow-up Wilcoxon signed rank tests. Responses to the follow-up open-ended question were summarized using an iterative inductive coding process.

Finally, we examined what the participants regarded as the most important communication characteristics of AHDs based on the frequency with which each characteristic was chosen. Responses to the follow-up open-ended question were again summarized using an iterative inductive coding process.

Results

Touch deprivation

More than half of our participants (57%) reported to miss having physical contact during the corona lockdown, 38.9% did not miss having physical contact with others, and 4.2% responded with "I don't know"/"other." Of the 152 participants who indicated they missed having physical contact with someone, 43.4% reported missing physical contact with "friends," 19.7% with "parents," 17.8% with "family," 16.4% with a "partner," and 2.6% picked "other" (mentioning, for example, close colleagues, children, or grandchildren). When asked which type(s) of touch they missed the most by this person, 92.8% indicated missing a hug, 25% kisses, 19,7% a stroke, 19.1% a pat on the shoulder, 14.5% handshakes, 3.3% chose "I don't know," and 2% chose "other" (mentioning, for example, the arm in the arm, a squeeze on the arm or a playful touch). From the 147 participants that continued filling in the questionnaire and who reported missing physical contact, average self-reported touch deprivation was $M = 3.30$ (SD = 0.96; on a scale of 1–5).

Intention to use AHDs

Quantitative responses toward intention to use AHDs

When looking at the mean intention (on a scale of 1–5) to use for each of the nine individual AHDs (see Figure 2) we see, on average, people expressed a stronger intention to use MST 3, see Table 1 with an overview of the AHDs and their labels ($M = 3.13$; SD = 1.22), Symbolic 1 ($M = 3.26$; SD = 1.37), Symbolic 2 ($M = 2.98$; SD = 1.39), and Symbolic 3 ($M = 3.30$; SD = 1.42; also Figure 3). People were less interested to use MST 1 ($M = 1.82$; SD = 1.22), MST 2 ($M = 2.17$; SD = 1.35), Awareness 1 ($M = 2.32$; SD = 1.42), Awareness 2 ($M = 2.08$; SD = 1.29), and Awareness 3 ($M = 2.08$; SD = 1.25).

Using the Friedman test ($n = 147$), we found our participants' intention to use AHDs to depend on the type of AHD (i.e., MST devices, symbolic communication devices, and awareness devices), with $\chi^2_{(2)} = 106.8, p < 0.001$. For the follow-up Wilcoxon signed rank tests, we set our significance level at $\alpha = 0.0017$ to correct for multiple comparisons. Results revealed a statistically significant higher intention (on a scale of 1–5) to use for symbolic devices ($M = 3.18$; SD = 1.26) as compared to MST devices ($M = 2.38$; SD = 1.18) and awareness devices ($M = 2.15$; SD = 1.21), with $Z \leq 8.36$ and $p < 0.001$. No differences were found between MST and awareness devices, with $Z = 2.43$, and $p = 0.015$.

Qualitative responses toward intention to use AHDs

After having indicated their intention to use each specific AHD on the 5-point response scale, the participants were required to explain their choices *via* an open-ended question. These qualitative responses were analyzed by means of a thematic analysis (Braun and Clarke, 2006). Data were analyzed by the first author and the second author together. First, both authors individually went through the data and developed the initial set of themes and sub-themes. Next, they discussed their findings and through an iterative process came to the final set of themes and sub-themes. The final analysis revealed four main themes (see Figure 3). These will be discussed below alongside the subthemes.

People's attitudes and intention to use AHDs differ

From the analysis, we see that people's attitudes and intention to use AHDs are mixed. This is reflected in the participants' responses, which expressed both criticism and positive aspects of AHDs, for some participants even in a single response, *"I am quite skeptic about all these devices, especially for the shaking hands, feeling someone's heartbeat and someone's movement activity. I would not get any satisfaction of it. Hugging remotely and showing someone I am thinking of him or her seems to be nice in my opinion, since it feels warm."* Furthermore, people are critical toward these devices, reporting skepticism regarding the abilities of such devices in compensating for a lack of touch, *"I don't believe that technology will be able to relieve the need for physical contact"* and expressing they do not believe the technology could simulate real touch, *"you can't replace the feeling of a real kiss, so I wouldn't use that."* We see that the critique in some cases depends on the device, resulting in intention to use for one device while indicating a critique toward other(s), *"Some things are a bit too strange to do for me, but I like the idea of a hug since it is funny and cute."*

People also expressed that they would find it strange to interact through these AHDs, *"It seems weird to have a machine to kiss and hug,"* and some people expressed discomfort regarding the use of such devices, *"I would feel really uncomfortable with this type of technology."* However, there were also people who saw the benefit of AHDs. Some participants expressed seeing value in AHDs as an enrichment of current technology by, for example, communicating to someone that you are thinking of them and to communicate affection, *"It is nice if someone knows you are thinking of them, that makes them feel less alone. Furthermore, it would be nice to comfort someone through a device,"* and *"Getting a hug really helps from the emotional side to feel better."* Moreover, people also expressed interest in touch acts they missed and/or normally experienced prior to the COVID-19 pandemic, *"I would like the device to give a message to the person which is similar to the physical contact I would normally have with this person."*

From the data, we also see several people expressing concerns regarding the intrusiveness of AHDs, *"This sounds very intrusive, no thanks."* Furthermore, some people were critical about mimicking something as personal and private as physical contact through technology, *"I also think that physical contact is private and should not be intervened by technology."*

AHDs need to match the relation type

Another theme that we identified from the analysis is people expressing that AHD(s) were not suitable for use with the person in mind, because of the intimate nature of the device, *"The more intimate options are undesirable for contact with a friend."* This resulted in some people finding it strange to use a device for the person they had in mind, while acknowledging it might be suitable for interacting with someone else, such as a romantic partner, *"Some of these use-cases seem a little strange or unusual. Sharing heartbeat is something I'd consider doing with my wife, not with a friend. I like the idea*

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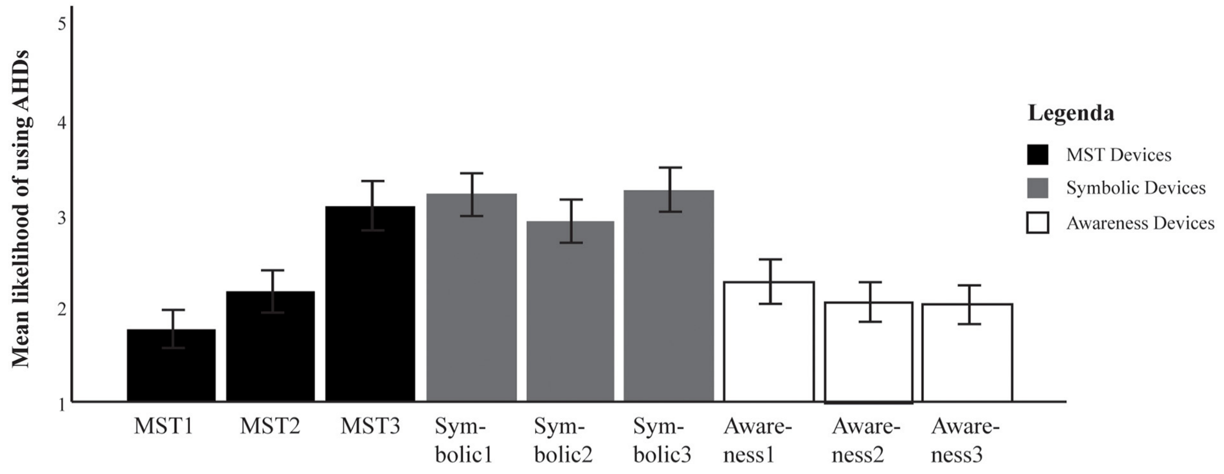

FIGURE 2
A bar graph visualizing mean likelihood of using AHDs for each individual type of AHD, with error bars indicating 95% confidence interval.

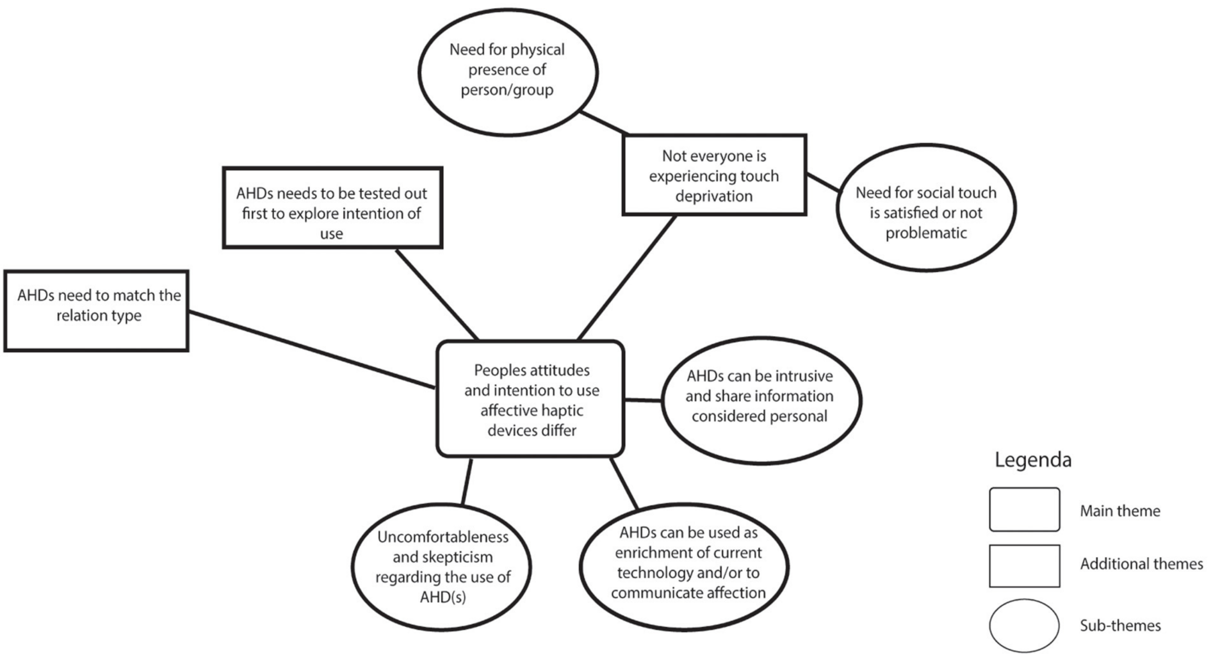

FIGURE 3
An overview of the themes and subthemes and their underlying relation.

of being able to give an indirect hug through such a device or being able to let someone know I'm thinking about them, though." For some people, the fact that some AHDs were not suitable for the person in mind also resulted in a more critical attitude toward using the technology, *"Technology is not the same as real physical contact. Maybe if it would have been my mom, I would have used one of these devices. But in my case, I'm just referring to a friend."* For more comments by the participants about touch in specific relationships, see the Supplementary materials.

AHDs need to be tested out first to explore intention of use

From the analysis, it was also found that several people first needed to try out the technology before knowing if it would be valuable for them. As this technology is rather new, some people had a hard time imagining what the possibilities of these devices would be, *"I'm not sure how these technologies would take shape, making it hard to imagine if I would want to use such technology."* Therefore, it was hard for some people to decide what their views were on a device, because even though they might be positive/negative now, they needed to try out the devices first before coming to a more definite conclusion, *"I think I prefer skin contact and would think the use of a device is weird and not the real thing. I have not tried it though so I wouldn't really know."*

Not everyone is experiencing touch deprivation

Our analysis showed that not everyone was experiencing a strong need for social touch. Some participants expressed the lack of social touch was not the problem for them; rather, physical presence of the other was missed, *"I long the feeling of being together with my friends and being able to attend activities together. A handshake will not help me."* Other people expressed they were not experiencing the loss of social touch with certain people (e.g., friends or parents) as problematic, *"I do not feel the need for physical contact with my parents so badly that I would use these devices as compensation."* Furthermore, it was expressed by some that their need for social touch was already satisfied, as they lived together with someone, *"I personally don't need these devices, as I am living with my partner and am not in desperate need of being touched."*

From the analysis, we also saw that, for some of the participants who did not have strong experiences of touch deprivation, this also made them less inclined to use AHDs, *"I do not feel the need for physical contact with my parents so badly that I would use these devices as compensation."* However, several people mentioned this might change if the COVID-19 social-distancing measurements would persist longer, *"With my parents I don't need these devices of touch at home. Seeing them via Skype and sometimes in real life is enough for now. Maybe if the Corona measures are going to stay forever, my feelings toward these devices might change. For now, it seems weird and maybe even a little bit creepy to have such devices."* For more comments by the participants about increasing/decreasing the amount of social touch, see the Supplementary materials.

Relation between touch deprivation, technology readiness, touch aversion, and intention to use AHDs

Across all the participants, the average untransformed technology readiness (on a scale of 1–5) was $M = 3.51$ (SD = 0.85), and average untransformed touch aversion was $M = 2.10$ (SD = 0.85). For those 147 participants that indicated to have missed touch from a person during the lockdown, and who thus completed the intention to use AHDs items, the average untransformed technology readiness was $M = 3.47$ (SD = 0.92), and average untransformed touch aversion was $M = 2.00$ (SD = 0.83). To explore whether there was a difference in touch aversion between the participants that did and those that did not miss touch from a person, the Mann–Whitney U-test was performed. We found the participants who reported not to have missed skin-to-skin contact to score higher on touch aversion (on a scale of 1–5) as compared to those that did miss having physical contact, with Z = 2.47 and $p = 0.013$.

To investigate how the intention to use AHDs relates to touch deprivation, technology readiness, and touch aversion, we first estimated the pairwise Spearman rank correlations (rho) between the four untransformed variables. The resulting correlation matrix includes the hypothesis tests needed for H1 and H2. Next, we conducted a moderated regression to test the combined effect of the three predictors, and the touch deprivation by technology readiness (H3) and touch deprivation by touch aversion interactions. The correlation matrix (see Table 4) revealed a positive and statistically significant correlation between touch deprivation and intention to use AHDs (rho = 0.48; $p = 0.00$), conforming our first hypothesis (H1). The association between technology readiness and intention to use was not found to be statistically significant, with rho = −0.02, and $p = 0.86$. In other words, we did not find support for our second hypothesis (H2). Although not hypothesized, we did find a small and negative correlation, rho = −0.19 and $p = 0.02$, between technology readiness and touch deprivation, indicating that individuals with a higher propensity to embrace and use new technologies may have experienced less touch deprivation during the pandemic.

Results of the moderated regression analysis ($n = 147$) with intention to use AHDs as the dependent variable, touch deprivation as a predictor, and technology readiness and touch aversion as moderators are presented in Table 5. The model explained 21.3% of the individual differences in intention to use AHDs. Consistent with the correlations reported above, touch deprivation (H1; $b = 1.70$, and $p = 0.00$) but not technology readiness (H2; $b = 0.01$; $p = 0.39$) was found to affect intention to use AHDs. No support was found for H3 as the technology readiness by touch deprivation interaction was not found to be statistically significant, with $b = 0.06$, and $p = 0.28$. In addition, no (moderating) effects of touch aversion were found (see Table 5).

Possible use scenarios AHDs

The participants were asked to indicate how likely it would be for them to use AHDs in various use cases (on a scale of 1–5), such as a long-distance relationship or when a loved one is in the hospital (see Table 3 for an overview of all the scenarios). Based on the Friedman test ($n = 131$), we found statistically significant differences between the various use cases on the average likelihood to use AHDs in these scenarios,

TABLE 4 Correlations (Spearman rho) between touch deprivation, technology readiness, touch aversion, and overall intention to use AHDs.

	Intention to use AHDs	Technology readiness	Touch deprivation	Touch aversion
Intention to use AHDs	0.92[a]	−0.02	0.48**	0.07
Technology readiness	**−0.02**	0.87[a]	−0.19*	−0.07
Touch deprivation	**0.53**	**−0.22**	0.88[a]	−0.10
Touch aversion	**0.07**	**−0.08**	**0.12**	0.84[a]

Values in bold are corrected for measurement error attenuation.
[a]Diagonal contains reliabilities (Cronbach's alpha); *p < 0.05; **p < 0.01.

TABLE 5 Moderated regression predicting overall intention to use AHDs from touch deprivation, touch aversion, and technology readiness.

Model	b	SE(HC3)	*t*	*p*	LLCI	ULCI
Constant	2.59	0.08	32.05	<0.01	2.43	2.76
Touch deprivation	1.70	0.32	5.32	<0.01	1.07	2.33
Touch aversion	−0.15	0.48	−0.31	0.76	−1.10	0.81
Touch deprivation x Touch aversion	−0.46	1.40	−0.33	0.74	−3.23	2.31
Technology readiness	0.01	0.02	0.86	0.39	−0.02	0.04
Touch deprivation x Technology readiness	0.06	0.05	0.28	0.28	−0.05	0.16

The normality-transformed predictors and moderators were used in the analysis. The predictors and moderators were mean centered. Standard Errors (SEs) are heterogeneity consistent using the HC3 method.

with $\chi^2(4) = 86.58$ and $p < 0.001$. Follow-up signed rank tests, with the significance level set at $\alpha = 0.0005$ to correct for multiple comparisons, revealed that the Long-Distance Relationship scenario was, on average, rated as a significantly more likely scenario for the use of AHDs ($M = 3.90$, SD = 1.12; also Figure 4) as compared to the scenarios Spread of Dangerous Virus ($M = 3.46$, SD = 1.29), Parents in a Caring Home ($M = 3.53$, SD = 1.41), and Stay in Contact with Loved Ones (M = 2.98, SD = 1.43), with Z ≤ 6.58 and p <.01. No significant difference was found between the Long-Distance Relationship and the Loved Ones in the Hospital scenario ($M = 3.71$, SD = 1.40), with $Z = 1.94$, and $p = 0.052$. The Stay in Contact with Loved Ones was rated as the least likely scenario in which to use AHDs as compared to all other scenarios, with $Z \leq 6.57$ and $p \leq 0.01$.

To arrive at a better understanding of people's rationale behind their evaluations, we asked them, for each scenario, to explain their answers in an open-ended question. These were analyzed by iteratively going through the data to create a summary of people's comments. Again, our participants indicated that they had difficulties with evaluating the use cases without actually having used AHDs in these scenarios. This was mentioned by various participants in all but the Stay in Contact with Loved Ones scenario. Below, we summarized, for each scenario separately, the—often rather critical—comments of our participants.

Although some people expressed a critical view on AHDs, overall, people were positive toward the use of AHDs in Long-Distance relationships. People indicated that such relationships result in a lack of intimacy and that touch is very important in a romantic relationship, *"We are in a long-distance relationship right now, and this would be a great way to reintroduce touch"* and *"Touch is important to me in a romantic relationship."* Furthermore, it was expressed that AHDs could facilitate couples in connecting with each other and to feel closer, *"Then my partner would feel closer to me and I could let him know I think about him."* and *"I think it would help connect."*

The responses were rather mixed for the use of AHDs during the spread of a dangerous virus. On the one hand, people expressed no need for this type of intimacy with family and/or friends, *"For friends and family, I can perfectly well survive without touching them as long as I can still talk to them"*. Moreover, some people expressed this technology being too intimate for use with certain people (e.g., friends and/or family), *"I would probably use it, but I feel less comfortable with using touch technologies for friends or family. It might feel too intimate."* Additionally, some people expressed current technologies to be sufficient for staying in contact, *"I think that so far is my situation since my family lives across the ocean, but it has been like that since I came here, so the video calls are really good and I don't feel like anything else is missing."* On the other hand, there were also

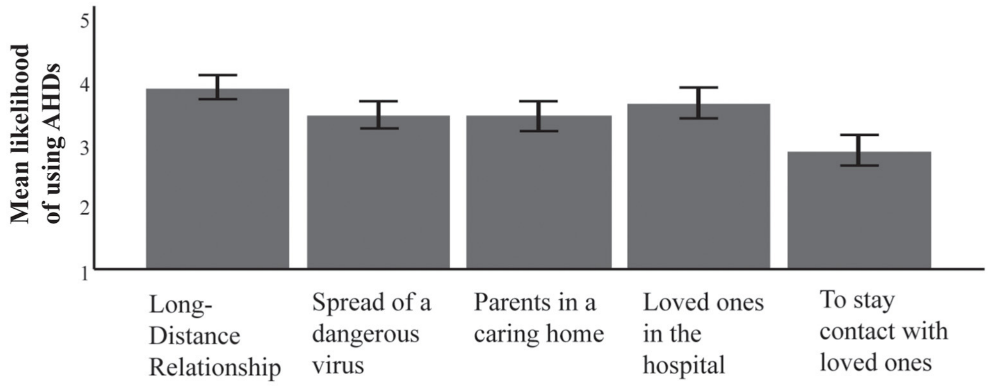

FIGURE 4
A bar graph visualizing mean likelihood of using AHDs for the various scenarios, with error bars indicating 95% confidence interval.

people who were still in doubt about the use of AHDs. Several people expressed the possible length of the lockdown period would influence their intention of use, *"I am not sure, if the regulations call for a 5-year lockdown, then yes, sure. Otherwise, not likely."*

Some participants explicitly mentioned that the uncertainty of the duration of the pandemic was a reason for expressing an intention to use AHDs, "*Since we do not know how long this is going to last and there is no end date to look forward to, I would be more willing to try."* Others expressed it was depended on the circumstances, *"If I know that they are at home safe, then it wouldn't be so important to me. I would prefer then just to send a regular message or to call"* and how their loved ones felt about using AHDs, *"I think this would depend on the situation and how me and my loved ones are feeling."* However, others were more inclined to use AHDs because of a need for intimacy, *"Currently, I'd love to have one to hug my grandparents"* and *"This is the situation which is currently in my country. As I miss the contact at this moment, it would be really nice to have such a touch technology."*

Regarding the scenario of having parents in a caring home, the participants expressed several reasons to use AHDs. Some explained it could be beneficial for their parents, *"Since they might be lonely."* It was proposed that AHDs could help in getting closer to each other and to show/receive affection, *"this way it is possible to have the feeling being closer to the other."* Others expressed the use of an AHD to depend on the needs of their parents, *"It depends on what they'd want, I would be open to the option."* It was also mentioned that AHDs could be a solution for the scenarios where physical interactions were limited or not possible, *"If you are not able to go see them, this would be a nice way to still do so."* However, many people expressed they preferred a real visit, "*I would still rather visit than use the technology, but it might be a good addition"* and, for that reason, did not intent on using AHDs, "*I would rather visit them every time I think of them than to replace my need to see them with technology."* The participants also mentioned that they did not intent on using AHDs because they believed that video communication is sufficient, *"I think that video chat will be more than enough,"* and, "*Normally, with my parents, I don't have a lot of touch connection, so it's nothing I am missing."* It was also remarked that AHDs are too intimate in this scenario, *"I would probably use it, but I feel less comfortable with using touch technologies for friends or family. It might feel too intimate."*

For the use of AHDs in a hospital, similar to the scenario where parents are in a caring home, several people expressed that intention to AHDs depended on the needs of the other person, *"Only if the person really requests or requires the feeling or touch would I be using it."* Furthermore, it was once more mentioned that AHDs could be used when visiting was not possible, although, visiting was preferred, *"I would prefer actually going there, but, if that's not an option, it's a good way to show you want to send more support."* Some people conveyed that, under these circumstances, it is important to show love to the person in the hospital (e.g., by means of a visit) not by interacting through a device or purely touching someone, *"I think showing love to this person is by visiting this person, and not touching"* and *"A hospital is temporary, of course, that person needs extra love, but not via a device."* Several people were critical toward the use of AHDs in a hospital, because it might not be suitable, *"I don't think it helps in that situation"* also because they thought that AHDs could interfere with equipment, *"may interfere with the hospital technology."* Additionally, people expressed no need for such a device, for example, because of the short stay in a hospital, *"The hospital is, most of the times, for a short period; therefore, I think I would use it less"* or because video communication is sufficient, *"For me, video is enough in this case."* However, other people expressed AHDs could be beneficial because they can be used to show affection, *"To let them know I am thinking of them and, maybe, they will feel better,"* especially during times where it matters, *"It's very heartbreaking if I cannot see and hug them because it may be the last time. So I think this technology can help with that"* and *"You want to support them"*.

