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# Interpersonal Haptic Communication: Review and Directions for the Future

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ABSTRACT

Touch between people is an integral part of human life. Touch is used to convey information, emotions, and other social cues. Still, everyday remote communication remains mainly auditive or audio-visual. The theme of this article, interpersonal haptic communication, refers to any communication system that supports mediation of touch between two or more persons. We first present a scoping review of the state of the art in interpersonal haptic communication, including physiological and psychological basis of touch, affective and social touch, and mediated social touch. We then discuss emerging research themes that shape the future of interpersonal haptic communication, identify research gaps and propose key research directions for each theme. Finally, societal impact and ethical aspects are discussed.

## Introduction

Touch has an important role in social communication, regulating physiological states and biological and social development (Montagu, 1972). Hertenstein et al. (2006) state that because of its importance in early life, touch may establish the foundation of all other forms of human communication. Even though the frequency of touch contact decreases after childhood, interpersonal touch is equally important in adulthood (Jones & Yarbrough, 1985). Touch can have common meanings between cultures, and fundamental uses include communication of comfort, attachment, and aggression (Hertenstein et al., 2006).

The role of touch in everyday non-remote communication between people (Gallace and Spence, 2010) is not supported in remote communication. Haptic communication systems can be divided into two broad categories based on the type of information communicated: task-oriented or affective. The bulk of research has focused on task-oriented, non-affective communication. For instance, it is possible to send haptic guidance cues to a person walking towards a point of interest (Scheggi et al., 2014) or convey information of person's presence (Lenay et al., 2011). Task-oriented information can be communicated by using Tactons (Brewster and Brown, 2001; Hoggan et al., 2009) or systems like Tactile Braille (Rantala et al., 2009; Rantala et al., 2013a).

This article is focused on interpersonal haptic communication, with a specific emphasis on affective touch. With interpersonal haptic communication, we refer to any communication system that supports mediation of touch between two or more persons. The scoping review was prepared as follows. First, we collected an extensive set of all studies from the most relevant fields in interpersonal communication. Amongst the chosen fields were physiology of the skin, human emotions, the role of touch in social communication, haptic technologies, social communication, multimodal technologies, human perception, psychology and computer-mediated haptics. We first identified potentially interesting and relevant peer-reviewed publications (i.e., journal articles and conference papers) in English. The searches were carried out in ACM Digital Library, IEEE Xplore, MDPI, Elsevier, Scopus and Google Scholar databases. We also used the reference lists and lists of papers referring to chosen studies of all selected papers and articles to find additional relevant papers. After an analysis of words contained in the title, abstract, or index terms, we selected potentially interesting papers. The papers were retained only if they contained information related to interpersonal haptics or the scientific background (e.g., physiology of the skin) important to design haptics.

This article is structured as follows: After the introduction in Section 1, we present the sense of touch in Section 2, focusing on discriminative and affective touch. Section 3 contains a concise summary of haptic technologies. Mediated social touch and its applications are presented in Section 4. Section 5 contains the discussion, starting with emerging themes for the future, followed by societal impact and ethical considerations. Finally, Section 6 concludes the article.

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## Physiological basis of touch

To understand interpersonal touch, it is important to separate discriminative touch and emotional touch (McGlone et al., 2007). We rely on discriminative touch when manipulating objects or exploring our surroundings. Emotional touch is mediated by a different system that gets activated via a range of haptic social interactions such as grooming and nurturing (McGlone, 2007). In the next sections, we provide concise overviews of both discriminative and emotional touch with focus on the latter.