Regarding the use of AHDs to stay in contact with loved ones, some people expressed a preference in using current technology, *"I rather stay in contact in other ways probably, video calls or messages."* Other people expressed that it would be beneficial to become closer and to show/receive affection, *"to keep and increase warmness in the relation."* Moreover, several people expressed the use of AHDs to depend on the situation, *"If I could physically visit, I would; otherwise, I would definitely use technology,"* and *"It depends on the situation, will use technology only if we are not in the same household,"* and also the person they would use it for, *"It depends on which of my loved ones. With my friends, I feel a lot less need for touching each other than with my family/partner."*

Important communication characteristics for AHDs

In order to better understand which communication characteristics people find most important in AHDs, we asked the participants to choose their top three characteristics from a list of 12 (see Table 2). We found the characteristic "bi-directionality" or the ability to both receive and send a touch message to be the most frequently chosen one (see Figure 5). People expressed such reciprocity to be an important characteristic in social touch, as a social touch typically involves a mutual interaction, *"Touching is always an act of consent, and mutual participation is the key."* Therefore, this characteristic was found to be important in digital touch as well. The participants, for example, expressed that if you send a message, you want to receive something back in return and *vice versa*, *"If you would send a message to someone, it would be nice if it would be reciprocated."* Such a mutual interaction can create a feeling of connection, *"I think it's really nice to both be able to send 'messages' to each other, to both feel the connection."*

Albeit less frequently than bi-directionality, also synchronicity, reviewability, symmetry, modalities and actuation were often chosen as important characteristics to have in AHDs. Synchronicity, or the ability to receive the touch message in real time without a delay, was found to be important for its role in providing a real-time communication, and, hence, a more realistic, mutual interaction. Rather than having to wait on the response of the other, synchronicity was regarded to result in a stronger feeling of connectedness, *"I think it is important that if you give someone a hug or touch through the device, then that the person immediately receives this gesture. I think this is the only way it feels more real, as you can immediately respond to it and integrate it into your conversation/contact."* For circumstances where real-time communication is not possible (e.g., because a person is not available), reviewability was seen as a promising solution, *"Finally, if one of the members of my family is not available but I have the need of feeling that person, then it would be nice if I can reply the latest message as a reminder."* Additionally, people expressed it can be nice to re-experience a touch message, similar to text messaging, *"Replaying the touch is nice, just as rereading messages. It can help you experience that feeling again."*

Symmetry, or for both users to have the same modalities (i.e., touch, sound or video) at their disposal, was chosen as important because it would result in the sharing of a similar experience, *"I want both my partner and I to have the same experience."* Moreover, symmetry was argued to aid in the creation of a shared meaning, *"I think it's most important that there is an equality of the devices used to make sure it carries the same meaning."* If touch devices are identical to each other, then this can result in a better understanding of what the other end will be experiencing. Having additional modalities besides a tactile or haptic channel was found to be important as the presence of supplementary cues can aid in the formation of the meaning of the touch message, *"It would be nice to be able to explain the touch message by a text or sound message."* Furthermore, additional modalities were argued to provide information regarding the context of the touch (e.g., the sender of the touch), *"I think it is important that the touch goes together with either a video or sound message so that you know where the touch is coming from or whether to send a touch (e.g., your family needs a hug because they just lost their job)."* It was also expressed that these supplementary cues can accommodate making the experience more realistic as this involves multiple senses, which are present in a naturalistic social touch setting, *"Furthermore, to make it feel more real, I think it is important to include other modalities as those would be present in real life as well."* The importance of a realistic touch experience was also reflected in the importance of actuation, or the physical sensation that is provided through the touch device. People underlined the importance of the touch sensation being realistic, as it, otherwise, cannot compensate for lack of touch and has no added value to them, *"It would be important that the sensation is equivalent to a real touch or hug. Thus, I think quality is an important factor. Otherwise, I would just stick to social media and text messages and videos."*

Discussion

In this paper, we presented the results from an online survey study of people's intention to use AHDs that was conducted during the COVID-19 lockdown in the Netherlands. This situation offered an opportunity to investigate people's perceptions of and intentions to use AHDs under circumstances where prospective use cases for these devices might be more apparent to the participants. While our research was mainly explorative, we also sought to provide answers to three hypotheses.

Our first hypothesis (H1) stated that experiences of touch deprivation are positively correlated with people's intention to

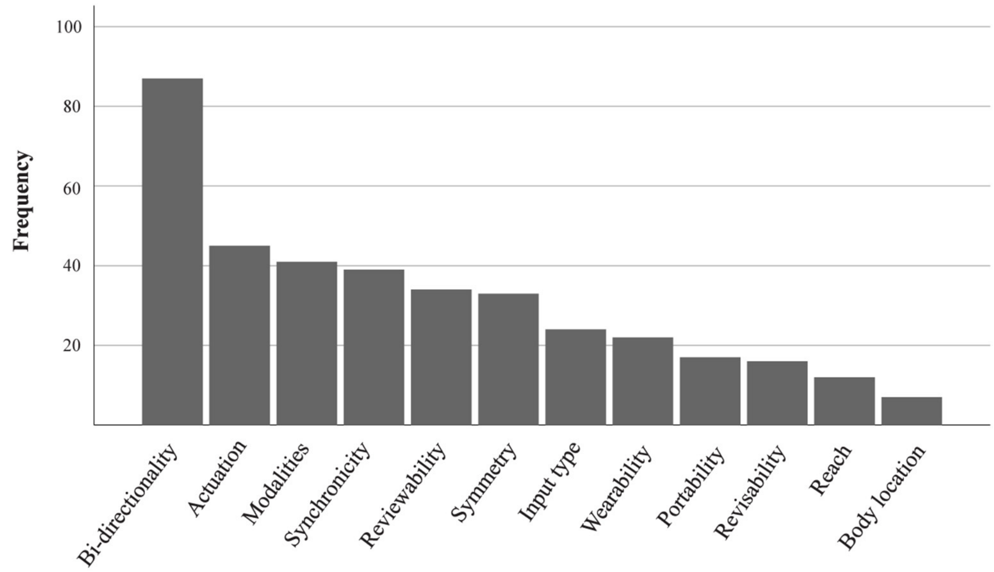

FIGURE 5
A bar graph visualizing the frequencies in which a communication characteristic was selected as being among the top three most important ones for AHDs.

use AHDs. Findings from the survey show support for H1. We found a moderate and positive correlation between the participants' reported touch deprivation and their intention to use AHDs. The more touch deprived an individual is, the more inclined he or she is to use AHDs. Responses to the open-ended questions underlined this relationship, with the participants who experienced a need for social touch, in some cases, expressing a stronger intention to use AHDs. This observation is further supported by the participants' responses to the five scenarios for which they were asked to indicate their intention to use AHDs. The participants were more inclined to indicate using such devices in the scenario where one is in a long-distance relationship—a situation where one might encounter a stronger need for social touch by one's partner—a finding which resonates with the participants' responses to an experienced lack of intimacy and to the importance of touch in romantic relationships (Gallace and Spence, 2010; Suvilehto et al., 2015; Jakubiak and Feeney, 2017). These findings suggest that, on average, the participants that experienced touch deprivation the most during the COVID-19 pandemic also had a stronger intention to use AHDs.

Our findings do not support H2. In contrast to previous research (Wiedau et al., 2015), we did not find technology readiness to affect the intention to use AHDs. In other words, despite AHDs being a novel technology, we found no evidence that suggests the intention to use AHDs to be dependent on an individual's reported technology readiness. More research is needed to confirm this finding.

Our findings also do not support H3. Although, we hypothesized technology readiness to be a moderator of the relation between touch deprivation and intention to use AHDs, no evidence was found in our data. However, we did find a negative correlation between technology readiness and touch deprivation. Although it remains speculative what explains this correlation, a possible explanation could be that the participants scoring low on technology readiness have less access to, are less inclined to use, and/or are less satisfied with the use of other communication platforms (e.g., Facebook, Skype, WhatsApp) to stay in contact with their loved ones. This might have resulted in them experiencing a higher need for social contact, social touch included. While questions regarding technology use were included in our survey, variance in the data was too low to conduct meaningful analysis. Moreover, we did not find evidence of age being a covariate; similar to the variable technology readiness variance in the data was too low to conduct meaningful analysis. More research is needed to further elucidate these points.

Touch aversion was not found to have any influence on people's intention to use AHDs. On the one hand, a negative association could have been expected as touch aversive individuals may have little interest in communication technologies that utilize the tactile and/or haptic modality. On the other hand, a positive correlation could have been expected as AHDs provide a more controllable and less intimate kind of social touch. However, by only selecting the participants that reported to miss skin-to-skin contact with a specific person, we have limited the variance on our touch aversion measure. Indeed, our results showed that the participants who reported not to have missed skin-to-skin contact scored higher on touch aversion as compared to those that did miss having physical contact. It is important to note that this finding does not indicate *per se* that people with touch aversion do not experience touch deprivation (see Debrot et al., 2020). Moreover, we must also acknowledge that touch aversion comes in many different forms (Johansson, 2013); each of which possibly affecting the intention to use AHDs differently. Unfortunately, the one-dimensional instrument used to measure touch aversion in this study cannot differentiate between various types of touch aversion. Clearly, more research is needed to understand these issues.

Our findings reveal that people differ in their intention to use and in their attitudes toward AHDs. While some participants indicated that AHDs have potential as an enrichment of current communication, others were more critical toward this type of technology, reporting discomfort and skepticism about AHDs being able to compensate for a lack of touch. As such our results are in line with earlier findings by Rognon et al. (2021). The more critical views on AHDs might stem from AHDs being a rather new type of technology. Because of this novelty, people might be unfamiliar with AHDs in terms of quality, functionality, and potential value (Rognon et al., 2021). Indeed, the participants often indicated that they needed to try the devices first before being able to evaluate them. The fact that some participants were skeptical might also have indicated a deeper aversion against AHDs in general. Our findings show that people are particularly averse to AHDs that aim to simulate or replace social touch (i.e., MST devices), with the exception of hugging. Remarks by the participants illustrate that, for some, social touch is too intimate to ever be mediated through technology. The participants, on average, indicated a stronger intention to use symbolic devices as compared to MST and awareness devices. It seems from these findings that people are most interested in using symbolic haptic and tactile messages for communicating affection (Jones and Yarbrough, 1985; Hesse et al., 2020) and offering social support (Sailer and Leknes, 2022), possibly because these functionalities are found to be limited in current communication media (Rognon et al., 2021).

AHDs for creating awareness about each other's presence (e.g., by letting another person feel one's body movements) were found to be the least interesting to the participants. One explanation for this is that the use of these devices, in contrast to the use of devices in the MST and symbolic categories, lacks intentionality. With intentionality, we mean that a message is sent to the other person as a conscious act with a certain aim, rather than being automatically triggered by, for example, one's heartbeat. Indeed, the participants remarked that they would like to be in control of what they share and when, rather than sharing signals more autonomously. Additionally, our findings suggest that the intention to use AHDs might also depend on the type of relationship one has with the communication partner, resembling earlier findings (Rognon et al., 2021). In the questionnaire, people had to indicate whether they currently miss social touch from one or more loved ones. They were then asked to select the person from whom they missed social touch the most and to fill in the remaining questions with this person in mind. We chose this approach to make the potential use cases for AHDs more concrete for the participants. However, for some participants, this resulted in them choosing a person with whom they found interactions with AHDs to be inappropriate.

In terms of what the participants considered to be particularly important characteristics of AHDs, bi-directionality was most frequently chosen by the participants, who stressed in their remarks the importance of a mutual interaction (Mueller et al., 2005). Additional characteristics found to be important were synchronicity and symmetry. When looking at the data, the participants indicated that the message having a shared meaning was important corresponding to findings of Jewitt et al. (2019). According to the participants' responses, this is something that can be more easily achieved with devices that operate symmetrically (i.e., with the same input and output). Moreover, the participants expressed the importance of a mutual interaction, something received through synchronicity (i.e., receiving the sensation in real time). Furthermore, the types of modalities were indicated as important (e.g., inclusion of video and sound). Looking at the responses by the participants, the importance of this characteristic relates to the notion that additional cues can provide a clear context to the interaction (e.g., knowing who the sender of the touch is). Indeed, the interpretations and experience of a social touch are highly dependent on context (Saarinen et al., 2021; Sailer and Leknes, 2022). In naturalistic social touch, multimodal cues are important for the interpretation and creation of the meaning of a tactile sensation (van Erp and Toet, 2015). It seems that people look for such additional multimodal cues in settings where touch is mediated by technology as well. Additionally, the characteristic actuation (i.e., the quality of the sensation) was found to be important as this relates to providing a realistic social touch experience.

When looking at the various communication characteristics that our participants indicated as most important, it becomes clear that these primarily resemble characteristics of face-to-face communication, of which social touch is a form (e.g., bi-directionality and synchronicity). At the same time, however, symbolic AHDs, which do not need to rely on natural face-to-face characteristics, were regarded as the most interesting category of AHDs. This presents us with somewhat of a paradox: The participants, on the one hand, deemed it to be important that AHDs share the communication characteristics of face-to-face interaction but were, on the other hand, relatively negative toward devices which aim to simulate social touch in face-to-face interactions (i.e., MST devices). This may, in part, be explained by the participants' skepticism toward MST but also indicates that, currently, our participants are best supported by AHDs that provide a form of symbolic communication that is bi-directional, synchronic, and symmetrical, without being a literal translation of naturalistic social touch. Designers of AHDs could take a broader view on touch communication, focusing not solely on haptic technology mimicking social touch but on developing novel forms of haptic communication, which are more symbolic in nature, providing an alternative communication style alongside current mediated communication (e.g., calling or texting).

Examples of devices that would meet at least some of these characteristics have been around for quite some time already (e.g., InTouch; Brave and Dahley, 1997). At the same time, the participants also indicated that they found reviewability (i.e., being able to replay or re-feel a received tactile or haptic message multiple times) important. This is a characteristic that is not available in naturalistic social touch but that can be an added value of mediated communication devices, such as AHDs. Alongside developing new forms of haptic communication, future work could also investigate how to avoid the discomfort of affective haptics that can be induced when aiming to simulate naturalistic social touch by carefully balancing the characteristics of AHDs and studying the context (e.g., the communication partner and presence of other communication modalities) in which they are used.

However, it must be noted that not all MST devices were approached with the same level of skepticism, and that the participants were, in fact, quite positive about AHDs that would allow a person to hug someone over distance (i.e., a type of MST, Rognon et al., 2021). More research is needed to explain why this particular type of simulated touch was seen as more promising than simulated handshakes and kisses; perhaps, the former were seen as more plausible or technologically feasible than the latter types. Moreover, the observed positive relation between touch deprivation and intention to use AHDs in general, including MST devices, does illustrate that AHDs can offer a solution for those circumstances where interpersonal physical contact is constrained. Future research should focus on disentangling in a more systematic fashion how attitudes toward specific AHDs relate to an individual's specific needs (e.g., individuals experiencing touch deprivation in specific social contexts) while taking into account individual differences in skepticism with respect to technological feasibility and functionality as well as anticipated comfortability or privacy-related concerns.

This study had several limitations. In the questionnaire, we only measured touch deprivation and intention to use AHDs for the group of people who indicated to have missed physical contact with one or more loved ones. Although requiring participants to answer the questions with a specific individual in mind provided a more concrete use-case for the participants, this did have the consequence of excluding data on touch deprivation and intention to use AHDs for people who do not miss physical contact. Although we cannot confirm this, one would expect people not missing physical contact to experience little lockdown-related touch deprivation. If so, then we have possibly reduced the variance in the measurement of touch deprivation, which, consequently, will have affected negatively the size of correlations with other measures, including intention to use AHDs.

Furthermore, our findings were based mainly on a student population. We should, therefore, be careful about generalizing these findings to the general public. Students have been affected by the lockdown differently than other population groups (Shanahan et al., 2020), and may, in general, have different priorities. Moreover, the young age of our sample might have had an influence on interest in new technology. Past work has shown that age can influence technology adoption (Morris and Venkatesh, 2000).

A second limitation was that our survey was conducted in the Netherlands. Social touch practices are culturally depended (Field, 2014). Therefore, it would be valuable for future work to study other cultures with different social touch behavior (e.g., the USA or France) to see how cultural differences affect perceptions of AHDs.

A third limitation of the current study is that AHDs were described as "touch devices." We decided to do so because we felt that term would be more easily understood by the participants than affective haptic devices (AHDs). Nevertheless, it is possible that the term "touch devices" primed the participants to compare AHDs primarily with naturalistic social touch, neglecting other forms of mediated and face-to-face human communication. This may have affected how certain questions were responded to, for example, with respect to what characteristics they found most important in AHDs.

Fourth, several participants indicated that they found it difficult to evaluate the devices and use cases without trying out the AHD first. Although, this is a logical consequence of a study that aims to investigate people's evaluation of AHDs prior to having used one—we did not ask whether this was, indeed, the case, but we deem such prior experience unlikely, given that the commercial availability of AHD is very limited—we may have supported the participants better in envisioning what it would be like to use the AHDs in practice. Future studies should consider providing participants with illustrations or movie clips demonstrating the workings and usage of the AHDs, perhaps, also including design concepts of future AHDs. At the same time, we must acknowledge that people's *a priori* evaluations and thoughts about AHDs may change (e.g., as to what system characteristics are most important) after having actually used the device. Hence, to fully understand people's experiences and attitudes toward AHDs the current study needs to be extended with fieldwork where people get to experience the devices firsthand, preferably for an extended period of time.

Finally, our study was conducted during a COVID-19 lockdown. Although this presented a unique opportunity to investigate people's perceptions of and intentions toward using AHDs, the current study may not generalize to other situations in which social touch is restricted. In other words, more research is needed to investigate whether and, if so, how the present findings would change when other, perhaps more mundane touch deprivation situations are studied, such as long-distance relationships or when one's spouse is in a hospital or nursing home.

Despite these limitations, this study provides important insights into what drives people's perceptions of and intentions to use AHDs, and into the kind of media characteristics they find important in them. In general, our findings illustrate the complexity of designing AHDs, the form of which will depend on the specific needs and use-case of the user. To our knowledge, this study is unique in that it not only focuses on a wide range of AHDs (i.e., MST, symbolic communication, and awareness systems), but in that it investigates people's intention to use these technologies during a time where many people experience a lack of physical contact. The COVID-19 pandemic has emphasized the importance of touch, and we hope that this study will contribute to designing effective haptic communication devices in support for human wellbeing.

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 Eindhoven University of Technology, Ethics Committee of Human-Technology Interaction. The patients/participants provided their written informed consent to participate in this study.

Author contributions

SI performed all the statistical analysis and wrote the first draft of the manuscript. GH collaborated on writing the draft of the manuscript and reviewed the sections of the manuscript. SI and GH conducted the thematic analysis. AH provided feedback on the thematic analysis. SI, GH, and AH contributed to design of the study. All the authors contributed to manuscript revision, read, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fcomp.2022.795927/full#supplementary-material

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Uncovering terra incognita in the AHD design space: A review of affective haptic devices

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Affective haptic devices (AHDs) have been developed with the aim of communicating touch acts, symbolic messages, emotions, and/or providing a sense of social awareness. Within AHDs, three categories can be distinguished: mediated social touch (MST), symbolic communication systems, and awareness systems. For each of these categories, prototypes have been developed and discussed in the literature. Each such prototype, however, describes but a small part of the design space of AHDs. What is lacking is a description of the design space itself—of all choices that can be considered during the design process. Such a description will allow for a more systematic exploration of AHD designs and provides a means of combining insights gained from individual point solutions (i.e., existing prototypes). Therefore, in this article, we provide a systematic description of the design space of AHDs and its underlying dimensions based on general (e.g., revisability or synchronicity) and AHD-specific (e.g., actuation type) communication system characteristics. This resulted in 17 design dimensions, each consisting of two or more categories (the design characteristics). Based on a systematic literature search from devices up to 2019, 89 AHD prototypes were identified, and each was classified on the design dimensions. The empirical analysis of where these AHDs are located in the design space revealed, first, that potentially interesting characteristics from mediated communication, such as revisability and reviewability, are underexplored in AHDs. Second, MST devices were found to often lack those system characteristics, such as real-time modalities, that seem crucial for providing the affordances needed to simulate social touch. In particular, when comparing symbolic and awareness devices to MST devices, we found the latter to more frequently lack some of the key characteristics of face-to-face communication (i.e., bi-directional and symmetric communication). Limitations and implications are discussed.

KEYWORDS

mediated social touch, social touch technology, haptic technology, communication characteristics, classification, design space

Introduction

Communication is an essential aspect of our human life. Over the past decades, communication media, from the physical letter and the telephone to modern-day social media, have drastically changed when, where, and how we communicate. In contrast to face-to-face communication, mediated forms of communication provide unique characteristics, such as the possibility of asynchronous communication (i.e., conversation that is not real-time) or adjusting a message before sending it to the other (revisability).

To date, most mediated forms of communication are not yet able to provide the richness of face-to-face communication, in which typically most of our sensory modalities are involved (Nadler, 2020). Past communication tools have largely focused on communication through the modalities of audio, text and/or video. Communication through a haptic modality has been less prominent in current communication technology. However, over the past years, there has been a rise in the development of so-called affective haptic devices (AHDs), which can be defined as devices aimed at communicating affective messages through a haptic modality (e.g., warmth, vibration and/or force). The promise of these AHDs is that they can enrich mediated communication in different ways. They can facilitate the communication of emotions, touch acts (e.g., a hug), symbolic messages (e.g., letting someone know you are thinking of them), or enhance social awareness. Currently, there are a wide range of AHD prototypes (e.g., Dodge, 1997; Teh et al., 2009; Pradana et al., 2015) as well as several commercial devices (e.g., Bond Touch, HB Ring[1]) that have been developed. Alongside these protypes, dedicated experimental devices have been developed (e.g., Haans et al., 2007; Cabibihan et al., 2012) with the purpose of investigating affective and/or behavioral responses toward affective haptic stimuli in controlled laboratory studies.

Three types of AHDs

The concept of AHDs is linked closely to that of social touch (or interpersonal physical contact). References to the importance of social touch for human wellbeing are abundant in the existing AHD literature, and the focus of the field has in earlier reviews been described as to be on mediated social touch (MST; Haans and IJsselsteijn, 2006) or social touch technologies (Huisman, 2017). While it is true that many articles in the field of AHDs focus on enabling social touch, such as hugs (Teh et al., 2012) or hand-holding (Erk et al., 2015), over a distance, close inspection of the available literature reveals that this is not the sole purpose for which AHDs are designed. At least three different types of AHDs, and thus three different design intentions, can be identified in the literature. First, there are AHDs aimed at facilitating an affective or playful touch over a distance. They focus on mimicking social touch for circumstances where skin-to-skin touch is not possible, for example, the Remote Handshake which facilitates handshaking during a videoconference (Nakanishi et al., 2014). Another example is the Huggy Pajama (Teh et al., 2012), a system build to enrich parent-child communication by facilitating parents to give their child a hug over a distance. This category of devices we refer to as Mediated Social Touch (MST), as they attempt to simulate, at least in part, the experience of real—unmediated—social touch acts. Second, there are systems aimed at facilitating the communication of affection (e.g., I love you, I'm thinking of you) in a symbolic manner, thus being more abstract in the communication. For example, the ForcePhone (Hoggan et al., 2012) or RingU (Pradana et al., 2015) allow users to send tactile messages by squeezing the AHD. Although these haptic signals are abstract in nature, users can use these devices to create their own haptic symbol systems, or "language". Third and final, there are systems aimed at creating awareness of each other's activities, context, or status (Markopoulos et al., 2009), for example, *via* physiological- or location-based information. An example of such a system is CoupleVIBE (Blum and Cooperstock, 2016) which facilitates the sharing between two people of such information as activity level, distance to other person and physiological state. Another example is the air-pillow telephone (Iwaki et al., 2008), a pillow that provides force-feedback based on the head movement of one's partner.

Design space as a tool for thinking about design and design processes

One particular critique that has been expressed regarding the field of AHDs is that it lacks a systematic description of its design space, making it difficult to identify, describe, and validate the possible and essential parameters of mediated social touch systems (van Erp and Toet, 2015). Instead, the bulk of the work in the domain has focused on designing prototypical devices, including the ones mentioned above. Each such prototype has provided valuable lessons on what some of the choices are that can be made when designing AHDs, and on how these design choices may affect user evaluations. However, each study in isolation does not provide the type of systematic description of the design space of AHDs called for by van Erp and Toet (2015): They remain point solutions, each describing but a small part of the design space of AHDs. What is lacking is a systematic description of the design space itself—of all choices, good or bad, that can be considered during the design process.

Such a mapping of the design space is important for two reasons. First, it will provide a strong basis for research and

1 *Bond Touch*. (n.d.). Retrieved from: https://bond-touch.com/ (accessed March 25, 2021); *HB Ring*. (n.d.). Retrieved from: https://thetouchx.com/hbring/index.html (accessed February 5, 2021).

design, allowing, for example, for more systematic consideration of potential design options. Second, it will provide a means of combining insights gained from individual point solutions (i.e., existing AHD prototypes). By locating each existing point solution (i.e., AHD prototypes) in this mapped design space, we can, for example, provide an overview of already explored design choices, but also detect parts of design space that are yet to be explored (i.e., *terra incognita*).

We adopt the term design space from Dennett (2013) and define it as the universe of all possible AHDs, which includes all existing and non-existing devices regardless of whether they provide any value to its user or not (i.e., design failures). The question central to the design process of course is: Where in this vast design space are the functional and valuable AHDs located? Answering this method requires exploring the design space in an efficient manner to discover which system functionalities are most suitable for a given context (Kang et al., 2011; Pimentel, 2017). The present article aims to contribute to this process, not by locating where in the design space the most valuable AHDs are located, but by describing the design space itself. Mapping the AHD design space will allow researchers and designers in the domain to search for value in a more structured fashion.

Research aims

The aim of this article is to map the design space of AHDs in a systematic manner, elucidating the design dimensions underlying these point solutions. For this purpose, we developed a classification system based on general (e.g., bi-directionality and synchrony) and AHD-specific (e.g., actuation type) communication system characteristics. Next, existing AHDs were identified *via* a systematic review of the literature[2], using the following databases: Inspec and ACM Digital Libraries. The conducted search included AHD literature up to 2019. Subsequently, these existing point solutions were classified on each dimension of our classification system. Finally, we empirically explored where in the design space of AHDs, the devices included in our analysis are located. To our knowledge, such a systematic classification of AHDs has not yet been performed. However, similar systematic classifications exist for haptic and force feedback devices (see Haptipedia; Seifi et al., 2019).

By mapping the design space of AHDs, we aim to answer the following research questions:

RQ1: What design choices have to date been made with respect to the communication characteristics of AHDs?

RQ2: How do these design choices differ between AHD types (i.e., MST, symbolic devices, awareness systems)?

By answering these questions, we aim to get a better insight into not just what design choices have been made, but also which communication characteristics seem underused in the literature up to 2019—thus highlighting possible unexplored areas of the design space (i.e., terra incognita). Since the three types of AHDs represent different design intentions, we expect such design choices to differ between them. Hence, the empirical comparisons of the three AHD types on their communication system characteristics are expected to contribute to our understanding of the underlying design choices.

In this study, we will also include AHDs that have been developed as part of an experimental study (e.g., Haans and IJsselsteijn, 2009a) rather than developed as a design artifact (used in for example design research) or commercial device. We found it important to include them in our investigations as experimental devices may perhaps include new characteristics not typically included in design artifacts or commercial devices. However, we acknowledge that these experimental artifacts typically are not designed to be complete communication systems. Instead, they are typically designed to provide a haptic stimulus as part of an experimental manipulation and may lack many of the communication characteristics of design artifacts. For example, the device used in the study by Haans et al. (2014) was developed to test the efficacy of the Midas touch with haptic technology. Although the device facilitated a touch over a distance, it is not yet a complete system (e.g., only one user has the possibility of receiving a touch, purely for the experimental set-up of this study). In these cases, the device is not designed to be functional within a natural communication situation. Therefore, the analysis will be performed twice: Once on all devices (both experimental and design artifacts) and once with the experimental artifacts filtered out. This allows us to investigate how the inclusion of experimental artifacts affected the results.

Classification system based on communication characteristics

Development of the classification system

AHDs can, of course, be classified in a variety of difference ways, for example, according to their technology readiness, their intended use case (e.g., people in a long-distance relationship), or a combination of both. Since AHDs are the first most communication devices, we decided to map the design space of AHDs based on the system characteristics of communication technology (see Table 1). Such a classification system would

2 In our mapping we have disregarded haptic technologies developed for sexual interactions. Although such technologies can be regarded as AHDs, our focus was on creating a classification system of AHDs facilitating non-sexual forms of social touch for multiple relationship types (e.g., friend, partner and family). For interested readers, see Döring (2020) for examples of AHDs facilitating sexual interactions.

TABLE 1 Overview of the dimensions and corresponding categories used for mapping the design space of Affective Haptic Devices (AHDs), which were based on communication and system characteristics.

Design dimensions	Category
General system categories	
Bi-directionality	Bi-directional, unidirectional, others
Input type	General, touch act, gesturing, abstract input, automatic input, others
Portability	Portable, not portable, others
Reach	One-to-one, many-to-many, one-to-many; many-to-one
Reviewability	Reviewable, not reviewable
Revisability	Revisable, not revisable
Richness of supplementary channels	No supplementary channel, low richness, high richness, others
Synchronicity	Synchronous, partly synchronous, asynchronous
Symmetry	Symmetric, asymmetric, others
System composition	One device, multiple devices, others
Wearability	Wearable, non-wearable, others
Haptic specific system dimensions	
Actuation	Force, warmth, vibrations, contactless haptic feedback, others, functional electrical stimulation (FES)
Body location	Face, hand, upper body, lower body, feet, others
Haptic real-time responsivity	Haptic real-time responsivity, no haptic real-time responsivity
Input-output mapping	Separate mapping, similar mapping, others
Local feedback	Local feedback, no local feedback

The design dimensions are listed separately for the general communication system and the haptic-specific system characteristics (in alphabetical order).

allow for the kind of systematic investigation of possible design parameters that van Erp and Toet (2015) called for.

The structure of our classification system is comparable to that of Haptipedia (Seifi et al., 2019) and allows for a similar kind of faceted navigation through the AHD design. The development of the classification system was done through an iterative process. In the first step, we derived an initial set of so-called design dimensions, which represent the system characteristics and communication affordances onto which the AHDs will be mapped.

This initial list was based on the framework developed by Clark and Brennan (1991) and communication dimensions from the media synchronicity theory (Dennis and Valacich, 1999; Dennis et al., 2008), consisting of dimensions such as revisability and reviewability. This initial list was complemented with additional system dimensions available in current-mediated communication technology, such as portability and wearability and with haptic-specific dimensions available in AHDs, such as actuation type and body location. In the second step, we classified the prototypes that we identified through the systematic review on the list of design dimensions, and, while going back-and-forth between the literature on these AHDs and the design dimensions, several changes to the design dimensions and their descriptions were made in order to create clear and unambiguous definitions of the dimensions. This included for example the inclusion of dimensions such as input/output mapping and morphological congruency to better describe and distinguish AHDs.

The end result is 17 more or less exhaustive and mutually exclusive design dimensions, each consisting of two or more categories (the design characteristics; see Table 1). In the remainder of this article, we use the term system to refer to the AHD prototype as a whole and use the term device to indicate one part of this system, for example, the InTouch (Brave and Dahley, 1997) is a system consisting out of two interconnected devices. In the following section, we will provide a detailed description of each design dimension and associated categories.

General system categories

Bi-directional

A bi-directional communication implies that individual users are able to both send and receive a haptic message. This facilitates reciprocal communication where if someone sends a haptic message, then the receiver is able to respond by means of a haptic message (Chang et al., 2002). In determining whether or not a device could be labeled as bi-directional, we first must consider the intention of the design. For example, although the Feelybean (Kontaris et al., 2012) was user tested in a uni-directional context (i.e., one person sending, the other receiving), it was mapped as bi-directional in our design space because it was designed to function as such. In cases, where the design intentions were unclear, we classified the prototype according to the experimental context or use scenario in which the device was tested. For example, in Haans and IJsselsteijn (2009a), the system was mapped as unidirectional as the experiment did not allow for the participant to send a haptic message back after receiving one. An example of a system classified as bi-directional is InTouch (Brave and Dahley, 1997). InTouch consists of two connected devices, each with three rollers. If one user moves the rollers of his or her device, the other person will feel their rollers move in a similar fashion, and vice versa. Examples of systems classified as "uni-directional" include, for example, the device developed by Israr and Abnousi (2018) who in their experimental set-up did not offer all users to both send and receive a haptic message.

Systems that were designed to function both in a bi-directional and a uni-directional mode were classified as "other".

An example of such a system is the Hug Shirt[3]. In the uni-directional mode, one user can use his or her cell phone to activate the hug shirt worn by their communication partner. In the bi-directional mode, both communication partners wear a Hug Shirt which then acts as both input and output devices.

Input type

This dimension distinguished devices according to how the haptic message is transmitted. We identified six different categories: general, touch act, gesturing, abstract input, automatic input, and others. We classified systems as "general" when input can be provided in a general way, for example, by pressing a button (e.g., InTouch; Liang et al., 2013) or, in the case of the Thermal Hug (Gooch and Watts, 2010), by clicking a button with your mouse or typing a specific keyword and clicking send.

Systems were classified as "touch act" if the input type resembled a social touch act such as kissing (e.g., Kissenger; Zhang et al., 2016) or placing a hand on a hand imprint (e.g., Hotmits; Gooch and Watts, 2010). Moreover, systems could be classified under "gesturing" when input can be provided by performing gestures (e.g., Hand Shaking Model; Abe et al., 2008). Systems that did not fall under any of these categories and where input was more open to the interpretation of the user (in contrast to for example general input types that resemble well-known ways of providing input) were classified as "abstract". These consisted of systems where input is provided by, for example, shaking a device (e.g., Strong and Gaver, 1996), moving a handle (e.g., Shanken, 2000), squeezing a device (e.g., Huggy; Teh et al., 2009), or by using a force-feedback device (e.g., Bailenson et al., 2007).

Systems were classified as "automatic" if the user does not have to provide an input consciously (e.g., by pressing a button), but rather output is sent automatically in the background through sensors in the system for example, through an accelerometer (e.g., FEELABUZZ; Tünnermann et al., 2014) or physiological measurements (e.g., AWE Goosebumps; Neidlinger et al., 2017). There are also systems that have multiple options for input type. We classified such systems as "other". An example of such a system is the AHD used by Ipakchian Askari et al. (2019), as the aim of the study was to investigate the influence of the input device. A system was used where input could be provided by tapping a touchscreen (the touch screen contained buttons with different body locations as labels) or by stroking a morphologically congruent input device (i.e., a rubber hand), depending on the condition.

Portability

This dimension distinguishes devices according to their portability, meaning whether or not the users can easily take the device with them and use it outside of their homes. Examples of systems classified as "portable" are Bond touch (see text footnote 1) and POKE (Park et al., 2013). Both are wearables (which we define later as worn on the skin) facilitating the use of the AHD outside of their home. Although a portable device can be wearable, this is not a prerequisite (e.g., LoveBomb; Hansson and Skog, 2001). Systems lacking the characteristics of portability are classified as "not portable". The Air-Pillow (Iwaki et al., 2008) and Telephonic Arm Wrestling (Shanken, 2000) are two examples of non-portable systems, both devices are not easily transported and require power cords, therefore preventing portable use.

Systems with a portable component as well as a non-portable one (e.g., a home station) are classified as "other"; an example of this is Cubble (Kowalski et al., 2013).

Reach

The design dimension reach represents how large the reach of a haptic message is, i.e., to how many recipients one can send a message to or receive a message from. This can be classified as "one-to-one", as is the case with RingU (Pradana et al., 2015). RingU consists of a pair of rings used to send a symbolic haptic message between two persons. However, communication can also be classified as "many-to-many", as is the case with Lovebomb (Hansson and Skog, 2001). With Lovebomb users can send anonymously a happy or a sad haptic message to fellow users located in the same radius of the sender of the message. Furthermore, Lovebomb users receive haptic messages from multiple users. Additionally, an AHD can also be classified as "one-to-many" or "many-to one". However, none of the devices identified in our prototype search were classified as one-to-many[4] or many-to-one.

Reviewability

Reviewability specifies whether the system offers the possibility to replay the haptic message after receiving it (Clark and Brennan, 1991; Dennis and Valacich, 1999). We classified systems with this feature as "reviewable" and systems without such a feature as "not reviewable". Reviewability means that a message is stored and can be replayed multiple times by the receiver. Storing a received message for it to be played at a later, perhaps more convenient time (e.g., as is the case with the Hug; DiSalvo et al., 2003) is in itself not sufficient for a system to be reviewable, as reviewability requires the storing of the message for replaying it more than once. Rather, this is a feature of the design dimension synchronicity, which is described later in this section. Feel Messenger (Israr et al., 2015) is an example of a reviewable application. The Feel Messenger application facilitates users in sending textual and haptic messages to one

3 Hug Shirt. Available at: https://cutecircuit.com/hugshirt/ (accessed December 3, 2020).

4 Although not present in our database search output, there is an existing AHD that facilitates one-to-many, see TapTap (Bonanni et al., 2006).

another through the IM interface. The messages can be replayed after opening.

Revisability

The dimension revisability is defined as the possibility in an interface to modify a haptic message prior to sending it (Clark and Brennan, 1991; Dennis and Valacich, 1999). We classified systems with this feature as "revisable". An example of such a system is FootIO (Rovers and van Essen, 2006). The FootIO is an instant messaging system in which text messages can be complemented with a haptic message by using so-called Hapticons (comparable to smileys), each of which represents a predefined set of vibration patterns. When composing the message users can select and revise their choice of these Hapticons before sending. Systems who do not facilitate this feature of revisability were classified as "not revisable" (e.g., SqueezeBands; Yarosh et al., 2017).

Richness of supplementary channels

The haptic communication channel can be accompanied by other modalities (e.g., a video or audio channel). The dimension "Richness of Supplementary Channels" specifies whether an additional communication channel exists beside the haptic one, and, if so, what level of richness is provided through these channels. Supplementary communication channels can provide contextual information that may aid in the interpretation of the tactile message, such as about the mood of one's communication partner. This seems particularly important for MST, as research has demonstrated that affective responses to MST are moderated by such contextual cues as facial expression (Harjunen et al., 2017) and the tone of a textual message (Ipakchian Askari et al., 2020). AHDs that provide supplementary channels high in richness (e.g., real-time video, audio, or a text chat) were classified under "high richness supplementary channel". An example of such a system is The Remote Handshake (Nakanishi et al., 2014) which offers users, beside the haptic channel, also a video and audio channel. Another example is HaptiHug (Tsetserukou, 2010), an add-on for the virtual environment Second Life.

The tactile channel can also be supplemented by less rich channels, such as consisting of emoticons or animations. An example of a device providing such a type of supplementary channels is Cubble (Kowalski et al., 2013), where users can receive feedback in the form of light or animations, which do not provide rich contextual information. We classified such systems under "low richness supplementary channel". Systems that offer a combination of high- and low-richness complementary channels were classified under "other". An example of such a system is the Hug (DiSalvo et al., 2003) where the haptic message is accompanied by real-time audio as well as customizable lights and sounds that can communicate the status of the communication (indicating for example that one is not at home)." Systems that do not offer a supplementary communication channel were classified as "no supplementary channel". An example of this is the TaSST (Huisman and Frederiks, 2013), which uses only a tactile channel for communication.

Synchronicity

In synchronous communication, the haptic message is received directly after the message is sent without any noteworthy delay (Dennis et al., 2008). A system is classified as "synchronous" when the system sends the message directly after input and is received directly by the user. Direct thus means that the message is intended to be directly received (disregarding unintended delays, or lag, in the communication, as for example due to network issues). An example of a synchronous system is Flex-N-Feel (Singhal et al., 2017). Flex-N-Feel consists of a pair of gloves developed for couples in a long-distance relationship. The gloves facilitate communication with their partner through a haptic channel. Partners can send a signal by flexing their hands. This signal is then directly sent to the receiving end. In our classification system, AHDs can also be classified as "partly synchronous", i.e., systems allow for synchronous communication as long as the user is present and willing to accept the message. An example of such a system is Haptic Text Messaging (Mullenbach et al., 2014). Although the message is directly sent the receiving end can decide to open the message at a later moment of time. Another example of when a system is classified as "partly synchronous" is when a message is stored when the receiving end is not present at the time the haptic message is sent, for example, as possible with the Hug (DiSalvo et al., 2003). The Hug facilitates users in sending haptic messages in real-time. However, when the receiving end is not present, the haptic message is stored.

Under the classification "partly synchronous", we also included systems where users have to grant permission before accepting the haptic message. For example with the system HKiss (Rahman and El Saddik, 2011). HKiss is a Second Life add-on enabling users to send one another a kiss. When a user sends a kiss, the receiving end first needs to accept this kiss. Other examples of systems classified as partly synchronous are systems where both users first need to hold the device before a haptic message is sent. An example is Hotmits (Gooch and Watts, 2012) where both users have to place their hand on a hand imprint, after which both imprints warm up. Other examples of partly synchronous devices are systems sending a message at a fixed time period, for example, every 12 s (Blum and Cooperstock, 2016).

We classified systems as "asynchronous", when a haptic message is not directly sent but a recorded haptic message is always played back (e.g., in the case of using Mid-Air Haptics; Obrist et al., 2015). While partly synchronous systems could still facilitate a form of synchronous communication if answering the messages happens at a fast pace, this is not possible with an asynchronous system. Such systems have too big of a lag to facilitate such communication.

Symmetry

Symmetry refers to whether or not the sender and receiver have access to the same modalities (e.g., text, touch, audio) within the system. Consequently, for a device to be classified as "symmetric," it needs to be bi-directional. An example of a symmetric device is POKE (Park et al., 2013), which enables users to enrich their phone conversations with haptic messages. The sender and the receiver have access to similar modalities (i.e., both can receive and send haptic messages during the conversation). While symmetric systems are by definition bi-directional, the opposite is not necessarily the case. Although no such systems were uncovered in our prototype search, a bi-directional system can be designed to be asymmetrical, for example, when only one of the two users has access to real-time video. However, we did not find such a system in our prototype search. Also note that symmetry does not mean equality in other functionalities. The Cubble (Kowalski et al., 2013) for example consists of a home station and an app on your phone. Depending on which of the two applications is used for sending/receiving a haptic message, the functionalities of the system differ. However, the system is symmetrical as the sender and the receiver have the same modalities at their disposal (in this case tactile modality in combination with light and animations).

Systems without the feature of symmetry are classified as "asymmetric" (e.g., Wikstrom et al., 2017). It should be noted that although symmetry allows both users to have access to the same modalities, this does not necessarily mean both users make use of similar modalities in a communication, for example, a person can decide to turn off the webcam while the person on the other side has turned it on.

Systems that are designed to support both asymmetric and symmetric modes of communication are labeled as "other". An example of such a device is the system proposed by Guo and Sourin (2018). They designed a system for haptic interaction during video calls, which allows both users to send and receive haptic feedback. However, they also proposed a set-up where only one user received haptic feedback.

System composition

The design dimension system composition represents whether both input and output components are present on one and the same device, or whether the system consists of two separate devices (one for input and one for output). Systems composed of one device are classified as "one device". InTouch (Brave and Dahley, 1997) is a system classified as being composed of one device. However, there are also systems that consist of separate components for sending and receiving. These are classified as "other" (e.g., the Huggy pajama; Teh et al., 2012).

We classified systems where input/output can be provided through one single device as well as multiple devices as "other". Cubble (Kowalski et al., 2013) is an example of such a device. Cubble consists of two components: a home station and a phone application. Input and output can be provided/received on either one of these devices.

Wearability

The design dimension wearability represents whether users are able to wear the AHD on their body as a bracelet (e.g., FeelHey[5], necklace (Wiedau et al., 2015), sleeve (Israr and Abnousi, 2018), jacket (e.g., HugME; Cha et al., 2009), scarf (Pfab and Willemse, 2015), etcetera. Systems containing this feature are classified as "wearable". The difference between wearability and portability is the fact that the device is worn on the skin, for example, Comtouch (Chang et al., 2002) is classified as "portable" as it can easily be brought along. However, as the device is not worn on the body it is classified as "non-wearable". Portability is not a prerequisite for wearability. It is possible that a system is not portable, while actuation is provided through a wearable component, for example in the case of SqueezeBands (Yarosh et al., 2017).

Systems consisting of a wearable and non-wearable element are classified as "other". An example of such a device is Intimate Transactions (Hamilton, 2007), where users receive haptic feedback through a haptic pendant (i.e., a wearable) and a smart chair (a non-wearable component).

Haptic-specific system categories

Actuation

This dimension distinguished devices according to the type of actuation used for the haptic or tactile message. Systems providing a haptic message through kinesthetic feedback (e.g., using force-feedback as in Telephonic Arm Wrestling; Shanken, 2000) or pressure (e.g., by means of air inflation as in Huggy Pajama; Teh et al., 2009) are classified under "force". Systems using warmth as an actuator are classified as "warmth" (e.g., Hothands and Hotmits; Gooch and Watts, 2012), and systems using vibrations motors are classified under "vibrations" (Darriba Frederiks et al., 2013). Systems where haptic feedback is provided through functional electrical stimulation (FES; e.g., Nishida et al., 2015) are classified as "FES". AHDs can also provide haptic and/or tactile feedback without the actuator being attached or placed on the skin. These systems are classified as "contactless haptic feedback" for example, mid-air haptic (Makino et al., 2015) or a magnetic field (e.g., Wiedau et al., 2015). We classified systems that make use of multiple actuation types as "other", as is, for example, the case with Vibrobod (Dobson et al., 2001). The Vibrobod uses both warmth and vibration.

5 FeelHey. (n.d.). Retrieved from: https://feelhey.com/collections/hey-touch#gref (accessed March 29, 2021).

Body location

Haptic messages can be provided on various body locations, and some devices may address more than one body location. For system addressing a single location on the body, the following labels were used: "The face" (e.g., CheekTouch; Park et al., 2012), "hand" [this also included touches experienced on the fingers; e.g., HB Ring (see text footnote 1)], "upper body" (this includes touches on the stomach, torso, shoulder or forearm; e.g., TaSST; Huisman and Frederiks, 2013), "lower body" (this includes abdomen and legs; e.g., Blum and Cooperstock, 2016) and "feet" (e.g., ComSlipper; Chen et al., 2006). However, some systems provide haptic stimulations on multiple body sections (e.g., Stitchies; Stenslie et al., 2013) or the body location is dependent on where the device is placed or hold (e.g., FEELABUZZ; Tünnermann et al., 2014). For a system that addressed more than a single location of the body, we used the label "other".

Haptic real-time responsivity

When engaging in a naturalistic touch act (e.g., a handshake), one experiences immediate haptic feedback by means of the resistance of the skin or the response of the other. Such immediate haptic feedback can also be provided in a mediated setting and is defined as haptic real-time responsivity to haptic inputs. Systems where users feel real-time resistance to their own actions, thereby receiving feedback from the other are classified as "Haptic real-time responsivity". An example of a system facilitating haptic real-time responsivity is Telephonic Arm Wrestling (Shanken, 2000), enabling users to arm-wrestling with one another over a distance. During arm-wrestling, both users feel resistance linked to the force that is exerted by their interaction partner.

Systems providing haptic real-time responsivity to only the sender of the touch, for example, a sender receiving feedback based on the body location of the receiver is also classified as haptic real-time responsivity. An example is HugMe (Cha et al., 2009), where only the sender of the touch received haptic real-time responsivity based on the body location that is touched. Systems do not need to apply haptic real-time responsivity through the actuation type "force" to be classified under haptic real-time responsivity. Systems using vibration to provide haptic real-time responsivity are also classified under haptic real-time responsivity. An example of such a system is Haptic Virtual Touch (Mullenbach et al., 2014), which is an application where users can remotely draw on a tablet. If both the fingers of both users intersect, then a haptic pattern is felt.

For a system to be classified as having haptic real-time responsivity, it does not require input and output to be present on one and the same device. Even though sending and receiving take place on two different devices the signal for sending and receiving between users can still be provided to users by haptic real-time responsivity. An example of a device with this feature is Hand Shaking Model (Abe et al., 2008), although the device has two separate devices for sending and receiving the user still experiences haptic real-time responsivity based on the input given by the other end. Systems that do not contain haptic real-time responsivity were labeled as "no haptic real-time responsivity."

Input/output mapping

The design dimension Input/Output mapping represents whether or not the AHD uses the same haptic display to provide both input and output. Meaning, participants can both feel and send a signal through the same part of the device. In our classification, such systems are classified under "similar mapping". InTouch (Brave and Dahley, 1997) is an example of such a system where input is provided by means of moving rollers, and output is also experienced through these rollers.

There are also systems where input/output mapping is at separate locations, these systems are classified as "separate mapping". An example of such a system is Bond touch (see text footnote 1). Bond touch is a bracelet used to send haptic messages by tapping on the front of the bracelet. Output is provided through vibrations. In the case of Bond touch input and output is provided through separate parts of the system.

Systems where input/output mapping can be similar as well as dissimilar are classified as "other". The article by Guo and Sourin (2018) describes an example of such a system. A force-feedback device provides the input and output for this device. However, the input can also be provided by making hand gestures, resulting in a system with separate input/output mapping.

Local feedback

The dimension of local feedback classifies whether systems provide the sender of the message with feedback on the intensity of the haptic signal they transmit (Chang et al., 2002). With some input types, such as a dial or slider, the user may already have some intuition as to the intensity of the haptic message they sent, as there is a visible minimum and maximum of the intensity range. Systems that offer real-time responsivity often give the user direct feedback as to the intensity or force they apply. An example of such a system is InTouch (Brave and Dahley, 1997). The InTouch consists of two devices, each with three physically coupled rollers. If a roller on one device is rotated, then the corresponding roller on the other device will rotate in the same way, thus offering the illusion of interacting on the same device. Providing real-time responsivity in this case, hence, also provides local feedback. For other input types, for example, those based on the force that a user applies to an input sensor, some form of local feedback may be required to determine the intensity of the haptic message that is being transmitted. An example is the ForcePhone (Hoggan et al., 2012), where the sender receives visual information about the relative pressure level of their haptic message. Devices that provide some form of local feedback—such as those described above—were classified as "local feedback." AHDs which do not offer local feedback were classified as "no local feedback." An example is the Vibrobod (Dobson et al., 2001). When applying pressure to the device to send the haptic message, the user has little to no information on how intense the tactile message will be. Devices such as the Vibrobod were classified as "no local feedback".