### *Discriminative touch*

When we use tools or interact with objects, discriminative touch is activated. During discriminative touch, humans typically touch surfaces and objects with the glabrous (i.e., non-hairy) fingertips and palms. While there are up to 12 classes of afferent fibers in the glabrous skin (Johnson et al., 2000), the afferents mainly responsible for discriminative sensibility are four mechanoreceptive afferents: Merkel receptors, Meissner corpuscles, Pacinian corpuscles, and Ruffini endings (Goldstein, 1999). These receptors respond to different types of touch stimuli: Merkel receptors sense low frequency pushing against the skin (Goldstein, 1999) via the mechanosensitive Piezo2 channel (Woo et al., 2014). Meissner corpuscles detect stimuli such as taps on the skin and small bumps or ridges on surfaces (Goldstein, 1999). Pacinian corpuscles sense poorly localized high-frequency vibration such as the hum of an electric motor and frictional displacement of skin when moving one's hand across an object (McGlone, 2007). Ruffini endings sense stretching of skin and movement of joints. In addition, thermoreceptors, chemoreceptors, and nociceptors also have specific roles in sensing touch. Thermoreceptors sense temperature such as feelings of cold and warmth (Darian-Smith & Johnson, 1977). Direct chemoreceptors react to chemical stimuli through taste buds in the tongue (Chandrashekar et al., 2006). Nociceptors respond to stimuli that can cause tissue damage and be perceived as painful (Scholz & Woolf, 2002).

### *Emotional touch*

A distinction worth mentioning is between the terms affect and emotion. *Affect* refers to the basic sense of feeling, often measured with two or three dimensions (valence: how pleasant or unpleasant one feels, arousal: how calm or agitated one feels, and dominance: how controlled or under control one feels). *Emotions* are the result of conscious cognitive behavior such as reflecting, weighing up the odds (Barrett, 2017). Emotions are more complex and constructed over time while affects are punctual demonstrations that one feels, and might not be aware of them. Affects are strongly related to visceral feeling and interoception, sensory perception from inside the body. The terms *emotional touch* and *affective touch* have been interchangeably used by the research community (McGlone et al., 2014).

The processing of affective touch begins at the skin level (McGlone et al., 2007; Morrison et al., 2011b). The anatomy of the skin and touch sensations varies between glabrous and non-glabrous sites of the human body (e.g., Olausson et al., 2008; McGlone & Reilly, 2010). The skin is a network of thin, slow-conducting afferent (C and Aδ) fibers which transmit information. Traditionally, mechanoreception was attributed exclusively to thick, fast-conducting (Aβ) afferents. Recent evidence, however, notes that C-tactile (CT) afferents present at non-glabrous body sites comprise a second anatomically and functionally distinct system signaling touch in humans (Björnsdotter et al., 2010). These unmyelinated, slow-conducting CT afferents are strongly associated with coding the emotional properties of pain, itch or tickle, and roughness and pleasantness sensations (Vallbo et al., 1996; Pawling et al., 2017; Sailer et al., 2020). Two important factors affecting CT afferents are the force and velocity of the stimulus. Overall, soft, slow, and short velocity movements tend to evoke more pleasant experiences than hard strokes (Sailer and Ackerley, 2019), and rough surfaces or fast velocity are experienced as less pleasant than smooth ones (Tsalamal et al., 2018; Greco et al., 2019). The density of the CT afferents varies between individuals and, therefore, affects the experienced pleasantness of tactile stimulation (Morrison et al., 2011b).

In addition, even though CT afferents are argued to be most prominent in non-glabrous body sites, recent evidence supports the existence of sparse amount of such afferents in the palm area (e.g., Watkins et al., 2021) supporting the ability to promote affective and emotional reactions when glabrous body sites are stimulated. Evoking painful or pleasurable tactile experiences on glabrous skin is also not excluded (e.g., Essick et al., 2010). However, touch is often perceived as more pleasant in non-glabrous than glabrous body sites (e.g., Ackerley et al., 2014).

Among the factors that affect the perceived pleasantness in glabrous skin are roughness, force, and temperature (Klöcker et al., 2014). The texture of the surface affects the rated pleasantness in both non-glabrous and glabrous body sites (e.g., Ackerley et al., 2014). The forearm is more susceptible to hardness of a stroke than the palm, providing additional evidence about the role of CT afferents as mediators of pleasant touch (Yu et al., 2019). The pleasantness rating of brush stroking gestures is higher when the stroking velocity is suitable for activating CT afferents (e.g., 3m/s) in comparison to other velocities (Löken et al., 2009) and prior exposures affect the ratings of both CT and non-CT touch (Sailer and Ackerley, 2019; Yokosaka et al., 2020). People who are touched rarely do not rate CT touch as pleasant compared to people who are touched regularly (Sailer & Ackerley, 2019). The pleasantness rating of tactile surfaces is also affected by finger movement velocity and force during object manipulation. People switch touch behavior depending on the manipulated object, e.g., pushing motions with unpleasant and gestures with pleasant objects (Yokosaka et al. 2020).