Morphologically congruent input

The design dimension morphologically congruent input represents whether or not the system makes use of an input medium representing a human form (e.g., a hand or a mannequin)—a so-called morphologically congruent input (see Ipakchian Askari et al., 2019). Systems with such a feature are classified as "morphologically congruent" and those without as "morphologically incongruent". HaptoClone (Makino et al., 2015) is an example of a system with a morphologically congruent input. HaptoClone enables users in sending a haptic message by touching a cloned image of the person at the other end. Under morphologically congruent input we do not include devices where users provide input through a wearable device placed on their body for example, as is the case with TaSST (Huisman and Frederiks, 2013), where input is provided on a sleeve attached to the user's arm. While these systems might facilitate an input that resembles a touch act, the form factor of the input device itself is not a human form (e.g., in the case of TaSST a sleeve). The input needs to be applied directly on a morphologically congruent input device. There are also systems that have the option of either a morphologically congruent or incongruent input (e.g., the system used in Ipakchian Askari et al., 2019). Such systems are classified as "other".

Mapping the design space of AHDs

Method

Two scientific databases were used to find relevant AHDs: Inspec and ACM Digital Libraries. These two databases were selected since they include the publishers, such as Springer, ACM, and IEEE. Taken together these publishers ensure that we included in our search various mayor journals (Virtual Reality; IEEE Virtual Reality; Frontiers of Computer Science; IEEE transactions on Haptics; Presence; Journal of Nonverbal Behavior) and conference proceeding series (IEEE Haptics symposium, including WorldHaptics; the ACM conference on Computer-Human Interaction, or CHI; EuroHaptics; AsiaHaptics; International Conference on Multimodal Interfaces; Machine Learning for Multimodal Interaction; Intelligent User Interfaces; Tangible and Embedded Interaction; UBICOMP). Based on a screening of articles discussing AHDs it was found that the majority of the AHD prototypes are described in these sources. The reviews from Haans and IJsselsteijn (2006) and Huisman (2017) were scanned for additional devices. For both databases a query was composed to identify publications that include in the abstracts keywords related to three categories: remote (virtual OR tele* OR remote OR distance OR mediated) AND affective (interpersonal OR social OR affective OR communication OR intimate) AND haptic (touch OR haptic* OR tactile). As this article only focuses on AHDs for human-to-human communication the query was extended to exclude entries that contained the keyword robot* in the title.

The search was conducted on July 2, 2019. We did not set a time limit to the time span of the published research, and the oldest article included in our selection was dated 1996 (i.e., Strong and Gaver, 1996). For a visualization of the different categories of AHDs present plotted over time please see Figure B.1. The database search resulted in 786 entries for ACM and 859 entries for Inspec. This selection was further narrowed by manual inspection of the titles and where needed abstracts or full texts. The selection process used the following inclusion criteria:

1. Work that is focused on creating or testing a device allowing human-to-human affective communication through a haptic channel (e.g., warmth, vibration, and/or force).

    a. For work regarding virtual collaboration systems, the abstract is read. Work is included if the device allows for affective interaction through a haptic channel.
    b. Work discussing devices developed for enhancing communication for blind individuals is excluded.
    c. Awareness systems were included if they explicitly mentioned a haptic channel and are aimed at personal purposes and not work-related purposes.

2. The article must describe enough detail about the AHD to allow it to be classified according to our classification scheme.

    a. The article needs to discuss both the input and output sides of the device.
    b. Articles should not be overly abstract or conceptual in describing the device.

When articles discussed the same or a highly similar device (e.g., a further iteration of the same design concept) only the most recent article was included in the analysis. Exceptions were made when the devices differed substantially. An example of such a case was the TaSST. Where in the earlier manuscript (Darriba Frederiks et al., 2013) the TaSST was described with one input possibility, this was extended to two possible inputs in a later manuscript (Darriba Frederiks et al., 2016). In the case that a manuscript described two different prototypes, both were included in the mapping exercise as separate devices. Figure 1 shows an overview of the selection process. The selection of articles was conducted in collaboration with a second rater. In case of doubt, the second rater took a second look. In case of

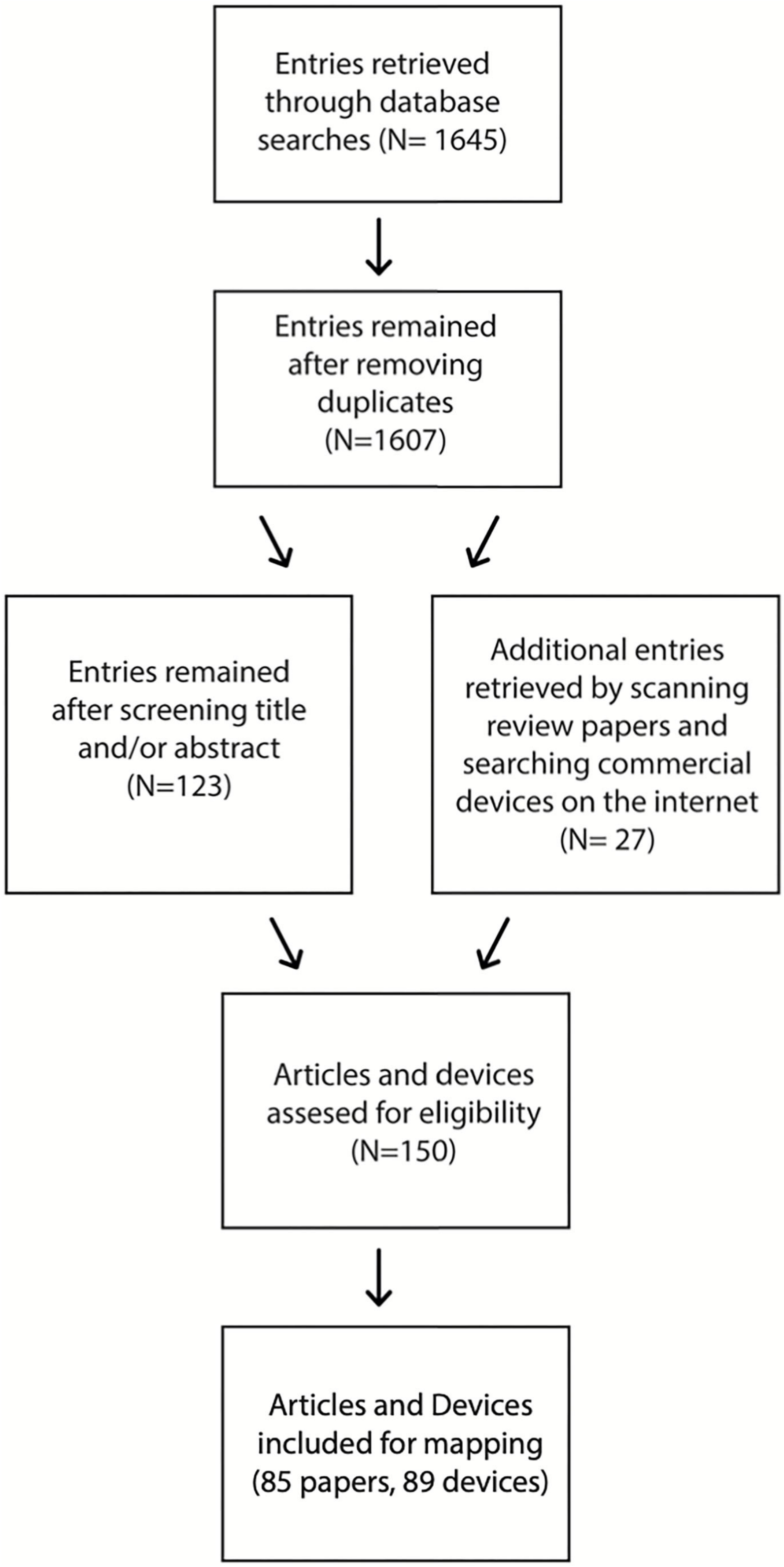

FIGURE 1
Overview of the selection process for devices to be used for mapping the design space of AHDs.

disagreement, discrepancies were discussed, and a final decision was made together. Through this process, a total of 89 AHDs were uncovered that met the abovementioned criteria.

Mapping of the AHDs into the classification system was performed by the first author. Similar to the selection process, in case of doubt, the second rater took a second look. Disagreements and discrepancies were discussed, and a final decision was made together. In the case that it was not possible to completely classify an AHD (e.g., because information about a concerning design dimension was lacking) we contacted the authors of the articles. if the information was not found this was reported through a missing value. In the Supplementary materials, the final categorization of each of the 89 AHDs is provided as a searchable Excel sheet.

To divide AHDs into three categories, MST, symbolic, and awareness AHDs were sorted based on the primary aim and functionalities of the AHD. We classified AHDs as MTS if the authors of the articles/websites referred to the device as a simulation of natural social touch. AHDs consisting of an automatic input type and/or aimed to create a sense of awareness rather than the communication of haptic messages were classified as awareness. Devices facilitating haptic communication of a more abstract nature were classified as symbolic.

Results

Distribution of AHDs across each of the categories of the dimensions

The classification of the 89 AHDs on each of the dimensions of our classification system can be found in Figure A.2, and consist of the proportion of devices being classified in a certain category (e.g., symmetric) on each dimension (e.g., symmetry). In the remainder of this section, we will highlight only those proportions that we found to be of particular interest.

Out of the 89 devices, most are **not revisable** (87.5%) and **not reviewable** (92.0%; see Figure A.2 for an overview). The majority of the systems were **synchronous** (81.8%) or partly synchronous (15.9%). Regarding the dimension bi-directionally, we found most systems to be **bi-directional** (73.0%). With respect to **reach**, we found most (95.5%) systems to be one-to-one and 4.5% many-to-one. The design dimension **symmetry** consists out of 73.0% symmetric and 24.7% asymmetric systems. With respect to the dimension focused on **supplementary information channels**, 43.8% of the systems were classified as touch only, 23.6% to complement touch with low richness supplementary channels and 24.7% with high richness supplementary channels.

Regarding the **input type** most systems used a touch act (31.5%) or a general input type (30.3%), and only 19.1% of the systems had an abstract input and 11.2% an automatic input. Regarding **actuation**, the majority of the systems (44.9%) used vibrations, 30.3% force, 13.5% others, 6.7% warmth. Regarding the **haptic real-time responsivity to haptic inputs** dimension, we found 85.2% of the systems to have a no haptic real-time responsivity.

On the dimension **body location**, most systems had the hand (37.9%) or upper body (35.6%) as body location. On the dimension **portability,** we found the majority of the systems (57.5%) to be not portable. Finally, 50.6% of the systems were **wearable**.

The results of our classification systems suggest a typical AHD to be synchronous and bi-directional, to complement the haptic channel with some additional non-touch communication channel (e.g., audio), but lack real-time responsivity, reviewability, and revisability. Since the AHDs here categorized were designed with various functionalities in mind, it is perhaps more interesting to investigate and compare the design choices that are made for the three different types of AHDs introduced at the onset of this manuscript: mediated social touch, symbolic devices, and awareness systems.

Differences per dimension between the three AHD types

To explore for differences in design choices between MST, symbolic devices, and awareness systems, we ran a series of Fisher exact tests (Kim, 2017), one for each dimension of our classification system. In the remainder of this section, we will highlight only those proportions that we found to be of particular interest (for the complete analysis, see Table 2).

The least common type of AHDs were awareness devices with only eight (i.e., 9.0%) of the devices classified as such. About half of the devices: 44 (49.4%) were classified as MST and 37 (41.6%) as symbolic. Results showed that for the design dimensions bi-directional, symmetry, the richness of supplementary channels, input type, system composition and portability there was a significant difference ($p < 0.01$) between the three AHD types (see Table 2 and Figure 2 for an overview of the results). A follow-up Fisher Exact test was conducted for each of these design dimensions to further explore differences using a pair wise comparison of two AHDs: MST vs. Symbolic, MST vs. Awareness, and Symbolic vs. Awareness.

For the dimension **bi-directionality**, there was a significant difference between MST and symbolic ($p = 0.008$). The characteristic bi-directionality occurred more often in symbolic devices (86.5%) than in MST devices (56.8%). Additionally, unidirectional devices were more prominent in MST (38.6%) than in symbolic devices (13.5%). Regarding the dimension, **symmetry** results showed a significant difference between MST and symbolic devices ($p = 0.008$): MST

TABLE 2 Distribution of all 89 AHDs (in %) across the categories of each design dimension separated per AHD type: MST ($n = 44$), symbolic ($n = 37$), and awareness ($n = 8$).

General system dimensions	Category	% per AHD type		
		MST[a]	Symbolic[b]	Awareness[ab]
Bi-directionality**	Bi-directional	56.8	86.5	100.0
	Unidirectional	38.6	13.5	0.0
	Other	4.5	0.0	0.0
		MST[a]	Symbolic[a]	Awareness[b]
Input type**	General	31.8	32.4	12.5
	Touch act	38.6	29.7	0.0
	Gesturing	4.5	2.7	0.0
	Abstract input	18.2	21.6	12.5
	automatic input	0.0	10.8	75.0
	Other	6.8	2.7	0.0
		MST[a]	Symbolic[b]	Awareness[b]
Portability**	Portable	25.0	54.3	75.0
	Not portable	75.0	42.9	25.0
	Other	0.0	2.9	0.0
		MST	Symbolic	Awareness
Reach	One-to-one	97.7	94.4	87.5
	Many-to-many	2.3	5.6	12.5
Reviewability	Reviewable	2.3	13.9	12.5
	Not reviewable	97.7	86.1	87.5
Revisability	Revisable	9.3	16.2	12.5
	Not revisable	90.7	83.8	87.5
		MST[a]	Symbolic[b]	Awareness[b]
Richness of supplementary channels**	No supplementary channel	43.2	48.6	25.0
	Low richness	9.1	29.7	75
	High richness	38.6	13.50	0.0
	Other	9.1	8.1	0
		MST	Symbolic	Awareness
Synchronicity	Synchronous	86.4	77.8	75.0
	Partly synchronous	11.4	19.4	25.0
	Asynchronous	2.3	2.8	0.0
		MST[a]	Symbolic[b]	Awareness[ab]
Symmetry**	Symmetric	56.8	86.5	100.0
	Asymmetric	38.6	13.5	0.0
	Other	4.5	0.0	0.0
		MST[a]	Symbolic[b]	Awareness[b]
System composition**	One device	38.6	70.3	87.5
	Multiple devices	56.8	27.0	12.5
	Other	4.5	2.7	0.0
		MST	Symbolic	Awareness

(Continued)

TABLE 2 (Continued)

General system dimensions	Category	% per AHD type		
		MST[a]	Symbolic[b]	Awareness[ab]
Wearability	Wearable	59.1	37.8	62.5
	Non-wearable	40.9	59.5	37.5
	Other	0.0	2.7	0.0
AHD specific dimensions	**Category**	**% per AHD Type**		
		MST	**Symbolic**	**Awareness**
Actuation	Force	43.2	18.9	12.5
	Warmth	6.8	8.1	0.0
	Vibrations	31.8	54.1	75.0
	Contactless	2.3	5.4	0.0
	FES	0.0	2.7	0.0
	Other	15.9	10.8	12.5
Body location	Face	4.7	2.8	0.0
	Hand	32.6	44.4	37.5
	Upper body	46.5	25.0	25.0
	Lower body	0.0	5.6	0.0
	Feet	0.0	5.6	0.0
	Other	16.3	16.7	37.5
Haptic real-time responsivity	Haptic real-time responsivity	20.5	10.8	0.0
	No haptic real-time responsivity	79.5	89.2	100.0
Input-output mapping	Separate mapping	72.7	59.5	87.5
	Similar mapping	25.0	40.5	12.5
	Other	2.3	0.0	0.0
Local feedback	Local feedback	25	37.8	12.5
	No local feedback	75	62.2	87.5
Morphological input	Congruent	11.4	0.0	0.0
	Incongruent	86.4	100	100.0
	Other	2.3	0.0	0.0

Results of the omnibus Fisher exact tests, one for each dimension, to test for difference in the distribution of AHDs between AHD types across a dimension's categories is indicated with asterisks: $*p < 0.05$, $**p < 0.01$. Follow-up pairwise comparisons were conducted for significant omnibus tests only. AHD types sharing the same superscript letter do not differ significantly with $p \geq 0.05$. A darker shade of blue indicates a higher percentage.

devices were more often asymmetric (38.6%) compared to symbolic devices (13.5%). Additionally, symbolic devices were more often symmetric (86.5%) compared to MST devices (56.8%).

On the **richness of supplementary channels** dimension, we found significant differences between MST vs. awareness ($p = 0.001$) and MST vs. symbolic ($p = 0.02$). More MST

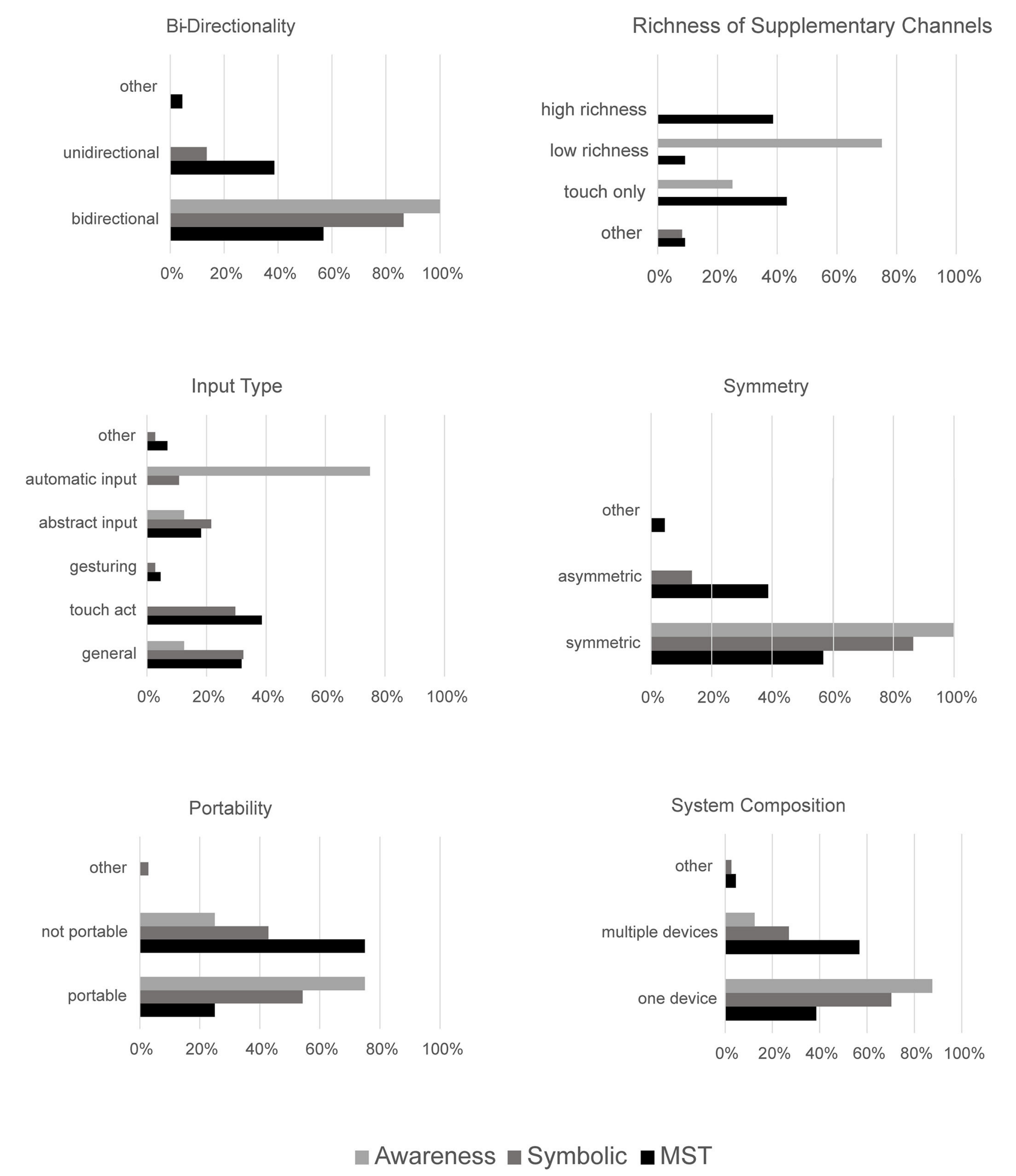

FIGURE 2
Bar graphs of the dimensions which were found to have significant differences between the types of AHDs. Each bar represents the percentage of devices within a certain AHD type classified to have that design characteristic.

devices (43.2%) were touch only as compared to awareness devices (25%).

Complementing a touch channel with **low-richness supplementary channels** occurred more often in awareness (75%) and symbolic devices (29.7%) than in MST devices (9.1%). Complementing touch with **high-richness supplementary channels**, however, was more prominent in MST (38.6%) than in symbolic (13.5%) and awareness devices (0.0%). For the design dimension **input type**, there was a significant difference between awareness vs, symbolic ($p = 0.005$) and MST vs. awareness ($p < 0.001$). As is to be expected, **automatic input** occurred more often in awareness devices (75.0%) as compared to symbolic devices (10.8%) and MST devices (0.0%). Additionally**, general input** and **touch input** occur more often in symbolic (32.4% general input and 29.7% touch act) and MST devices (31.8% general input and 38.6% touch act) than in awareness devices (12.5% general input and 0.0% touch act).

On the dimension **portability**, results showed a significant difference between MST vs. symbolic ($p = 0.007$) and MST vs. awareness ($p = 0.011$). Not-portable devices occurred more often in MST devices (75.0%) than in symbolic (42.9%) and awareness devices (25.0%). Additionally, portability occurs more often in symbolic (54.3%) and awareness devices (75.0%) than in MST devices (25.0%).

To examine whether or not the inclusion of experimental devices in the analysis may have affected outcomes, we repeated the analysis with all experimental devices excluded (i.e., including only the design artifacts). With 20.2% of the devices in the original dataset being labeled as experimental, a sample of 71 design artifacts remained for these analyses. The exclusion of the experimental AHDs did not change the interpretation of the findings, except for the dimension **system composition**. With the experimental artifacts excluded the difference between MST and awareness devices was no longer significant with $p = 0.17$. The difference between MST and symbolic devices remained significant with $p = 0.012$ (see Table A.1 for an overview of these results).

Discussion

Over the past few years, there has been a rise in the development of AHDs, resulting in many prototypical devices described in the literature. As valuable as each of these point solutions is in exploring the possibilities when designing AHDs, they each describe but a small part of the AHD design space. As argued by van Erp and Toet (2015), the field lacks a systematic investigation of the possible parameters to consider when designing and researching AHDs. Therefore, the aims of the present study were (a) to develop a classification system based on general (e.g., reviewability) and AHD-specific communication characteristics (e.g., type of actuation) with which to map the design space of AHDs, (b) to identify existing AHDs in the literature, and classify these point solutions according to this classification system, (c) to empirically explore where in the design space of AHDs the devices included in our analysis are located—and thus to identify what design choices are most popular—, and (d) to elucidate differences in these design choices across different types of AHDs: MST, symbolic systems, and awareness systems.

The location of included devices in the design space of AHDs

Regarding RQ1, our analysis of the distribution of AHDs across each of the categories of the dimensions revealed that several design characteristics were proportionally underrepresented in our set of AHDs including, for example, devices employing unidirectionality or asymmetric communication. Similarly, various input modes and actuation types were underrepresented, including automatic input, gesturing, multiple input types, FES, and contactless haptic feedback. Additionally, the categories with multiple options for input/output mapping and similar mapping were underrepresented. AHDs which were both symmetric as well as asymmetric, in particular, were rarely observed. Communication *via* media technology allows for unique possibilities not present in face-to-face interaction, such as reviewability, revisability, and one-to-many reach. Still, relatively few AHDs were classified to possess such characteristics.

From the latter analysis, it is impossible to tell why certain design choices are underpopulated in the set of AHDs included in our study. One possible explanation may be that some of these design characteristics are deemed unsuitable for AHDs. In their review, Haans and IJsselsteijn (2006) argued that many designers of AHDs make reference to the importance of social touch in every day live. A naturalistic social touch is not revisable (it is to think before you act), not reviewable, and typically one-to-one (group hugs are an exception). It is perhaps because of this ever-present linkage between AHDs and naturalistic social touch, that categories such as reviewability, revisability, and one-to-many remain rare. However, if this is indeed the case, then we would expect differences in the use of these characteristics between AHD types as the linkage with natural social touch is probably stronger in MST that aims to simulate social touch. However, when comparing MST with symbolic and awareness systems, the latter two were not found to be more often reviewable or revisable.

A second possible explanation could be the technical difficulties that arise when certain design choices are made. Categories such as automatic input, gesturing as input or contactless haptic feedback, FES, similar input-output mapping, or hybrid in wearability add a considerable level of technical complexity to AHDs; resulting, for example in more sensors, actuators and/or larger online storage facilities, which might prevent designers in using them, especially when wanting to make low-fi prototypes that are easier to adjust based on user-feedback. Of course, the third explanation for these observations is that certain possibilities in the design space of AHDs have simply been overlooked by designers and researchers alike. Put differently, some of the observed underpopulated areas of the design space may have been ignored not because of rational decisions or technical limitations, but because these possibilities were never considered to begin with. Especially for these cases, a systematic mapping of design space, as performed here using communication media characteristics as a classification method, can be useful.

Insights on awareness type of AHDs

The least common type of AHDs was awareness devices. MST devices appeared to be the most common type of AHD, followed by symbolic devices, as can be found in section Differences per dimension between the three AHD types. This was to be expected as in contrast to MST devices, awareness devices are not restricted to the tactile or haptic modality; note that the same applies to symbolic devices. Moreover, awareness devices (whether affective haptic or not) appear in general to be a less explored type of media technology. When looking at the common characteristics for awareness AHDs the results are by and large in line with what one would expect for this type of device. Automatic input seems the appropriate input type for the information send by awareness devices (e.g., physiological signals), as according to our definition communication through such devices go often automatic, meaning users do not have to send a message themselves, rather these are sent automatically through the system.

Findings regarding MST and comparison to other types of AHDs

When focusing in particular on MSTs—which make-up the large majority of the AHDs—, it becomes obvious that certain design choices are, at least in our opinion, at odds with the goal of simulating naturalistic social touch. First, despite a significantly higher proportion of MST devices supplementing the haptic channel with a non-touch communication channel, the absolute number of MSTs classified as having a rich supplementary channel was rather low (i.e., 38.6%). This is surprising as social touch is more than tactile stimulation alone, and is accompanied by a rich set of multimodal cues, for example, physical closeness, facial expressions, and perhaps verbal communications that together establish the intention of the toucher (Haans et al., 2014). Second, and perhaps most strikingly, is that regarding RQ2 in comparison to symbolic and awareness devices—which do not intend to simulate social touch—it was the MST devices that more often lacked fundamental features of face-to-face interactions, such as bi-directionality and symmetry, as was found from the Fisher exact test. This is surprising given the reciprocal nature of social touch. MST was relatively overrepresented, as compared to awareness and symbolic devices, on only two of the more fundamental characteristics of face-to-face social touch: high richness supplementary channel and touch acting as input type.

Possible explanations for design choices made regarding MST devices

As mentioned above, we can only provide possible suggestions as to what explains these observed differences between MST on the one hand and awareness and symbolic AHDs on the other. One logical explanation is that mediated social touch—or any type of mediated communication that has many of the characteristics of a face-to-face interaction for that matter—remains technologically challenging. Simulating social touch in a realistic manner will possibly require more advanced technology in terms of sensors and actuators and therefore also larger installations. We do indeed see in our analysis that MST devices, compared to symbolic and awareness devices, are more often static, not portable and consist out of multiple devices. Apparently, there is a trade-off between portability and realism in designing MST. This may explain the popularity of vibrotactile actuators as they are more easily implemented in portable or wearable devices. Technical complexity may also explain why the use of a morphological congruent input medium is not common, despite previous work suggesting it can influence touch experience (Haans and IJsselsteijn, 2009b; Ipakchian Askari et al., 2019). It may also explain why non-sexual MSTs are currently limited to touches to the upper body and the hand, even though naturalistic social touch can be provided on multiple body locations.

Finally, the technological complexity of the realistic stimulation of touch can also explain why such fundamental characteristics of face-to-face communication, such as bi-directionality and symmetry, are less common in MST as compared to awareness and symbolic devices. It is already difficult enough to allow one person to remotely touch another convincingly, and it may still be too difficult to recreate a reciprocal social touch experience for both. In contrast to MST, symbolic and awareness devices can probably rely on less rich tactile or haptic output and hence can more easily be bi-directional and symmetrical. Another explanation could be that haptic stimulation is less abstract in MST than in symbolic devices. Given the more abstract nature of symbolic information, some of the symbolic devices identified in the literature (such as the InTouch; Brave and Dahley, 1997) require bi-directionality and symmetry as this supports the negotiation of meaning. It may of course also be the case that some designers of MST devices would argue that social touch over a distance is possible even with rather impoverished communication characteristics, such as vibrotactile stimulation, unidirectionality, and asymmetry. More research is needed to confirm whether this is the case, or whether such categories as unidirectionality and symmetry (and hence reciprocity) are fundamental characteristics without which the technological simulation of social touch becomes difficult. Our findings thus raise fundamental questions related to when and why AHDs should be labeled MST. Does the inclusion of a tactile or haptic display in a communication medium suffice? Should a device match all characteristics of social touch, including its reciprocal nature, or should other criteria, perhaps not related to the system characteristics be used (e.g., strong response similarities with naturalistic social touch; see Haans and IJsselsteijn, 2006)? Clearly, more research is needed to answer these questions and to uncover what the essential characteristics of social touch are that need to be reproduced by MST to turn tactile stimulation into a social touch.

Limitations

One limitation of the present study is that our database search has been conducted in 2019. After this period, new research has been published that contains additional AHD prototypes. Hence, the reported findings may not be representative of the state-of-the-art in design choices in the domain of AHDs. However, any type of review article is necessarily retrospective—describes only a fixed window of time in the past. Ours encompasses the beginning of research and design work on AHDs up to 2019, spanning over 23 years of published research. It is important for this type of research to be repeated in the future, as to illustrate how design choices have changed since 2019. The concept of a design space, the proposal to decompose AHDs in different types (i.e., MST, symbolic, and awareness), as well as the developed classification system as put forward in the present article, provides the necessary tools for doing so. This does not mean that this categorization of AHD types, or the developed classification system may not need changes in the future. The dimensions of the AHD design space presented in this study were based on existing communication literature and on an iterative process that aimed to optimize the dimensions and their categories to the differentiation between existing AHDs. This, however, does not guarantee that all communication characteristic dimensions have been uncovered. More and novel types of AHDs may emerge that our classification system may not be able to differentiate amongst. The number of categories per design dimension may need to be expanded, for example, to be able to differentiate between the perhaps increasing number of devices that would now be categorized as "other". Similarly, additional design dimensions may need to be included. One example of such an additional dimension could be "morphological congruent output" which can differentiate between devices that do or do not provide actuation trough a haptic display that is congruent to the human body; a design choice that is becoming increasingly considered (see, e.g., the Future Affair installation; Dekker et al., 2021).

A second limitation of the present work is that we can neither guarantee that the set of AHDs uncovered in our literature search, although extensive and structured, is complete, nor that it is a representative (and thus unbiased) sample of all AHDs whether prototypical or commercial. Our search, for example, only focused on published literature and did, for example, not include white papers such as JoyHaptics (Tuovinen et al., 2022). It also did not include some of the more technical journals, such as the Journal of Dynamic Systems, Measurement, and Control, which sporadically publishes work on AHDs (e.g., Pedemonte et al., 2017). Similarly, we have not included the proceedings of early editions of such conferences as AsiaHaptics and EuroHaptics. Such omission may have affected the conclusion presented in this article.

A third limitation of our study is that we classified the AHDs on the basis of the communication characteristics that were implemented in the current version of the device, and did not take into account the possible envisioned end product. It may well be the case that various AHD prototypes, especially when in an early stage of development, may not yet have implemented all characteristics as envisioned for the final product. Consider, for example, the Air-Pillow (Iwaki et al., 2008). Being designed as a pillow to be used by geographically separated couples, it is obvious that the authors did intend for the final product to be portable. Nevertheless, we categorized it as non-portable as its current implementation does not easily allow the user to take it along with them. We opted for this manner of classifying the AHDs, as design intentions are not always made explicit in the literature; thus, requiring additional assumptions to be made on our part had we decided to take such intentions into account in the classification process.

A fourth limitation of the present work is that we focused only on communication system characteristics to classify AHDs within the design space. As mentioned in the method section, we could have used other systems, such as based on technology readiness, or the intended use case (e.g., simulating social touch between people in a long-distance relationship, or comforting a loved one in the hospital). Any such classification system would yield other insights than here presented. Future research should focus on other such classification systems, and when more data is available it would be of particular interest to investigate if and why AHDs designed for different use cases have different communication system characteristics. To do so, however, more data need to be available per intended use case than now is the case.

The fifth limitation of our work is that we have not yet provided insights into which combinations of design dimensions represented in our classification system are frequently co-occurring or incompatible with each other. Certain combinations of dimensions, for example, revisability and synchronicity are conflicting. An interesting analysis for future research is to explore such correlations between system characteristics. This, however, requires a larger dataset.

Finally, in the current article, we distinguished and made comparisons between three different types of AHDs, namely MST, symbolic devices, and awareness systems. We felt such distinction between different AHD types to be necessary as they present different design intentions that may lead to specific design choices. Although perhaps sufficient for the analysis here presented, we do acknowledge that the three proposed AHD types may be somewhat of an oversimplification, and that additional (sub-)categories, for example within the varied class of symbolic devices, may exist. More work is needed to further describe the different functionalities that AHDs can offer. The three types of AHDs here proposed are an important starting point, as it makes explicit that there is more to AHDs than the simulating of social touch, and thus that references to natural social touch are not always necessary when designing or commercializing an AHD.

Conclusion

The design space of AHDs is the infinite universe of possible AHD designs and includes amongst the non-functional designs those designs that can bring actual value to people. Over the years, various prototypical designs have been suggested in the literature, each of which is valuable for unveiling a small part of the design space—unveiling a small part of the possible design choices that can be made. In the present article, we aimed to locate these point solutions in the AHD design space, with the aim to provide a more systematic overview of the design choices considered up to 2019, but also to highlight those design possibilities that for various reasons have not yet been described. For this purpose, we proposed a multi-dimensional classification system based on media system characteristics. Our analysis pointed to various system characteristics being underrepresented in existing AHDs, in particular characteristics that are rather unique for mediated communication, such as revisability, reviewability, and one-to-many reach. Another finding was that, compared to symbolic and awareness AHDs, the MST devices in our dataset more often lacked some key characteristics of social touch in face-to-face interactions. Although we could only suggest potential explanations for these and other findings, our mapping exercise revealed various future research and design directions that can be addressed. Identifying and answering such questions is important to find value in the vast design space of AHDs. We hope that the current article contributes to this.

Data availability statement

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

Author contributions

SI conducted the prototype search, mapped the AHDs into the classification system, performed all the statistical analyses, and wrote the first draft of the manuscript. AH acted as the second coder for the mapping of the AHDs into the classification and contributed to writing the draft of the manuscript. SI and AH composed the selection and exclusion criteria for the prototype search. SI, AH, and WI developed the classification system. All authors contributed to the writing of the manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fcomp.2022.795772/full#supplementary-material

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Tinkering with social touch technology

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Social touch technology, haptic technology to mediate social touch interactions, potentially contributes to reducing negative effects of skin hunger and social isolation. This field is developing and while there are a number of prototypes, few became products and less persisted in the market today. Viable social touch technology is essential for research on social touch and it has an unexplored market potential. Making prototypes and evaluating them is the approach of generating knowledge in Research through Design (RtD). In RtD, researchers investigate the speculative future, probing on what the world could and should be, leaving the exact method of designing prototypes open. One possible method is tinkering, characterized by a playful and creative exploration. Tinkering environments, however, need a careful design of toolkits and setting. In this study, we report on the toolkit and setup we used for a tinkering-based teaching unit on social touch technology, held within an introductory course of an Interaction Technology master program, and describe the resulting prototypes. With a qualitative analysis of the results, we consider the teaching unit as a success, w.r.t. the diversity of the concepts developed. Tinkering is well-known as a playful method for education in Science, Technology, Engineering, and Maths, aiming at school children and high school students. It is not yet established as a design method in itself, and not considered as element of an academic skill set. Here, we argue that tinkering is a valuable design method in the context of social touch technology, and that it has a place in the design approaches within an academic setting. In a further step, we also want to include experts from other domains in the design process, such as psychologists or fashion designers. For that end, we suggest expanding a current toolkit for wearable technology with concepts from the teaching unit, more scaffolding tools, a variety of tactile actuators, and a software tool that allow for (re)configuring designs rather than programing them.

KEYWORDS

tinkering, social touch technology, teaching, Research through Design, toolkit design

1. Introduction

1.1. Social touch in social touch technology

Social touch plays a key role in close social relationships and fulfills an important role in the regulation of physical and emotional wellbeing (Field, 2010). However, distance and social isolation create barriers for social touch, and, overall, a decline in social touch over the past two decades is signaled (Jewitt et al., 2021). Negative effects of touch deprivation can be partially mitigated by mediating social touch through technology, known as social touch technology or STT (van Erp and Toet, 2015). However, while there existed already a range of prototype applications (Huisman, 2017), only few concepts made it to commercially available products, where even less persisted. Two factors may play a role here. One is that the potential for innovative future applications and products is huge and not yet explored and understood. In this line, Jewitt et al. (2021) presents a call to action to designers, developers, and researchers to rethink and reimagine social touch through a deeper engagement with the social and sensory aspects of touch. The other factor that may contribute to the low persistence of products on the market may be found in low acceptance. Technology Acceptance Models (TAM) indicate that perceived usefulness and perceived ease of use are main reasons for the intention to use a product (Davis, 1989). Accordingly, these have to be addressed in the design of products for the market. Both factors will be addressed and discussed in this study.

Above observations motivated us to develop an innovative approach based on tinkering to design STT that increases the chances of end-user acceptance and market success. We report the development of the tinkering approach and its first results, and provide a toolkit with tinkering components and a set of "scaffolding" cards ready to be used in educational and other settings.

From the technological point of view, there are solutions such as (almost) real-time connection over internet, and small electronic building blocks allowing for wearability. Actuators for social touch, however, are still restricted; vibration motors are the most simple and accessible realization, but are noisy and give a restricted tactile sensation, that is different from a human touch in many ways. Other technologies such as servo motors, shape memory alloys, and pneumatic or hydraulic actuators can stimulate different sensory receptors, but come also with different drawbacks (e.g., they are bulky and noisy) that make them not yet suitable (for wearables) for mediated social touch. However, a number of initiatives and research lines are busy with the development of textile actuators or new developments in wearable pneumatic actuators that will be available in the near future (Maziz et al., 2017).

From an application point of view, STT is still coming short in the replication of a human touch. In Huisman (2017), the author states "Mediated social touch is less sensory rich than actual social touch, not just in terms of cutaneous and kinesthetic feedback, but also in terms of feedback from other modalities which may not necessarily be present in mediated social touch."

At this point, we want to take the perspective that (a) human-to-human touch might be an inspiration for applications of STT, but technical applications of social touch may supersede human possibilities (imagine a full body hug with ten arms) and (b) that achievement of the positive effect on social needs is more important than a replication of a human touch. This leaves space for a wide range of out-of-the-box concepts.

1.2. Research through Design and tinkering

For novel applications, creative ideas are relevant, and, beyond these, also knowledge on how to address new characteristics introduced by social touch over a distance, such as inherent asymmetry in comparison to a direct human-to-human touch, the non-reciprocity (in a physical touch, the toucher also feels the touch s/he gives), ambiguous attribution (who is actually the initiator of a touch if there is, e.g., computation involved) (Huisman, 2017), complex agency (e.g., is the vest touching me or the person who gave me the vest?), or intrusiveness (a touch might be unexpected and not fitting a situation). In the context of STT, Research through Design (RtD) could be a suitable approach to gain this knowledge. "RtD asks researchers to investigate the speculative future, probing on what the world could and should be" (Zimmerman and Forlizzi, 2014). It builds on generating knowledge by introducing prototypes into the world, and reflect, measure, discuss, and analyze the effect, sometimes the coming-into-being, of these artifacts (Stappers and Giaccardi, 2017). According to Gaver (2012), making is part of the paradigms of RtD, i.e., most of us agree that the practice of making is a route to discovery, and that the synthetic nature of design allows for richer and more situated understandings than those produced through more analytic means. While in this, approach design is driving part of research, RtD does not define how to generate and design new prototypes. It is method agnostic (Stappers and Giaccardi, 2017), in the sense that the method of designing prototypes can be filled in various ways.

In this study, we suggest that tinkering is a suitable design approach for out-of-the box prototypes in the context of STT. Tinkering is characterized by a playful way of working, stimulating creativity, where goals are self chosen, evaluated, and re-defined in an iterative process. In tinkering, the design space is explored in a hands-on manner, inviting to get into a conversation with the material (Schön, 1992), experience its possibilities and restrictions, and getting inspiration from these. Tinkering is a process having trial-and-error at its core (Martinez and Stager, 2013), where trial-and-error should not be understood as randomness, but more as a way to explore and experience material properties. Depending on the background of the tinkerer, this exploration can be very systematic (as we have seen in tinkerers with an art school education), but are always guided by curiosity and background (including professional background). Following this process, tinkerers are open to serendipity, observation of the unexpected. There is no expectation that others following the same process would produce the same or even a similar final artifact (Zimmerman and Forlizzi, 2014). Especially in the context of haptics, experiencing the material is also a key factor in the exploration. Insights that need to be experienced are, for example, a stroke by a series of vibration motors is very different from a stroke by a hand, feeling one's own heart beat via a vibration motor is awkward, and the noise of a (vibration) motor can spoil the touch experience, but a vibration motor still can generate a pleasant feeling of massage on a shoulder. There is an endless list on the qualities of touch experiences, and contexts in which they are perceived differently, that need a hands-on approach for evaluation. The hands-on approach shows limitations of the material, but at the same time also shows new possibilities and stimulates creativity.

Most tinkering approaches in teaching aim children in primary schools or high school students, as in-school activities as well as out-school activities, and the approach is especially popular for Science, Technology, Engineering, and Mathematics (STEM) education (Vossoughi and Bevan, 2014). However, as the authors elaborated in Quinn and Bell (2013) and Mader and Dertien (2016), tinkering can also be a valuable contribution in academic teaching. At our university, we are applying tinkering-based teaching approaches in several courses of our bachelor program on Creative Technology as well as in a master program on Interaction Technology. In both, it has demonstrated its value for creating innovative concepts and prototypes.

1.3. Tinkering with social touch technology

We expect that the need for innovative applications of STT makes tinkering a promising approach that stimulates the creation of prototypes with novel concepts. Especially for touch, it is important to create tangible prototypes; it is inherent to this sensory modality. User evaluation of these prototypes drive insights in the RtD approach (Zimmerman and Forlizzi, 2014), and has the potential to increase the body of knowledge on STT, and further on also to improve the maturity of concepts.

According to these expectations, we come to the following research question:

Is tinkering a design approach that can foster the finding of novel applications in STT?

In this study, we will answer this research question based on the results of a tinkering-based teaching unit on STT in an Interaction Technology master program.

Tinkering activities need the design of a setup, i.e., material, scaffolding, etc. We will describe the components of such a setup in general, and specifically for the teaching unit considered. The analysis of the students' results will provide an answer to our research question.

Students of Interaction Technology have technical knowledge beyond what a "general public" would have, which allowed them to manage the technical challenges of the tinkering task. However, we expect it to be valuable if multidisciplinary teams, with no specific technical background, could also tinker with touch technology. Therefore, as a step further, we would like to enable experts of other domains to explore the possibilities of STT, such as psychologists, fashion and interaction designers, or physiotherapists. They can bring in different perspectives of user needs and, accordingly, contribute to a better perception of usefulness and technology acceptance. To this end, we suggest further steps in the design of a toolbox for STT, building on an existing toolbox for tinkering with wearable technology.

1.4. Outline of this study

In Section 2, we report on a tinkering-based teaching unit on STT in an Interaction Technology master program. It builds on a generic framework for tinkering sessions, that is elaborated conceptually, and on the design of its key elements. Concept, material, and results of this teaching unit for two cohorts of students will be presented. We will discuss how the results of the students answer our research question. Section 3 is about the additional design steps needed for the toolkit to make it accessible for non-technologist. We describe material developed earlier for tinkering with wearable technology, and suggest extensions allowing broader groups of stakeholders to tinkering with STT. A discussion is contained in Section 4, and a conclusion can be found in Section 5.

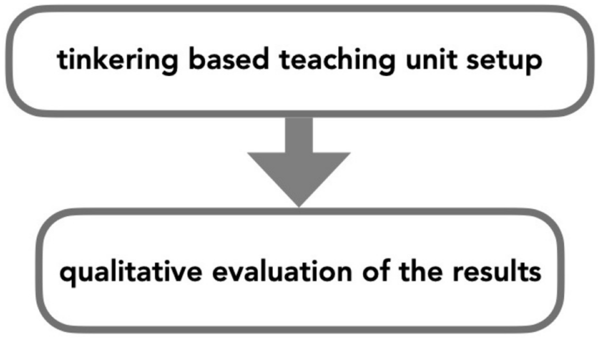

FIGURE 1
Abstract schema of the research methodology.

2. Tinkering for social mediated touch

In this section, we report on a tinkering-based teaching unit on social touch technology, and the evaluation of the results from that teaching unit.

To this end, we introduce the basic concepts of tinkering, and the relevant aspects that need to be designed for tinkering activities. We further describe how these concepts were instantiated in a teaching unit. The tinkering-based teaching unit on remote social touch was part of an introductory course "Foundations of Interaction Technology". In total, 34 teams, each consisting of two students, followed a 2-week haptics challenge. This course was given in the academic year 2020/2021 two times, where more students participated in the first round. The introductory course is part of the master program "Interaction Technology". Students participating come from different bachelor programs, such a Creative Technology (an ICT-based design program), Computer Science, Industrial Design, Mechanical Engineering, Electrical Engineering, Artificial Intelligence, and also from Psychology and other bachelor programs.

The abstract schema of our research approach is illustrated in Figure 1 and will be detailed later.

In our context, we understand tinkering as both a method and a mindset that can be applied in design and teaching, stimulating creativity, stressing ownership, and motivation.

Resnick and Rosenbaum (2013) give the following definition: The tinkering approach is characterized by a playful, experimental, iterative style of engagement, in which makers are continually reassessing their goals, exploring new paths, and imagining new possibilities.

Adding onto this definition (Mader and Dertien, 2016), tinkerers follow a process in which problems and challenges are self-defined and re-defined during the process. Depending on the background, the process may initially be seemingly undirected, or start with a systematic exploration of the material (as we have observed, e.g., for people with an education in art). Tinkering is driven by curiosity and playfulness. It is characterized by an iterative way of experimenting and prototyping, where observation and reflection lead to defining a new challenge. Failing is embraced as a vehicle for insight and progress (Ryoo and Kekelis, 2018). Many people in our culture have early tinkering experiences with playing Lego™, where often no goal was set in the beginning, and constructions were explored by experimenting.

The concept of tinkering as used was initially formulated by the Do It Yourself (DIY) and Maker Movement, and tinkering is often mentioned as an approach used in Maker Spaces. In the literature, the distinction between making and tinkering is often not sharp (Vossoughi and Bevan, 2014) and concepts gets mixed. A useful definition is provided by Martinez and Stager (2013):

- Making is about the active role construction plays in learning. The maker has a product in mind when working with tools and materials.
- Tinkering is a mindset, a playful way to approach and solve problems through direct experience, experimentation, and discovery.

Many making and tinkering activities aim school children, out-of-school or in-school activities (Martinez and Stager, 2013; Petrich et al., 2013; Vossoughi and Bevan, 2014). According to Vossoughi and Bevan (2014), its invitational potential may be a part of what is driving so much interest in making as an important innovation in teaching and learning practice, particularly after the predominance of text-based, test-driven, teacher-centered STEM instruction. Tinkering-based STEM activities are designed for different target groups, ranging from children in primary schools to high school students (Martinez and Stager, 2013; Petrich et al., 2013; Resnick and Rosenbaum, 2013; Vossoughi and Bevan, 2014). Learning goals of tinkering activities are broad, where often a range of process-related capabilities and higher order thinking skills are considered as relevant (Exploratorium, 2017).

In teaching, at our university, we have been applying tinkering approaches in several bachelor and master courses for a number of years. We argue (Quinn and Bell, 2013; Mader and Dertien, 2016) that tinkering can also contribute to teaching in an academic setting, as elements of scientific activities, such as observation, reflection, hypothesis forming, and experimentation, are also activities within a tinkering process. In addition to these generic tasks in science, learning goals in our programs also include design skills, i.e., that students can come up with novel concepts, realize them in working prototypes, and evaluate their concepts.

The main point is that even if the participants self-direct their process, a carefully chosen setting is relevant for the success of the approach. We identified a number of key ingredients (Resnick and Rosenbaum, 2013; Mader and Dertien, 2016) that constitute a setting for enabling participants to tinker, that we call a "tinkering playground".

Since the tinkering playground should contain everything regarding (or designed for) a tinkering activity, we also refer to the tinkering playground as the "whole": the combination of seed, toolbox, discovery (goal), and facilitation—bound to a location in time and space. In the following, we describe the elements of a playground, and how we implemented these for the haptics challenge.

2.1. Space, time, and basic equipment

In Resnick and Rosenbaum (2013), the authors state that "designing contexts for tinkerability is as important as designing kits for tinkerability." Tinkering takes place in a certain environment. Ideally, it should be a stimulating place, inviting to be creative, providing the space necessary. This includes the space for experiments, and also the space for interaction with at least the facilitator, or other tinkerers. It is bound by time, has a start moment, and a defined end.