Temperature and wetness sensations are also associated with the functionality of the pain – pleasantness system. The thermal subsystem consists of warm and cold receptors. Warm receptors fire to temperature increases up to 45°C (Stevens, 1991) with higher temperatures often activating the sensation of pain (e.g., Heller and Schiff, 1991). There is a tendency to rate warm stimulation under the pain threshold as pleasant (e.g., Sung et al., 2007; Salminen et al., 2011; Salminen et al., 2013). Sticky, cold, or wet textures temperatures are, on the other hand, often perceived as disgusting (e.g., Kanosue et al., 2002; Saluja & Stevenson, 2019).

## Affective communication through haptic technologies

Replicating the feel of real human touch contact is challenging. Even though current technology is not sophisticated enough to mimic all the qualities of real touch such as pressure, grip, dryness, and texture, different haptic technologies can simulate it (e.g., Huisman, 2016; Simons et al., 2020). In this Section, we present the technologies that have been used to produce touch stimulation for interpersonal communication.

### *Vibrotactile*

Vibrotactile stimulation is based on an eccentric rotating mass, voice coils, solenoids, piezoelectric elements, electroactive polymers, or other related technologies (Choi and Kuchenbecker, 2013). The advantages of vibrotactile actuators include simple and inexpensive technology as well as easy control. The actuators are typically either embedded in a portable device (e.g., Dobson et al., 2001; Rantala et al., 2011; Furukawa et al., 2012; Hoggan et al., 2012) or attached to a wearable (e.g., Cabibihan & Chauhan, 2017; Huisman et al., 2013). The vibration can be localized so that only a specific area of the skin is stimulated, or it can be generalized so that an entire device vibrates. The downside is that vibrotactile actuators have limited expressiveness as vibration of the skin is only one of the qualities of interpersonal touch. Nevertheless, even a degraded touch cue based on vibration can be perceived as a stroking gesture and resemble real touch (Huisman, 2016; Rantala et al., 2013b). Taxonomies of emotional terms associated with vibrotactile stimuli have been made available to help haptic designers identify more efficient vibrotactile emotional signatures (Seifi et al., 2015; Seifi et al., 2018).

### *Thermal*

The most typical approach to temperature is to use Peltier elements that create a temperature difference at the junctions of two dissimilar conductors when a DC current passes through. Depending on the direction of the used current, one side of the Peltier cools and the other side heats (Jones & Ho, 2008). This makes it possible to create both warming and cooling sensations. Heating elements have been attached, for example, to a belt (Gooch & Watts, 2010), model of a hand (Gooch & Watts, 2012), bracelet (Suhonen et al., 2012) and mobile phone (Wilson et al., 2011). Challenges in using temperature variations include the limited range of different sensations, spatial and temporal sensitivity (Jones & Ho, 2008), and high-power consumption. Due to the poor spatial sensitivity, dense arrays of thermal actuators rarely provide benefit. Additionally, the temporal modulation of the temperature requires a few seconds to feel the variation. The amount of information that can be communicated with thermal actuators is lower than with vibrotactile actuators.

### *Force*

Force feedback devices can stimulate the muscles, joints, and tendons. Typically, these devices are used for exerting forces on the torso or limbs. In interpersonal haptic communication scenarios, force feedback can be used in diverse ways when stimulating only the skin is not sufficient. A vest or a jacket can apply pressure around the upper torso to mimic a hug (Teh et al., 2012; Tsetserukou, 2010). Additional devices have emerged such as armbands for creating a squeezing sensation on the upper arm (Wang et al., 2012), robotic hand for mediated handshaking (Nakanishi et al., 2014), rotating rollers for playful interaction (Brave & Dahley, 1997), and haptic knobs for communicating emotions (Smith & MacLean, 2007).