Due to COVID-19 regulations, the haptics teaching unit was given online, and the students worked from home, i.e., most students in a team also worked in remote places. For regular education activities, our university provides a stimulating learning and prototyping environment in the DesignLab, that includes open space available, with tables, whiteboards, basic materials like paper and post-its, a mechanical and an electrical workshop, sewing machines, 3D-printers, and laser cutters, inspired by FabLab or MakerSpace concepts.

2.2. Toolbox

In general, a toolbox contains different sorts of building blocks. In the first place, these may be physical building blocks (paper, clay, and electronics), but also can be virtual (software and algorithms) or concepts (social media and serious games). Moreover, a toolbox always also contains what a person brings in, skills and knowledge or templates gained by experience. The toolbox, therefore, does not only contain what is provided but also the background of a tinkerer, and is therefore also a very personal and growing set. Mature tinkerers can extend their toolset independently, and finally, take the whole world as a source. Higher level knowledge can certainly be part of a (personal) toolbox of a tinkerer, and can range from, e.g., knowledge in the electrical domain like resistance of wires to existing examples or insights on the context in the domain of interest, as well as scientific results in an academic context.

For a specific tinkering activity, a toolbox tailored for the aims of the activity is required. The choice for a good toolbox is not only about an adequate selection of material. Rather, some material needs to be designed to be accessible in a tinkering workshop for a specific target group, taking the area of interest into account. In Resnick and Rosenbaum (2013), identified immediate feedback, fluid experimentation, and open exploration as key principles guiding the design of toolboxes (kits). Fluid experimentation, according to the authors, includes the ease of getting started and connecting objects.

For ease of connection, we consider affordance of the toolbox objects as of one of the crucial criteria. In short, affordance describes the property of an object to self-explain its usage (Norman, 2002): a button invites to push it, Lego™ does not need much explanation how to stick blocks together. In a tinkering session, it should be easy for the participants to find out how to use the building blocks. A card set with explanations for each toolbox element can be one useful option here.

For the ease of getting started, a toolbox needs to be introduced. Scaffolding exercises, like small step-by-step instructions, can help participants to start using some of the tools or techniques. For example, needle and thread, hot-melt and cardboard, soldering iron and connecting wires, wiring up sensors to an Arduino board, and starting up and using a certain programing environment.

In general, the elements of a toolbox have to be designed for the target users (learners or designers) in a way, that they can focus on a general theme of the tinkering playground, and do not need to spend a major part of the time on getting the supporting material to work. Participants without programing experience cannot be expected to learn to program an Arduino as part of a tinkering session. A dedicated graphical interface allowing to select, position, and connect components to a configuration that then generates Arduino code would be an example for such a design effort to take. As another example, one of the authors designed through a number of editions of a tinkering workshop on inflatables, a paper-cup construction with a powerful copter motor and fan as the easy-to-use core technology for inflation (Neidlinger and Dertien, 2015; Dertien and Neidlinger, 2016).

For the haptics challenge, the tinkering part addressed a conceptual level and a material level. Accordingly, the toolbox also contained these two levels. The conceptual part of the toolbox was covered with an introductory overview presentation on haptics and social touch. These included the sensory system, the role and relevance of touch, the effect of touch in different contexts, examples for touch technology, and more. For the material part of the toolbox, students received a list of hardware components to buy (usually, we provide boxes of material, due to remote teaching in this year, students needed to get the components themselves). For sensing touch, two sensors were chosen, a bend sensor (60 mm) and touch sensor (capacitative sensors can be constructed using aluminum foil and wires). Vibration motors (3 × vibration DC motor module) as actuators were added to the toolbox. For the control, an Arduino nano v3.0 microcontroller was selected. In addition, cables, a breadboard and prototyping wires, resistors (4.7kΩ, 3 × 1MΩ), and tape were required. Additionally, students could make use of whatever material they had available, especially a laptop or PC with internet connection, textile, stuffed animals, garment, or other. Concerning software, the programing environments of Processing and Arduino including a WebSocket library for the internet connection (standard available in Processing) had to be downloaded and installed. Instructions for these components, actions, program fragments for the respective sensors, and references to websites with more detailed explanations and instruction how to use the material were given. The students were composed in teams, such that in each team, knowledge on Arduino programing and prototyping was present. Specific design of the toolbox components was not required here.

2.3. Seed

A tinkering process needs a starting point, a "prompt" or "trigger". This point should be a stimulant to enter a self-directed process. There are various possibilities for a seed: beginners, not experienced in tinkering, may need a small example project to perform, with the idea that they understand the possibilities of the toolbox and can proceed with an own idea. An alternative for a seed is to give a first goal to achieve, which is less defined than an example project. There, the process and specific building blocks needed to get there, are still open. For more experienced tinkerers, simply a new material or interesting new piece of technology could work as a seed. Also, on a conceptual level, a theme might also be seed to start a process. The seed needs some introduction, e.g., a step-by-step group exercise, or an easy to follow description how to set up an example project.

For the haptics challenge, on the conceptual level, the seed is basically the theme of the challenge, remote social touch. On the material level, an example project of a remote handshake was provided as a seed, building on the toolbox given. This example project consisted of building instructions and code.

2.4. Process

The overall process includes introduction of the topic and mindset, the setting, the toolbox, and possibly also the seed. Times for feedback or breaks may be included, or starting moments for new iterations. The timing of the process is also a relevant design step for a tinkering session. Altogether, the start-up exercises should take only a small fragment of the overall time available. The core part of a tinkering process begins with the seed. The process is driven by curiosity, creativity, and serendipity as guiding principles. It needs observation and reflection to learn from experiments and early discoveries, to extend and improve for the next discovery. It is ideally an iterative process with a series of discoveries and starting over again. The process depends very much on the maturity and experience of the tinkerer, and it also forms the core of the tinkering mindset. Many of tinkering activities for children span only over a block for a few hours, but, especially in an academic teaching context, can also be spread over a longer period.

The teaching unit on haptics took 2 weeks overall. Students had approximately 26 h available for the teaching unit, of which 8 h were scheduled and 18 h for their individual tinkering process.

- To provide the conceptual basis as toolbox ingredients, two presentations on social touch and haptics were given, as mentioned above.
- The tinkering period started with an introductory lecture on the setting and procedure.
- As preparation to the introductory lecture, students were asked to get a networking example running, to receive help during the lecture in case it would not work.
- During the introduction, students were asked to set up the example project of a remote handshake based on the networking example, using the bend sensor and a vibration motor. In the session, they could get help with the example project.
- After the introduction session, students could tinker in a first iteration with the material and brainstorm on an application.

- In a second session, students pitched their concepts and received feedback from peers and lecturers.
- Afterward, students started with a second iteration, and realized that in a prototype.
- A teaching assistant was available for a technical help session.
- Finally, the results were presented.

2.5. Facilitator

The facilitators have many tasks. They introduce the toolbox and a seed, or help to identify a seed. They are guarding the mindset, stimulate reflection, give feedback, and give support in scaffolding. They are setting the mood, creating an atmosphere where it is not only ok to fail but faults are considered as stepping stones (Ryoo and Kekelis, 2018). They set the threshold low, the ceiling high, and provide wide walls (Resnick et al., 2018), manage the pace, help to get unstuck (Petrich et al., 2013), and keep the flow.

For the teaching unit on haptics, two of the authors provided the introductory presentations on the conceptual level, followed by the introduction to the tinkering-based haptics challenge. One of them was also main responsible for the teaching unit, and was available for questions of the students during the whole period. For the technical support, a teaching assistant was in charge. Chairing the presentations with feedback and peer feedback was shared between members of the research group.

At this point, the abstract methodology shown in Figure 1 can be detailed as shown in Figure 2.

2.6. Discovery

A crucial aspect of a tinkering process is that the tinkerer decides on her or his own goals. The discovery is self-defined; it might be a new product or prototype, where it is sufficient, if it is new for the tinkerer. It might also be a new or better way of doing things, or a new concept. The self-definition of where it goes makes the tinkerer real owner of the result and the path. The ingredients of the toolbox mentioned above can stimulate in the definition of result and path, but it is also the personal background and experience resulting in story telling that forms a goal for the tinkering efforts. A tinkerer might get help with stimulation, reflection, feedback, or getting unstuck when necessary.

The following descriptions of the discoveries in the haptics challenge are the first part of the evaluation as illustrated in Figure 2.

We first give a few specific examples from the students' results, before analyzing the overall results.

The first example is a ball game. The game starts and ends with a fist bump of the two players, realized with a vibration motor, bend-sensor on the hand, and an accelerometer. One player virtually possesses a ball, and can throw it physically, where the accelerometer would measure the throwing speed. Through a visual, the other player can see the ball approaching, and also feel it through increasing intensity as the virtual ball is "approaching". When the ball has reached his position, he can catch it, also initializing a vibration at the side of the thrower. Figure 3 shows the visualizations that both players can see while playing the game. The setup and prototype can be seen in Figure 4.

The next example is about a remote social touch for a family member who has to undergo diagnosis in an MRI scanner. A patient is there lying in a tube and may feel lonely and scared. The social touch is meant to calm and comfort the patient, and realized by a pair of sleeves. The patient can indicate that she wants to receive a touch by bending her fingers. The remote family member feels this wish by a vibration, and then can give either a soft or strong touch by touching capacitative sensors on his sleeve with a fingertip or with the full hand. The patient would receive a stroking touch through three vibration motors on her sleeve with a fixed stroking illusion pattern, vibrating either soft or strong. Figure 5 shows the setup of the project and the prototype realization.

In the following example illustrated in Figure 6, the students want to enrich texting on a smartphone by touch and physical elements. For that purpose, they extended existing bunny phone cases with electronics. When pressing the left or right back side of one smartphone, the ears at the other smartphone would move. Also the tail would wiggle and a vibration motor would send a touch.

In the fourth example, the student referred to her childhood. When she was stressed her mother would put her hand on the child's forehead, to comfort her. As the student now lives in a different country, the prototype suggested should realize this gesture on distance. Figure 7 shows the concept. The electronic setup here is very simple, consisting of a bend sensor and vibration motor on each side, integrated in an animal-shaped wash cloth for each side. Technically, the example does not go much beyond the warming up example the students did in the course, but it has a strong story telling part.

The last example is a remote version of the rock-scissors-paper game. As illustrated in Figure 8, the three gestures for a rock, scissors, or paper, respectively, and also for a fist, are detected by a number of bend sensors and capacitative sensors. The winner of a game receives a vibration touch as reward.

For the haptics challenge, the students had, as mentioned above, some general lectures of social touch, and for technology scaffolding, a "hello-world-example" connecting a bend-sensor on one side to a vibration motor on the other side, connected via internet. The categories used to characterize the projects are identified a posteriori, to understand and describe the breadth of projects. The categories were not presented to the students beforehand. The article of Ipakchian Askari et al. (2022) provides an excellent taxonomy of applications in STT. This taxonomy would have been an alternative to analyze the students' projects. Unfortunately, at the time when the characterization was done, the article was not yet published. However, we assume that the main conclusion from the analysis would be similar.

The students' discoveries included a context and interaction for mediated social touch and a prototype. The social contexts students addressed were people in a relationship, grandparents and grandchildren, relatives, (study) friends, or colleagues, children in a

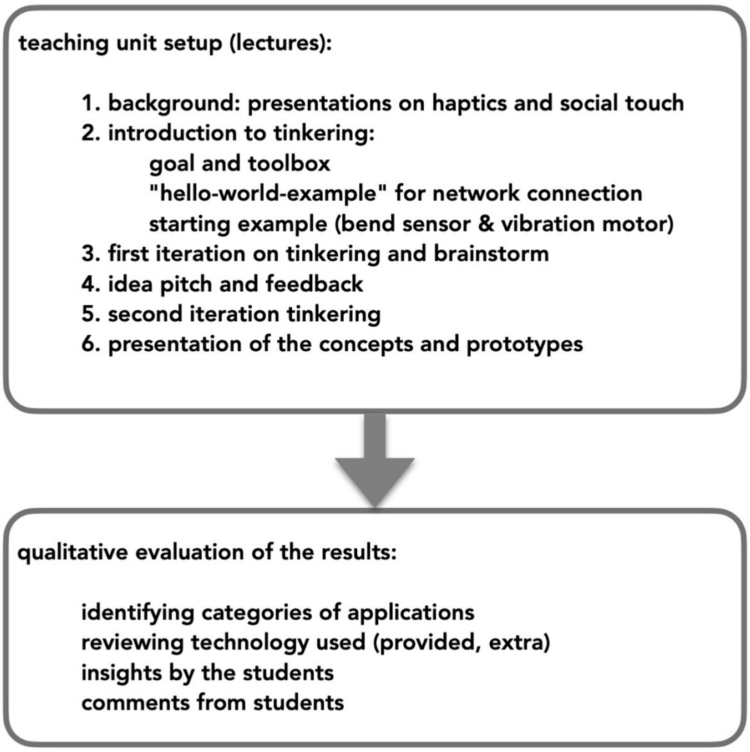

FIGURE 2
Detailed schema of the research methodology.

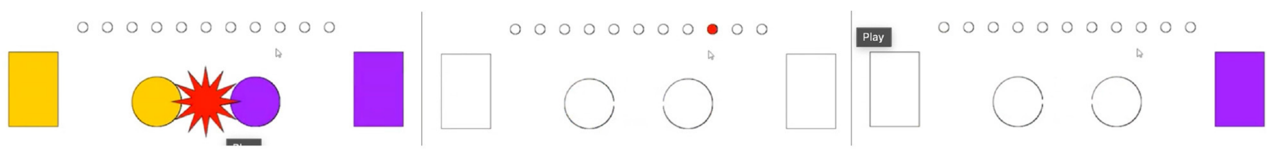

FIGURE 3
Visualization of the ball game for the remote players. Fist bump **left**; ball approaching in the **middle**; ball caught on the **right**.

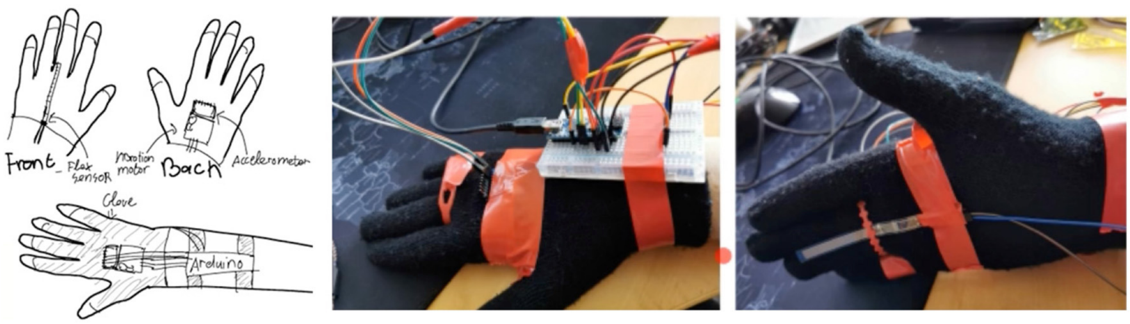

FIGURE 4
Left sketch of the setup and **right** prototypes of the ball game for the remote players.

hospital and their parents, or a family member in a radio treatment in a hospital.

The social interactions considered were basically of two different categories:

- Exchanging or giving touch as main activity in itself. The touches should represent stroking, caressing, hugging, tickling, tapping on the shoulder, a handshake, or a high-five (28 teams of 34). These touches had the intended meaning to

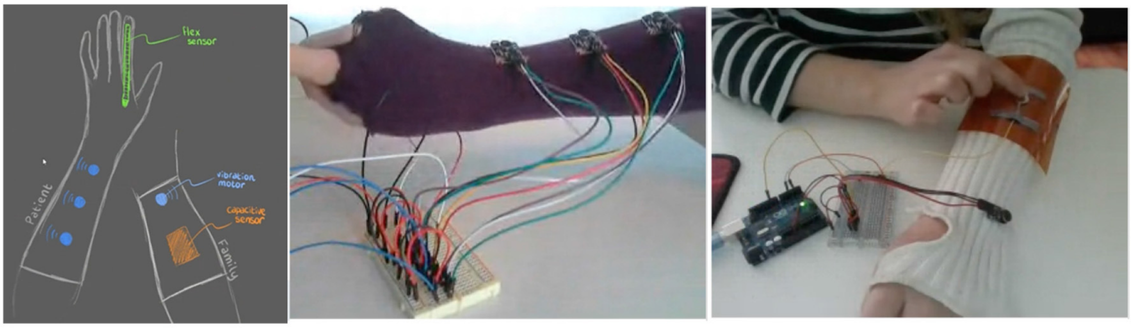

FIGURE 5
Left sketch of the setup and **right** prototypes for a comforting touch of a family member during an MRI scan.

confirm and intensify the relationship, and/or to comfort or de-stress the receiver.
- Augmentation of another shared activity, a ball game, rock-paper-scissors, texting on a smartphone, watching a movie, doing workout, and relaxation movements. These touches had two intended functions, intensify the experience of the activity, and create a feeling of connectedness (7 teams of 34).

The objects they made were:

- Symmetric devices, such as stuffed animals, cushions, squeeze balls, smartphone extensions, or gloves, where symmetry describes that both devices are functionally identical, and a touch can be sent either way.
- Asymmetric devices such as a glove or other touch device connected to a different device, such as a glove, sleeve, facial mask, shoulder wrap or sweater, where asymmetric means that a touch can be sent only one directional, so there is a dedicated sender and receiver of the touch.

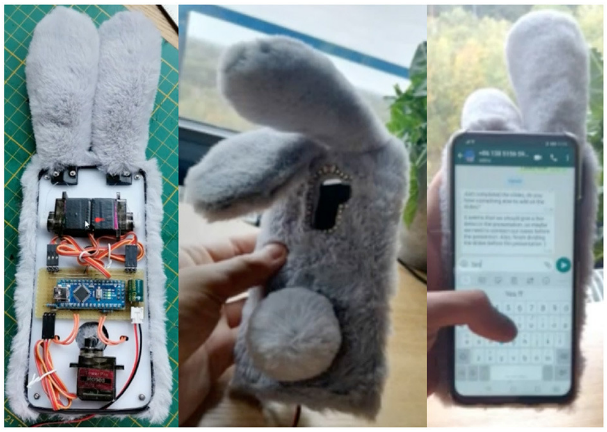

FIGURE 6
Smart phone extension allowing for adding social touch and physical ear movement.

2.7. Observations and further evaluation

2.7.1. Story telling

For almost all students, the starting point of their prototype was a story and context (32 out of 34). As the challenges took place during the COVID-19 pandemic, most students took the need for touch due to the contact restriction in this phase as main motivation (24 of 34). Four teams had a combination of other and COVID-19 related contexts, such as in the ball game illustrated in Figure 4 which is also suitable for grandparents who cannot run to play with a grandchild. Four teams had a motivation not connected to the pandemic, such as the example of a family member in an MRI scanner from Figure 5.

2.7.2. Technical level required

Technically, all teams could cope with the technology of the toolbox and the instructions given. In all teams, experience with Arduinos or other microcontrollers was present. All had more or less working prototypes, several with common problems with bad electric connections or poor internet connection. Some prototypes were more elaborate, depending on extra skills of the students concerning sewing, 3D printing or internet technology, and physical computing, such as the examples of the smartphone case in Figure 6 or the ball game in Figure 4. Most used the internet connection provided (31 of 34), and some teams (3 out of 34) used WIFI or MQTT as a data transmission protocol.

Concerning the technology, most teams used the components for the toolbox given [i.e., capacitative sensors (16 of 34), bend sensors (24 of 34), vibration motors (34 of 34)], several students used LED lights (7 of 34), and only a few used other technical elements not contained in the toolbox, such as stronger servo motors (1 of 34), piezo speaker (2 of 34), or a resistor network for temperature (1 of 34). Our conclusion here is, that, even if the number of components of the toolbox was very limited, it allowed for a variety of prototypes and concepts. The toolbox, therefore, met the requirement of wide walls allowing for a wide range of different types of projects (Resnick et al., 2018). An explanation here might be, that working on a conceptual level, vibration motors were

FIGURE 7
The touch device should allow the mother to give her daughter a comforting touch on the forehead as she has done physically in the past.

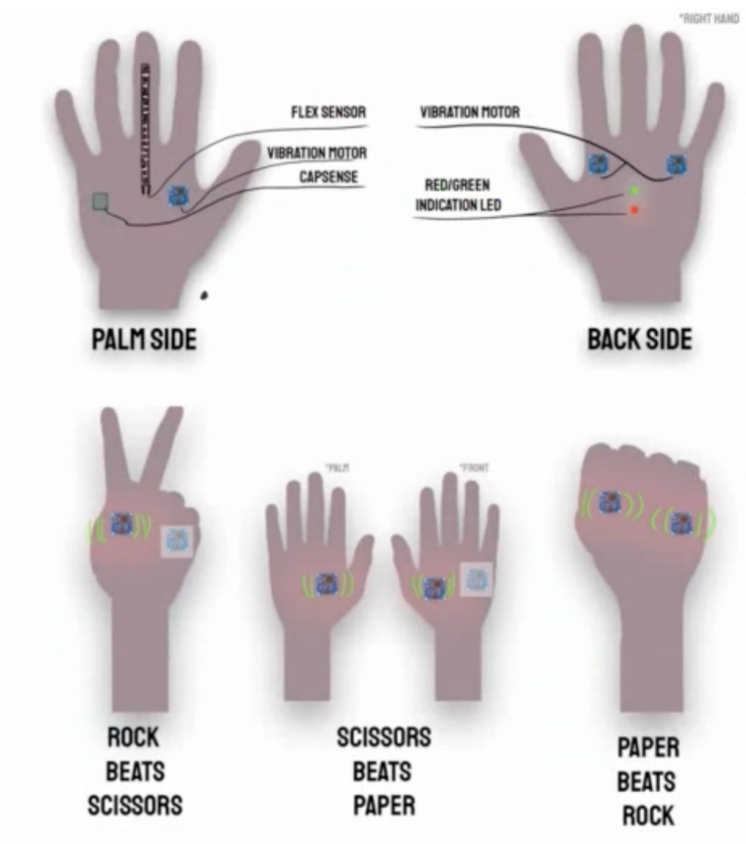

FIGURE 8
A remote version of the rock-scissors-paper game with a touch for the winning partner.

considered as a placeholder for touch technology that generates different stimuli.

2.7.3. Variety of the results

The example students were given for the technical setup test was a simple handshake (with a bend sensor and vibration motor). In the examples of STT presented in the course, most were related to hugs, and, of course, students had access to publications on social touch, especially the overview article of Huisman (2017). Out of the 34 teams, 9 teams chose for stuffed animals (or similar, like a cushion) and 7 teams had an application including a glove, which was definitely in the range of what was expected. The range of versions of social touch that was addressed, such as stroking, caressing, hugging, tickling, tapping on the shoulder, or high-five, was beyond what was presented in the course for STT, but could have been found in the literature also. A huge variety was in story telling perspective of the projects, ranging from applications for lovers, children and parents, grandparents, relatives, or just friends. Definitely beyond expectation, were applications, where social touch was not used as the primary goal of the exchange, but was added to another form of social interaction to intensify the experience of the activity on one hand, and also create a feeling of connectedness on the other hand. The applications here were diverse, like a ball game, rock-paper-scissors, making music together, texting on a smartphone, watching a movie, doing workout, and relaxation movements, as mentioned above. It is difficult to define a metric for diversity in storytelling. The abstract properties that can be counted still reflect aspects of diversity, but cannot capture the creativity of the concepts.

A few teams also addressed problems on a conceptual level of STT and, e.g., considered different protocols for consensus of receiving touch (7 out of 34), how to initiate and agree on touches over distance, addressing problems of synchronicity, and intrusiveness of remote touch technology. In the case of synchronicity, one problem that was identified was that the sender could not "see" if the receiver was indeed receiving the touch, and, therefore added an option to store a touch, such that the receiver could get the touch later when (s)he would be available. Other students implemented a step of consensus to their protocol, which addresses synchronicity (the receiver is indeed available) and intrusiveness (the receiver is ready to receive a touch). The students did not use definitions from literature of "intrusiveness" and "synchronicity", but did describe the problems behind.

On top of this, one team added also vibration feedback for reciprocity. The sender could feel when the receiver got the touch. The teams that had primarily another shared activity, which was augmented or intensified by touch, and had all protocols for conditions when to trigger the touch.

Our conclusion based on these results, are two-fold, on one side concerning the teaching perspective, and on the other side concerning the research question of this study.

For the teaching perspective, the question is whether the setup of the course and material led to the intended outcomes. The intended outcomes include a design aspect and an academic (reflection) aspect. On the design part, the main criterium is the diversity of the solutions. Although there were 9 out of 34 prototypes including stuffed animals, and 9 with gloves, the overall diversity is broad, even more than expected, and we can conclude that the choices taken for the setup and toolbox were appropriate. This conclusion follows the statement of Resnick: if we see a great diversity of projects, to us that's a sign of success. Additionally, for the academic part, results from the course were promising. Several teams (7 out of 34), in the discussion of their prototypes were able to identify concepts inherent to touch technology (i.e., synchronicity and intrusiveness) that were not addressed in the course, in a relatively short teaching unit.

At this point, we want to answer the initial research question: Is tinkering a design approach that can foster the finding of novel applications in social touch technology?

The same arguments as above, the diversity of projects, and the generation of project beyond the expected, support a positive answer to our research question.

We also see support for our initial suggestion that tinkering might be a suitable design approach in the context of Research through Design (RtD). The perspective of RtD is that the creation of prototypes is a stepping stone to understanding the conceptual complexity of an application domain. As mentioned above, through designing and realizing a prototype, some of the students were able to identify inherent problems (and possible solutions) of mediated social touch.

3. Accessibility of tinkering for touch technology

The target group of the tinkering challenge in the previous section were university students, where most of them had a knowledge base in technology. As the challenge was set up, experience with sensors, actuators, and microcontrollers was present in each student team. The design effort required to make a toolbox accessible for the target group of tinkerers was very low for the student group, enabling them to create prototypes. Still a few students reported that this caused an imbalance in effort.

In a further step, we would like to open up the approach of tinkering also for different target groups, who probably have more or different knowledge on the conceptual level and less on the technical level. Supporting multidisciplinary design efforts, we would like to include psychologists, fashion and interaction designers, haptologists, physiotherapists, or other stakeholders in a tinkering process on applications in haptics. On a conceptual level, experts from other domains can bring in different expertise and other perspectives. They can contribute to a broader exploration of the design space, and come to richer or more meaningful set of prototypes. Additionally, their reflections also build on different expertise and perspectives. Altogether, knowledge derived by a multidisciplinary team has the chance to be more varied. In this context, we especially consider the hands-on aspects of tinkering as design activity as valuable. Active exploration with direct feedback gives more insight on the possibilities and the restrictions of the (technological) material available. On one hand, this can stimulate a creative process, and on the other hand, it connects concepts invented better to the state-of-the-art technology available.

In this section, we suggest a design of a tinkering playground on the next level, allowing broader groups of tinkerers, and requiring less technical knowledge to come to a working prototype. Following Stappers and Giaccardi (2017), this is a design for design effort. Starting point for our suggestions is a setup and concept for a tinkering playground developed for wearable technology. The toolkit was already designed for a target group of laymen. Experiences with it showed that the concept is suitable for people without technical experience. This setup will serve as basis for a social touch technology tinkering kit, as we consider the latter also in the wearables domain. In the following, we first will describe the ingredients of the wearable technology playground. In the second part, we will suggest extensions of this playground that supports a greater variety of prototypes for touch technology.

3.1. Tinkering with wearable technology

There can be different design goals for a wearable toolbox. For example, for the Lilypad family of components,[1] easy integration in garments and textiles was certainly a design goal. There, sensors, controllers, and actuators come mounted on printed circuit boards in round shapes with connection points that can easily be sewed by hand using conductive thread. Using these components supports already a high level of wearability of the garment created. Another example is the Wearable Bits (Jones et al., 2020b), that use felt-mounted sensors and actuators that can be connected using snaps. Integration in or to garments may even be easier there, as no sewing is required and connecting sensors and actuators is simple. How the integration and programing of a controller is solved, is, however, not clear. Another focus is set by Hamdan et al. (2018), where the realization of circuits is supported by embroidery technology. Also here, the textile properties are in the center of attention, more than a toolbox approach. In general, a toolbox for tinkering with wearable technology has to tackle one or more aspects of a multidisciplinary problem space, including fashion, design, electronics, electronics integration, and programing.

In past workshops, we had experienced that tinkering with wearable technology often suffers from a high threshold concerning technology skills. As a consequence, often the workshops did not go much further than a starting exercise of sewing led lights on garments or bags, or following some readymade recipes. It is not uncommon to get stuck with electronic connectivity tasks or programing. Our approach for a wearable technology toolbox emphasizes the exploration of novel concepts. Accordingly, our design focus was the support of easy prototyping. Here, "easy" refers to plug and play technology, where connecting components in a prototype is straightforward, and the programing effort reduced to a minimum. Core of the design is a microcontroller interface that allows to plug in maximal three sensors and three actuators in a uniform way. In addition to the components, tools, and materials themselves, we also provided a set of cards corresponding to these materials, as aid in exploring the toolbox, instruction, planning of a design, and as reference. The wearability aspect was kept simple and solved by a range of materials such as velcro and elastics, allowing to fix a setup on the body.

In November 2019, we organized two workshops with the aim to design novel concepts of wearable technology for a "general" public. This small series of events was organized by the local Media Lab and attracted a diverse audience of students in media/arts, designers, artists, or pensioners interested in arts and crafts. Due to COVID-19, not more editions of this workshop could be performed.

1 https://www.sparkfun.com/tutorials/133

3.1.1. Toolbox

The wearable toolbox consists of sensors, actuators, control, and connectivity. Table 1 contains a list of the components, and Figure 9 shows the toolbox elements with the respective cards. During the workshop, a set of tools and materials/supplies are provided which is also shown on the cards in Figure 10.

The design effort for the toolbox components consisted of the following: Where needed (for example, with the microcontroller and the bend sensor), 3D printed housing was designed to facilitate mounting and protect the electronics for reduced risk of short circuit. The vibration motors come with fragile connection so they have been fortified with a flexible compound (Sugru). The specific microcontoller (Arduino Beetle) is very small, it has the dimensions of a regular USB stick. It has been modified to connect three sensors and three actuators, all using the same 3-wire leads. Resistors and transistors required for the connection of the sensors and actuators were already integrated in the leads. The USB plug of the microcontroller (see Figure 11) can be connected directly into a laptop for programing, or directly into the powerbank for standalone operation, reducing wiring hassle. The leads of sensors and actuators are about 30 cm long and can be extended, such that they can easily be positioned anywhere on the body. The materials that have been provided to make "garments" or, at least, allow the components to be worn have been selected to build low-fi proof of concept designs rather than high-fi fashionable prototypes.

3.1.2. Seed

As process/conversation starters, a series of imaginary designs were provided on paper, consisting of a short description and the specific components (as cards) needed to create them. There is a careful balance to maintain with providing these examples. The example has to be clear, and just interesting enough. It should trigger participants to improve upon rather than to replicate. The starter themes were the following, where the components needed are listed on paper, and the corresponding cards explaining the projects are shown in Figure 12.

- **Party:** At a party, let your garment blink in the rhythm of the music or your heart (With microphone or heart rate sensor and led strip).
- **Posture Coach:** Give a sign (vibration or sound) when slouching for too long (With bend sensor and vibration motor or buzzer).
- **Tail:** When you are happy or frightened, wag your tail or set up spikes (With skin resistance sensor and servo motor).
- **Traffic:** On your bike, give the direction with a blinking led strip on your back by touch sensors (With led strip and touch sensor).

3.1.3. Process

At the start of the workshop, specific instructions were given to the participants aimed at exploring the toolbox and understanding

TABLE 1 Toolbox components for tinkering with wearable technology.

Sensors	Actuators	Control and connectivity	Tools and supplies
Bending (flexible)	Vibration motor	Microcontroller board	Self-adhesive Velcro
Capacitive touch	Miniature RC servo	(= Arduino Beetle)	Fabric (soft)
Light intensity	Light strip (neopixel)	Male–female 3-wire leads	Hot-melt glue gun
Heart rate / pulse	Buzzer	Powerbank	Tape (duct tape, cloth tape)
Skin resistance			Sewing machine
Audio level			Cable-ties
			Cardboard (rigid)
			Split pins and MakeDo plugs
			Staples and stapler

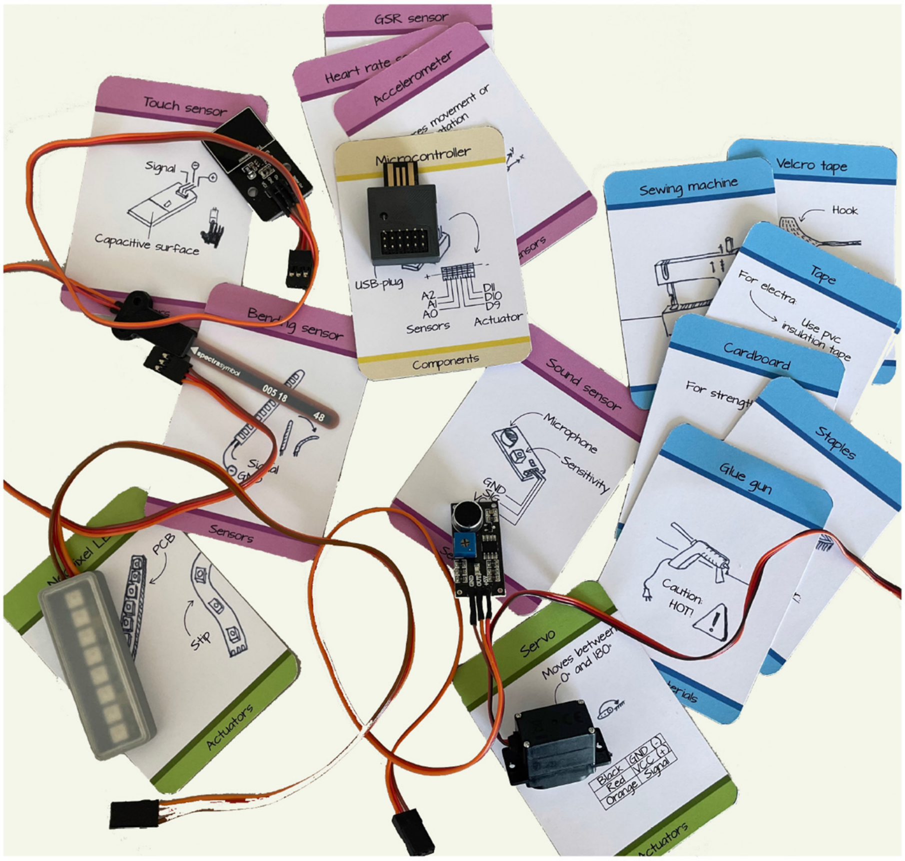

FIGURE 9
The designed set of tinkering components with a set of cards providing "scaffolding".

the available materials. In detail, the workshops followed the steps below:

1. A general introduction on wearable technology.
2. Explanation of the sense-think-act paradigm—whereas this paradigm is at the basis of our work, it turned out that it is not self-evident for a general public. The sense-think-act paradigm describes a cyclical process, where the sense-part consists of the collection of all the sensor values by a controller. The think-part refers to how the controller processes the input values. For the application considered here, much of the processing is in a style of if value is above a specified threshold switch on this actuator for this duration. The act-part of the sense-think-act paradigm then includes to the activation or deactivation of the actuators involved.
3. A short introduction to the ingredients of the toolbox;
4. Simple card-sorting exercise (find the part belonging to the card, do you understand what it does?);
5. The assignment for the participants to choose one of the predefined assignments and performing it themselves, if wanted;
6. The assignment to think of a concept and realizing that;

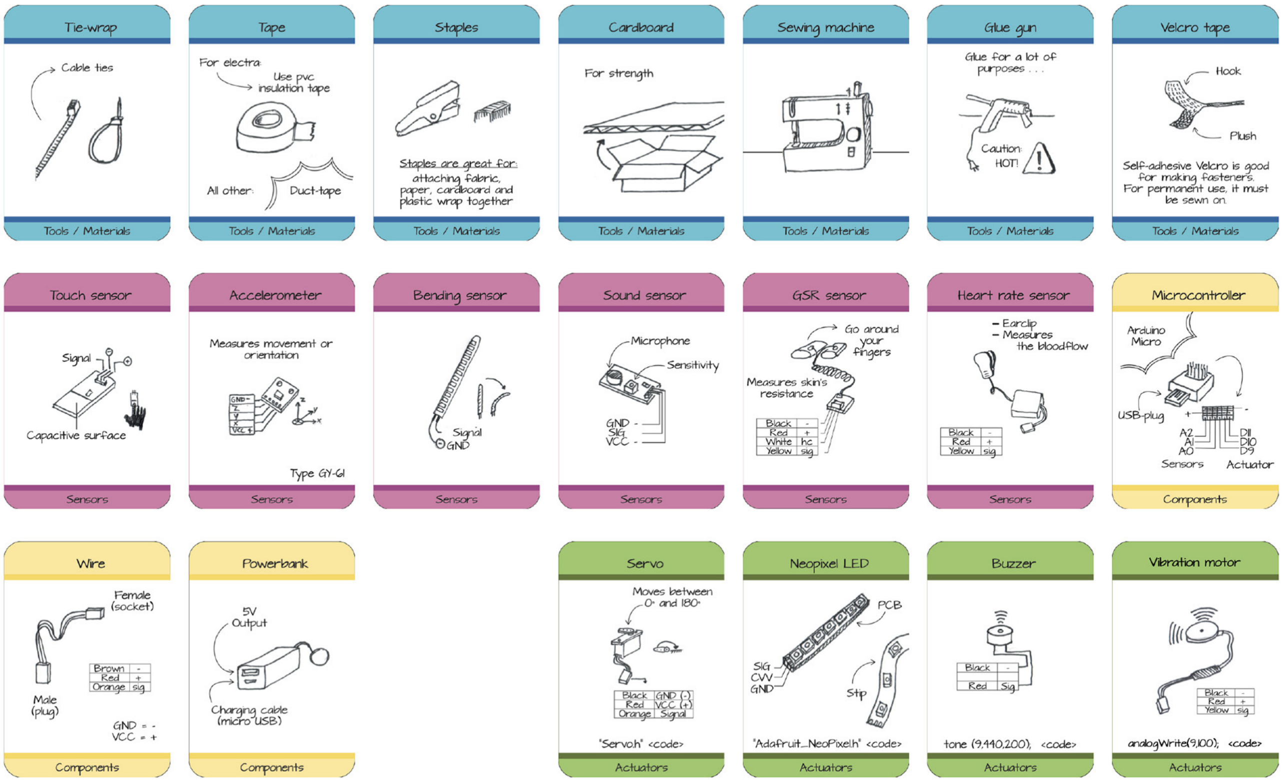

FIGURE 10
The card set describing the components of the toolkit.

7. Facilitation, stimulation, and answering questions;
8. Configuration of the controller program according to the concept of the participant.

3.1.4. Observations

The card-sorting exercise proved to be sufficient, but also necessary. The provided starter cards with example projects were a good pointer for participants that were immediately stuck. Other participants dived in right away and paid these example designs no heed. This coincides with our observations on different learning styles of (design) students. The two workshops gave indication, that the setup does work. Several participants stuck to the predefined examples, where their result would be the understanding of the concept. Some participants went further and had creative ideas they could realize comparably fast. One example was for cyclists at night, a light on the arm that starts blinking when the arm is raised, realized by a flex sensor and a LED strip. Another example was to prevent falling asleep while watching a film, where the head falling to the side would raise an alarm, realized by an accelerometer on a head-band and a vibration motor. programing was still a bottleneck, where the facilitators had to take over the programing. As the program schema given required more a configuration task than bottom-up programing, the effort was not very high. Still, it would be desirable to have a graphical programing interface that allows the participants themselves to generate code from building blocks that can be selected, connected, and equipped with conditions.

Altogether, we conclude that the workshops showed that participants without a background in electronics can use the components of the wearable toolbox to create prototypes for new, self-defined concepts.

3.2. A toolbox for tinkering with touch technology

As a next step, we suggest the design of a toolbox for tinkering with touch technology. There are not many existing toolboxes that focus on the quality of touch. Some focus on connectivity such as the toolbox kit by hapticlabs.io (Müller, 2020), or focus on a specific technology such as pneumatics by flowIo (Shtarbanov, 2021), or offer textile integration options such as the Swatch-bits (Jones et al., 2020a), but options for users to explore and link the quality of touch to conceptual development is largely lacking.

Based on the positive experience with the wearable toolbox, we would also emphasize here a focus on easy prototyping and integration of electronic components, and also the explanatory material in the form of card sets and example projects, as well as the process. For the multidisciplinary target groups in mind, this setup gives the possibility to create concepts and working prototypes without technical expertise. For the domain of touch technology, however, we consider not only the creation of concepts as relevant, but, as an additional design goal for the toolbox, also the possibility to explore the experience and

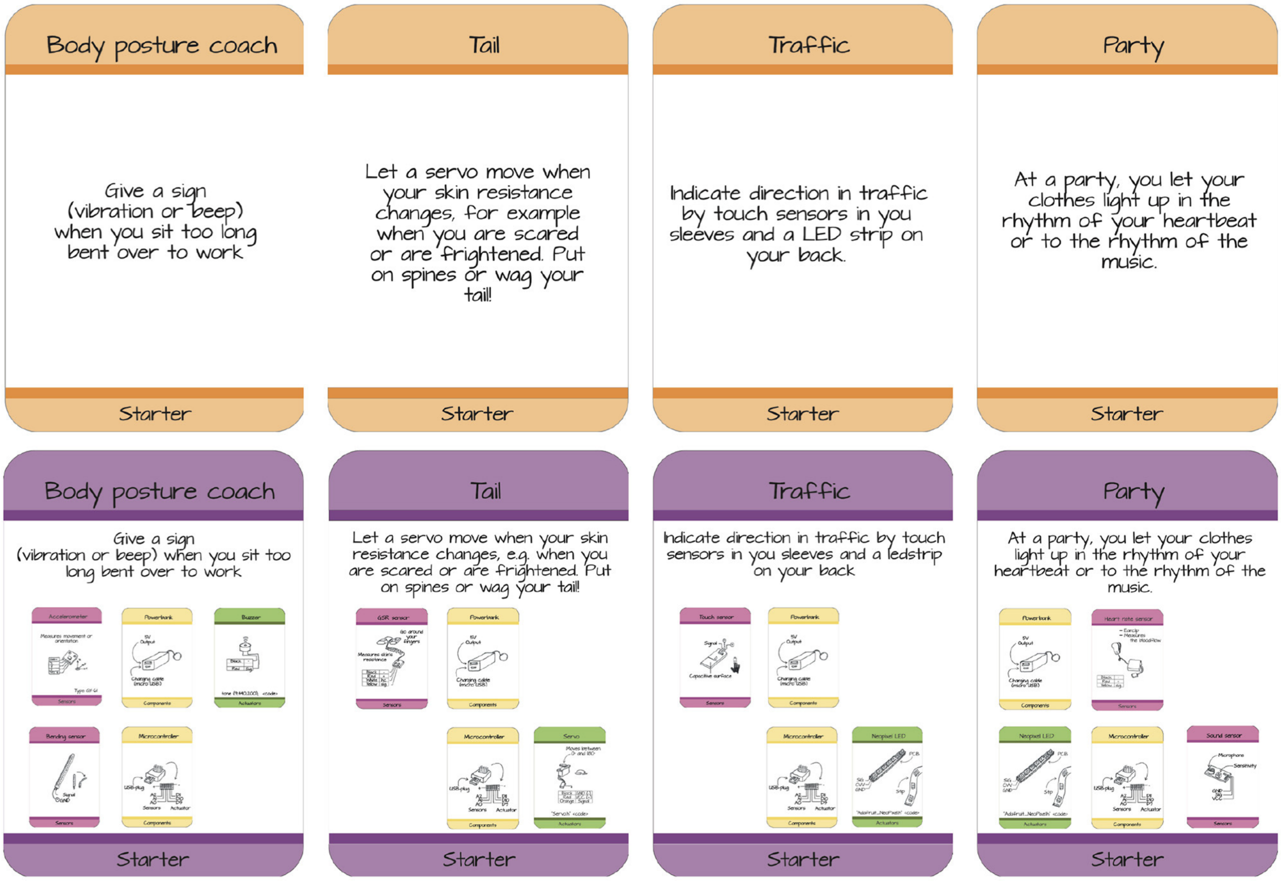

FIGURE 11
The seed projects, front and back side on **top** and **bottom**, respectively.

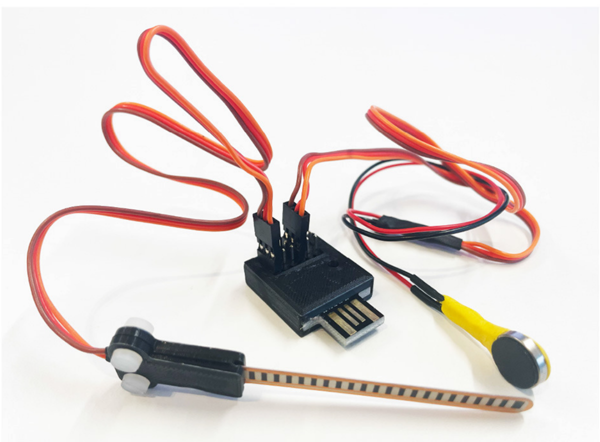

FIGURE 12
Simple setup for posture-warning device: microcontroller (plugs into a power bank directly), cabling, vibration motor, and bend sensor.

different qualities of touch. In short, we suggest an extension with the following items, which will be discussed in more detail below:

- **Actuators:** the most important extension is the option to use more diverse actuators for touch technology, i.e., a cluster or an array of vibration motors and pneumatic elements to explore different directions. Also heating/cooling actuators (Peltier), adjustable ribbons contracted by motors, and shape memory alloy can be considered (but are for now not explored into detail).
- **Sensors:** more sensors for sensing touch, the intensity of touch, and measuring of touch patterns.
- **Control and connectivity:** for taking the physical distribution of touch initiation and touch perception into account, controller boards offering wireless (internet) connectivity are necessary. For experimenting and experiencing more complex haptic sensations also specific control devices and hardware setups are relevant.

3.2.1. Actuators

The vibration motor has become a de-facto standard for haptics, at least it is a component many participants, students, and designers recognize from, for example, smartphones or game controllers. Many electronic and software solutions exist to improve the quality and versatility of haptics using these motors. Multiple vibration motors, together with a set of actuation patterns would be desirable. In addition, arrays or grids of vibration motors that allow the generation of haptic illusions could be a meaningful extension. To experiment with multi-channel output, a MIDI compatible miniature driver board (shown in Figure 13) has been developed as potential addition to the toolbox. This board has 14 output channels for vibration motors.

Although vibration motors are the most mature touch technology, they cover only a fragment of potential touch sensations. It would be desirable to offer other dimensions and qualities of touch to explore. There is a number of different actuation principles that generate different touch experiences, such as stroke or pressure. Motors could be used here that use a contracting mechanism for generating pressure or a squeeze like the Hey bracelet[2] contract adjustable ribbons or actuate pneumatic setups.

Inflatables or inflatable wearables have been explored (e.g., Neidlinger and Dertien, 2015), inspired by the soft robotics toolbox (Holland et al., 2014). Also McKibben muscles make use of pneumatics to provide touch through pressure, and can be integrated in textile (Backe et al., 2019). A system making use of pneumatics is typically more complex than a—just—electrically driven system. Where in previous examples, a servo or vibration motor can be connected directly to a powered controller, and for pneumatics, an air reservoir (pump, compressor, or pressurized canister) is needed, combined with air-tight tubing (electrically operated) valves and eventually an actuator, such as an inflatable pocket or bladder. Toy brands such as Lego™ and Fischer Technik[3] have proven that it is possible to offer a complete functioning pneumatic set at a scale suitable for prototyping of wearables. For experiments with haptic pneumatics, we experimented with a number of valves and pumps used in blood pressure sensors. Also coupling syringes (as manually operated pressure sources) to linear servos have proven to be a versatile (if a bit slow) solution to provide portable, low-power (low-noise) air supply.

To experiment with the design of McKibben actuators, the main ingredients for tinkering we found suitable are:

- Party balloons (1 m long, 5 mm diameter) as bladder
- Braided sleeve for cable protection, 5 mm diameter (stretched)
- Small barbed pneumatic connector pieces (LEGO T-pieces work well too)
- Pneumatic hose (LEGO pneumatic brand works well)
- Miniature cable-ties and heat shrink tube to seal the ends and make mechanical connection possible.

To experiment with inflatable pockets (which can act as pneumatic pressure actuator), we have been using the following ingredients:

- 3D printed casting mold
- EcoFlex 30-50 silicone casting compound
- Pneumatic hose (LEGO Pneumatic brand).

For both type of actuators, the McKibben muscles or inflatable silicone pockets, controlled supply of pressurized air is necessary. To explore pneumatic control, first a simple way of actuation is by using a syringe as pressure source. For controllable actuation, an addition of a linear servo with a stroke in the same order of magnitude works well, although the performance is too slow to generate a haptic "impulse".

Figure 14 shows the components we eventually selected for tinkering with pneumatic control. As an air supply, either a syringe or a small 3V electric pump (used in conventional blood-pressure measuring devices) can be used. For switching air supply, either a 3-way LEGO valve or SMC070 5V solenoid valves (which can be connected directly to a low-drop power driver, as used on the previously shown board in Figure 13) is used. For air routing, we use the flexible LEGO 4 mm tube with corresponding T-pieces. For sensing air-pressure either a LEGO compatible manometer or a Honeywell NBPDANN150PGUNV with compatible INA122 instrumentation amplifier is offered.

In this way, for all relevant aspects for exploration (supply, routing, measurement, and switching), we offer both a manual option as well as an electronic option.

Although pneumatic bladders or McKibben actuators are more complex to design and integrate than the previously mentioned vibration motors, build, construction, and control have proven to be possible within the bounds of a tinkering session. For example a one-day workshop is typically enough for exploring components, conceptualizing and designing a functional prototype, as demonstrated during a workshop at TEI (Neidlinger and Dertien, 2015).

The other actuation options mentioned, such as twisting yarn actuators using (DC)motors, servo/tendon driven mechanisms, and shape memory alloy-based actuators are still on the wish-list, but prove (for now) to be too much dependent on the integration in a garment as a whole. The actuators we deemed suitable for the tinkering toolbox are self-contained enough to be used, for example, with some simple velcro straps to explore the quality of touch. Eventually, they also allow for integration into the fabric, but it is not a prerequisite to do this from the start.

A special category are actuators that use (or produce) heat. Thermal foil, peltier elements, but also shape memory alloy produce heat, either as desired form of haptics or as a by-product (in the case of shape memory alloy). This requires careful consideration of control, power, and (thermal) protection. For now, these types of actuators have been experimented with, but they are not mature enough to become a building block in the toolbox yet.

3.2.2. Sensors

For the functional aspects of a wearable concept, the previously selected sensors for physiological measurements have proved to be sufficient. The following interesting applications can be conceptualized or prototyped.

- Heart rate (Grove Ear-clip optical heart rate sensor)
- Respiratory rate (Adafruit conductive rubber cord)
- Flexing motion (Spectra Symbol 4.5" resistive bend sensor)
- Muscle contraction (Sparkfun EMG Muscle Sensor v3 Kit or Myoware)

2 https://feelhey.com

3 https://www.fischertechnik.de/en/

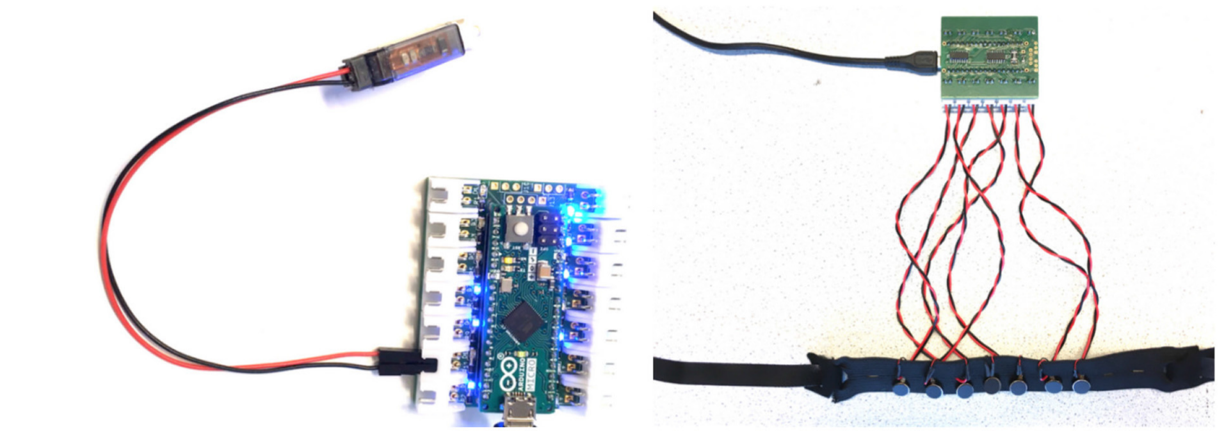

FIGURE 13
A 14-channel MIDI compatible control board, **left** controlling a pneumatic valve and **right** controlling 7 vibration motors.

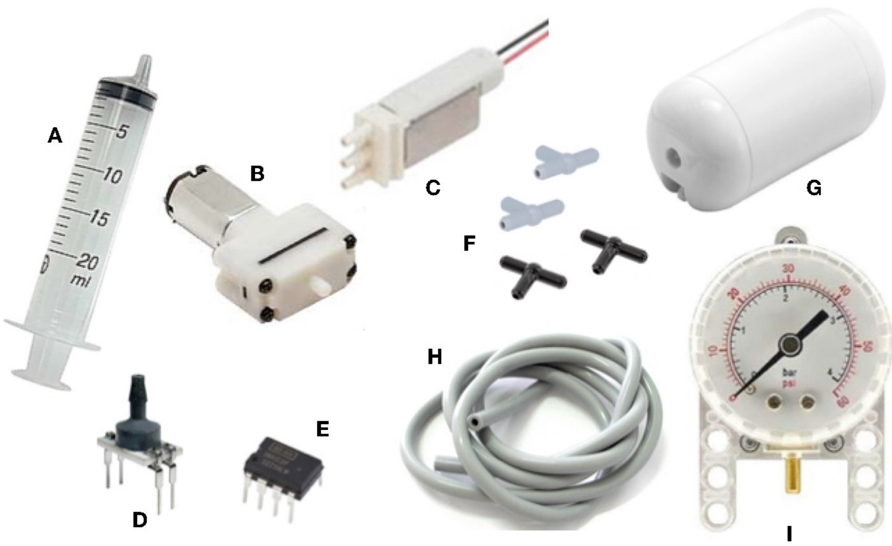

FIGURE 14
Selection of components for tinkering with pneumatic wearables: syringe **(A)** and small electric pump **(B)** for air supply; miniature SMC valve **(C)**, Honeywell air pressure sensor **(D)**, and fitting INA122 instrumentation amplifier **(E)**. For air routing, we use LEGO(R) T-pieces **(F)**, buffer tank **(G)**, hose **(H)**, and pressure gauge **(I)**.

- Skin resistance (Grove GSR-sensor)
- Displacement (Sharp GP2y0a21yk0f 10-80 cm distance sensor).

However, for many applications, a haptic wearable performs some form of mediation. A touch or gesture by one user is relayed to the wearable of the other, and vice versa. This means that preferably the haptic gesture (i.e., gripping a wrist, stroking an arm, and giving a pat on the back) should be sensed from the user perspective.

At the moment, the following components have been added to the toolbox for this specific category of user interaction, shown in Figure 15.

- Piezo resistive ink-based pressure sensors (such as FlexiForce and ThinForce sensors)
- Single point capacitive touch sensors (integrated boards by Grove, Adafruit, or Sparkfun)
- Multi-point capacitive touch sensors (grove board)
- Spectra Symbol SoftPot linear touch sliders
- Electric contact [Makey Makey (Collective and Shaw, 2012) style].

A complex aspect is that these sensors, although they are very lightweight and flexible, still do not allow full, flexible integration into a fabric. Using wires and electric contact allows for spatial layout of contact points in fabric; however, the durability of this

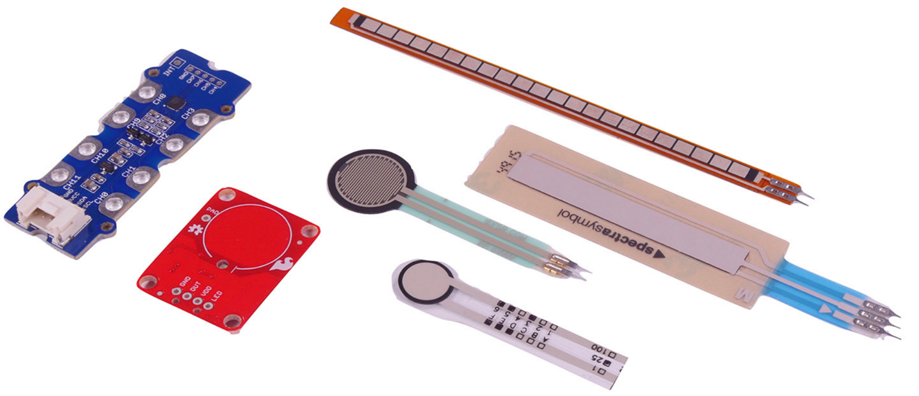

FIGURE 15
Sensors for sensing haptic gestures: a spectra symbol softpot flexible sliding sensor, two round piezo-resistive ink-based pressure sensors, a capacitive single-point touch sensor, and a Grove compatible 12-channel capacitive sensor board and a resistive bend sensor.

(and potential for short circuits) does not make it suitable for prototyping and tinkering.

3.2.3. Connectivity

Since the goal of the toolkit is to facilitate conceptualizing and making working prototypes, connection of components and electronics should take little time, be safe, simple, fault tolerant (without too much in-depth knowledge of electronics), and above all robust enough to continue working in a prototype that is actually worn by a user.

A selection of contemporary toolkits for prototyping of (wearable) electronics has been made focusing on differences in connectivity strategies and also looking at the basic contents and focus. The selection is shown in Table 2 and is shown in Figure 16.

Sets using the Arduino Lilypad (shown in Figures 16A) focus on sewable electronics. Components usually have large (3 mm) plated-through holes in a PCB which can be sewn onto cloth using conductive thread. This is an excellent way of experimenting with integration of electronics in clothing, but shifts focus from conceptualizing and prototyping to the more art-and-crafts side of making.

In other prototyping systems for embedded electronics, different connectivity designs are used. By far, the easiest to connect are LittleBits shown in Figure 16B: self-guiding magnetic locks automatically “snap” together. Since the connection has to be aligned well, this system is less suitable for wearable use: the system is very sensitive to motion (and works best on a flat surface or build support plate). In most Arduino starter kits (including the “official” starter kit shown in Figure 16C), a standard breadboard and jumper-wires are used. This makes connectivity completely dependent on component and is very cost efficient. A system build on breadboard is typically unsuitable for wearable use, and breadboard wires lack mechanical locking, so they rely on contact mechanics only. Hence, for the prototyping kit described in this study, we chose to find a flexible but uniform wire/cable system.

With systems such as gravity (3-wire, color indexed) and grove (4-wire, orientation lock), shown in Figure 16E, cables are grouped and uniform sockets have been chosen. This approach yields more robust connectivity at the price of having to supply (or manufacture) fixed length cables. Bitalino (Figure 16D) comes with a snap-off board which can be broken up in functional bits to wear the system on the body. For connectivity, a mini-USB (like) cable is used which again has to be obtained in correct lengths. Makeblock MakerX (Figure 16F) uses also a fixed length 4-wire lead, but instead of connecting each device individually to the main control board, the system uses a bus-system so all modules can be daisy-chained. Very robust, small, and flexible, but it comes with a price tag: every module has a small on-board microcontroller to handle bus communication.

As trade-off between complexity, price, and the desire to use uniform connectors, we chose to go for a three-wire link similar to the system proposed by DF-Robot’s Gravity. Instead of the form-factor of a large (standard) Arduino or shield, we chose a very small Arduino form factor (the beetle) and augmented this with a row of 3-pin connectors similar to the Gravity system.

For wires, standard extension cables for RC-servos (with Graupner/JR sockets) have been chosen. The wires can be obtained pre-made in different lengths, are very flexible, and cost-effective, and the color coding (signal: orange, VCC: red, and GND: brown) can be explained and used well.

3.2.4. Control

Many controllers exist allowing WIFI or Bluetooth wireless connectivity. Examples are the Adafruit Feather series or ESP32 boards. Although software development and templates/examples for connectivity are vital for prototyping interactive wearables, for the scope of tinkering with haptics and social touch, we put our focus on a different aspect.

To generate haptic patterns and emulate stroking motions (by controlling a sequence of pneumatic muscles contracting, or a series of vibration motors), the control board shown in Figure 13 can be controlled from a PC or laptop as a MIDI compatible musical instrument, facilitating the design of patterns, sequences, and loops and thus allowing for simple experiments with the quality

TABLE 2 Diverse prototyping sets for (wearable) electronics focusing on connectivity strategies.

System	Connectivity	Mechanical locking	Largest item size	Sensors	Actuators
Lilypad *source: lilypad.com*	Conductive yarn	Sewn, fixed	Main controller (flora/gemma) 8 cm diameter	Temperature, motion, light, color	Colored LEDs, sound, vibration
Gravity *source: dfrobot.com*	3-wire connection, color scheme	Mating socket and plug (3-lead)	Main board arduino form factor 6 × 8 cm	Light, sound, motion, proximity, distance	Light, buzzer
Grove *source: seed studio.com*	4-wire connection, orientation lock. Signals are I2C, serial, digital or analog	Mating socket and plug (4-lead)	Main board 6 × 8 cm	Light, sound, temperature/humidity	Servo, colored LEDs, display, buzzer
Arduino (standard kit) *source: arduino.cc*	Separate single wires in breadboard	Fragile breadboard connection	breadboard 6 × 16 cm	Sound, distance, light, temperature/humidity, tilt	Colored LEDs, servo/stepper motor, displays, buzzer
Littlebits *source: sphero.com*	Magnetic connectors	Must be on rigid base or flat surface	Arduino board: 10 × 5 cm	Sound, light, temperature, motion, pressure	Light, servo motors, sound
Hexwear *source: shop.stemcenterusa.com//products/hexwear-wearable-electronics-kit*	Sewable connectors and conductive yarn	Sewn, fixed	Main board diameter 10 cm	Sound, temperature	Colored LEDs, buzzer
Pimoroni bear kit *source: pimoroni.com*	Sewable connectors and conductive yarn	Sewn, fixed	Main board 4 × 5 cm	Tilt switch	Colored LEDs, buzzer
Bitalino *source: pluxbio signals.com*	Breakaway board, sensor leads, and boards	Mating socket and plugs (3-wire JST)	Main section 8 × 10 cm	EMG, ECG, temp, motion, GSR, light intensity	LED
Makeblock MakerX *source: makeblock.com*	4-wire bus leads, universal signal protocol	Mating sockets and plugs with lock (mini 4-wire JST)	Battery box: 5 × 5 cm	Distance, color, motion, vision, proximity, gas, light, temperature, capacitive sensing, heading	Sound, vibration, motors, pump, servo

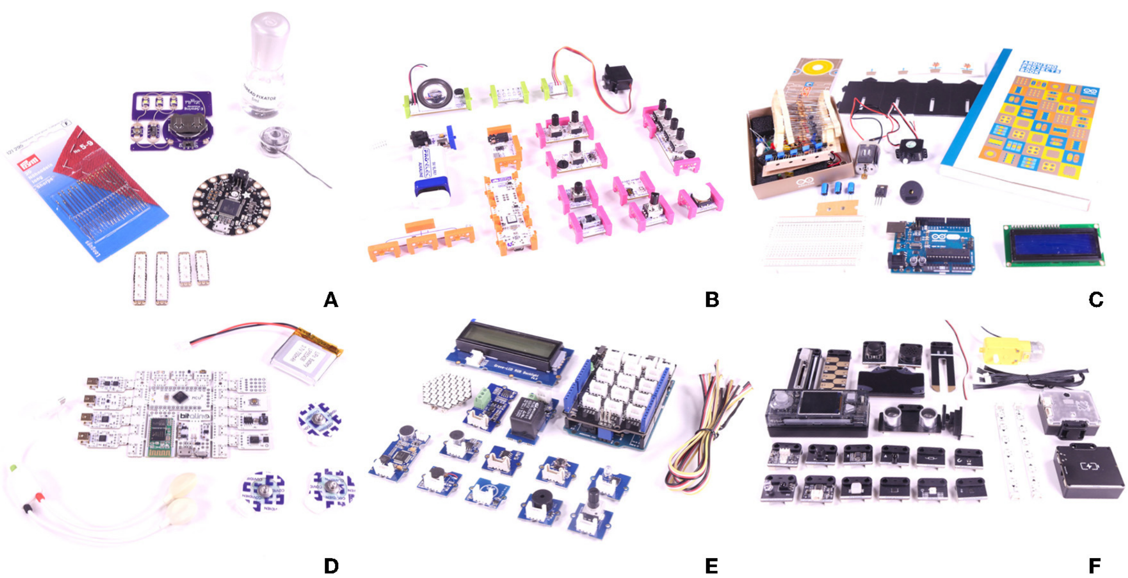

FIGURE 16
Platforms for prototyping of electronics considered for wearables: **(A)** Lilypad, **(B)** LittleBits, **(C)** Arduino starter kit, **(D)** Bitalino, **(E)** Grove, and **(F)** Makeblock.

FIGURE 17
The ROLI seaboard MIDI input device used to record haptic touch patterns.

of touch. Any audio scoring software (such as Garageband, Logic, Cubase, Ableton, etc.) can be used as a tool to "compose" haptic patterns.

Patterns can be stored, edited, played, and looped to explore the qualitative aspect. As user to generate patterns, we have been using diverse (musical) input devices such as piano keyboard style (i.e., Korg nanoKey USB MIDI), sampler pad keyboard style (i.e., AKAI MPX series), and a recent (and very suitable device) pressure key style (i.e., ROLI seaboard) shown in Figure 17.

Offering students and designers a ready-to-go setup consisting of the control board (Figure 13), a laptop with audio software (or simple installation instructions) and an input device shifts the focus of the design of haptic wearables for touch from the connectivity and control to experiential design.

4. Discussion

Our initial question was whether tinkering a is design approach that can foster the finding of novel applications in STT. A design challenge based on tinkering with 34 teams of students showed that this is indeed the case. The prototypes designed realized a diverse range of applications, which was the criteria for success. Especially, a category of unexpected results supports this conclusion. These unexpected results did not apply a remote social touch as primary goal, but are part of a shared activity. These shared activities included games such as catching a ball or rock-paper-scissors, making music together, doing workout, relaxation movements, adding touches on a smart phone to text chats, or watching a movie together.

4.1. Stimulating creativity in tinkering

Creativity seems to be stimulated by (at least) the following two sources: the dialogue with the material and story telling, which will be elaborated in the following.

Here, we want to emphasize the difference between "know what" and "know how" (e.g., Cross, 1982). Tinkering, as a hands-on activity, supports "know how". It is a "dialogue with the material", that leads to an understanding of the working principles, properties, and limitations of the material, e.g., how components can be combined or need to be combined. To some part, this is a practical skill that includes tacit knowledge, other than explicit criteria, rules, and procedures, and "knowing how" is often in-action (Schön, 1992). In small experiments, the tinkerer gets immediate feedback of effects and experiences generated by the material. Following experiments could be invented to intensify or smoothen the observed experience, set it in a specific context, or combine it with other effects. In this way, the experiences, reflections on them, and associations guide the tinkerer in the realization of prototypes, stimulating and making use of his or her creativity. In contrast to this path, "know what" would just include the knowledge on the components and their functionality. The effect of their combinations would be an imagined experience that possibly does not match with a real experience, and it is questionable to what extent this would stimulate further steps in a design process.

Examining the students' projects, it seems that story telling is also a motor of creativity, stimulated by the toolbox and tinkering playground. With story telling, students defined contexts for which they designed their prototypes. The stories were shaped by personal backgrounds, and, at this point in time, also by the shortcomings due to the lockdown situation. In an iterative tinkering process, by interaction with the material and toolbox, stories, contexts, and prototypes were refined.

The goal of STT products is to create experiences by remote touch that increase wellbeing. On one hand, the currently available technical components come short in the replication of human touch. On the other hand, an experience of touch is not constituted by the sensors and actuators alone. A context or metaphor contributes to a high degree to an experience of touch, like the mother's hand on the forehead, or the ball game from the examples of the students. In this sense, we see the story telling part in the tinkering process as relevant for the creation of experiences. Accordingly, people and experts with different lenses also can contribute different stories and contexts and, accordingly, to prototypes with a wider spectrum of touch experiences.

4.2. Design methods and tinkering

In classical science, observation is one of the first steps of scientific activities, as part of characterization (Brody, 2012). In the world of the artificial, the object of observations is not nature, but artifacts. In Gaver (2012), the author argues "... that an endless string of design examples is precisely at the core of how design research should operate, and that the role of theory should be to annotate those examples rather than replace them." We would like to add on this statement that there is not only an endless string of prototypes needed but also a diversity in the prototypes of that string.

Accordingly, we expect that other target groups for tinkering with a different background and expertise could increase the diversity of prototypes on STT, and in a next step, increase also the knowledge on STT gained through these. Psychologists, fashion and interaction designers, haptologists, physiotherapists, or artists have different insights about the possibilities and needs for social touch, which could be specific part of their individual tinkering toolboxes. To include these groups, the design step in the technology part of the material is needed to reduce complexity, and make it easily accessible.

Our motivation stemmed from the observation that STT suffers from low acceptance and/or market uptake. We, therefore, explicitly developed the described tinkering approach since it involves stakeholders early in the design process. Comparing the tinkering approach, as suggested in this study, to Participatory Design (PD) (Ehn, 2008), the inclusion of stakeholders in the design process is shared in both design approaches. In general, PD aims at a broader circle of stakeholders than what we have suggested here. However, the main characteristics of stakeholders that we mentioned in this study are that they bring in a different expertise on users' needs, and are not necessarily experts in technology. These characteristics would not exclude stakeholders as considered by PD. The design method in PD, however, is less specific as we see a tinkering approach, and it is more understood as a group process, which we did not emphasize here for tinkering. PD also starts more often with a more specific design question, whereas tinkering most often has a theme, but the design question typically is identified in the process.

Also in Design Thinking (DT) (Johansson-Sköldberg et al., 2013), the starting point is typically a problem to solve, and a team with heterogeneous expertise solves the problem together. Prototypes are also relevant for DT, but are only in one of many different steps in a design process, whereas tinkering is mainly oriented toward prototypes. Definitely, the management aspect in DT is absent in tinkering.

4.3. Technology acceptance

As mentioned above, only few STT products that made it to the market (Huisman, 2017), and of those that did enter the market, the majority does not persist very long. A major reason that STT products do not remain on the market is (probably) that they do not meet expectations of users. The Technology Acceptance Model (TAM) (Davis, 1989) tries to identify reasons that products are not used, one of them is the intention of potential users to really use the product. Main factors influencing the intended usage are perceived usability (PU) and perceived ease of use (PEOU) (Papakostas et al., 2021). The definition of PEOU is the degree to which a person believes that using a particular system would be free from effort (Davis, 1989). This can be directly interpreted also in the context of STT products. The definition of PU is "the degree to which a person believes that using a particular system would enhance their job performance" (Davis, 1989). As the goals of STT are not in the area of job performance, or performing tasks as efficient as possible, more suitable definitions have to be identified here. Instead, STT aims at wellbeing, social connectedness, comforting, sensoric stimulation, etc. (Jewitt et al., 2021). While it seems to be plausible that PU in the context of STT can be interpreted differently, it still needs to be validated to what extent results for PU in the original definition can also be interpreted for goals of STT mentioned. An extension of the TAM models to products of wearable technology (Chang et al., 2016) is also relevant to STT , including a range of other factors such as wearability, connectivity, social norm, and others.

On a different level, the haptics toolbox suggested itself is also a technology product that may find acceptance or not. Considering experts of other domains as users of this technology, also here technology acceptance has to be taken into account, the experts also have a role as learners. The main goals in toolbox design (Resnick et al., 2018) can be mapped directly to TAM elements: "low threshold" describes that the toolbox elements can be used with little effort, which clearly contributes to PEOU. "Wide walls" say that broad range of projects is possible, and "high ceilings" means that the projects allow also for complexity. Both are describing usefulness of a toolbox, and it is up to scaffolding (see also Section 2 for the role of a facilitator), to make this visible to the users to stimulate PU. Moreover, in Liu et al. (2021), it was shown for a learning context, concept maps have positive effect on PU and PEOU. The sense-think-act-paradigm, which is part of the introduction and scaffolding in our context, is an instance of a context map. Playfulness in a learning context was investigated as an external factor for TAM in Papakostas et al. (2022). It was shown to have a positive effect on PU and PEOU. As playfulness is a driving concept of tinkering, we assume that it also here has a positive effect on PU and PEOU. Altogether, we argue that the design criteria for the haptic tinkering toolkit and the tinkering environment described in this study do address the elements of TAM that are relevant for intention to use the haptic tinkering toolkit.

5. Conclusion and recommendations

In our study, we showed that tinkering is a suitable design approach for out-of-the box prototypes in the context of Social Touch Technology. In a teaching unit for a haptics challenge, students of a Interaction Technology master programme produced a wide range of prototypes and concepts on mediated social touch using tinkering. Moreover, it resulted in reflections on relevant concepts like intrusiveness, and how to deal with it.

Our initial motivation for this work was that there are no sufficient products of STT on the market that can mitigate needs of social touch. Increasing the variety of prototypes and concepts is one way to eventually identify the products that are really suitable, and, we showed that tinkering can contribute to the increase of the variety. Another way to identify the useful touch applications is to include experts in the design process who have more insight on the user needs, leading to prototypes that better meet the user needs and have higher acceptance. For this end, we suggest a better design of the tinkering toolkit. The current tinkering toolset is "ready to use" for people with a technical background. Making tinkering with Social Touch Technology accessible for people without technical experience, we recommend the design of a toolkit, with high-level building blocks for sensors and haptic actuators.

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

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The patients/participants provided their written informed consent to participate in this study.

Author contributions

AM, JW, ED, and JE substantial contributions to the conception and design of the work, the acquisition, and analysis or interpretation of data for the work. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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