### *Contactless*

Contactless alternatives are valuable especially in virtual and augmented reality applications, where requiring the user to touch or wear a physical device impedes natural user interaction (Sodhi et al., 2013), or decreases immersion (Rakkolainen et al., 2021). One approach to create contactless mid-air stimulation is to use controlled air streams that exert pressure again the skin. This can be achieved by using fans or pressurized air jets (Suzuki et al., 2005). Another approach is to use air vortex rings that transfer pressure to the skin or clothes upon contact (Sodhi et al., 2013). The most current contactless technology is based on the use of ultrasound (Carter et al., 2013; Iwamoto et al., 2008). With ultrasound, it is possible to exert pressure on multiple points on the skin (Rakkolainen et al., 2021). Users generally perceive ultrasound stimulation as vibration (Hoshi et al., 2010), but often these sensations have been described as flow of water, wind, or electricity (Obrist et al., 2013). A database of galvanic skin response (GSR) with self-assessment ratings evaluating ten mid-air stimuli has been made available to researchers investigating human emotional reaction and automatic emotion recognition (Gatti et al., 2018).

## Mediated social touch

The focus of this section is on affective, social distal touch. We first discuss the role of social touch in human communication. Next, mediated social touch is defined. Finally, we present a summary of research in mediated affective and social touch.

### *Social touch*

Social touch is often affectionate, promoting relational, psychological, and physical wellbeing by reducing stress (Jakubiak and Feeney, 2017). Besides stress reduction (Morrison, 2016), interpersonal touch can also decrease conflicts (Murphy et al., 2018), elevate relational well-being (Jakubiak and Feeney, 2019) and activate the neurocognitive processes underlying goal-directed behavior (Saunders et al., 2018). A detailed list of different responses associated with social touch in different age groups can be found in Field (2019).

Tactile behaviors and responses to touching are greatly affected by culture, gender, social closeness, and personality traits such as self-esteem (e.g., Hertenstein & Keltner, 2011; Gallace & Spence, 2010). Interpersonal tactile communication can trigger anxiety in people suffering from it (Wilhelm et al., 2001) while those with a higher need for interpersonal touch show an increased level of confidence after being touched (Nuszbaum et al., 2014). People adjust the degree of touch based on sympathy experienced towards the individual being touched (Strauss et al., 2020). Some people are touch avoidant (Johansson, 2013) such as individuals with autistic traits (Voos et al., 2013). Further, motives to touch another person reflect the well-being of the social relationship in question (Jakubiak et al., 2020).

The basic elements of social touch overlap with emotional touch. Skin is a social organ and interpersonal, skin-to-skin touch can be perceived as highly pleasurable (Morrison et al., 2010). Touching and sensing another person's skin is more pleasant than one's own skin (Guest et al., 2009). The pleasant experiences related to social touch can be evoked visually, by seeing caressing gestures (Morrison et al., 2011a).

Research on social tactile gestures and their responses has a long tradition. Jones and Yarbrough (1985) showed distinct meanings of touch in communicating, for example, positive emotions (i.e., support, appreciation, inclusion, sexual interest, and affection) or controlled touches (i.e., compliance, attention-getting). Gestures like squeezing and patting are associated with playfulness and stroking with sexual desire (Nguyen et al., 1975). Some tactile expressions have later been successfully associated with several emotions like anger, fear, or sympathy (Hertenstein et al., 2006), including simple social gestures like grooming (McGlone et al., 2016).

One important factor in pleasant touch is the human factor. Pleasant experiences evoked by an object are not as strong as those evoked by another human being (Wijaya et al., 2020). This aspect is not only important but also challenging in the design of haptic communication technology. The human aspect between touch and emotions needs to be fully understood to mimic, partially or fully, human-to-human touch using haptic communication technology; a sensation generated by a device would affect the user differently from a sensation received by a fellow human.

### *Definition of mediated social touch*

A central concept in this field is mediated social touch, which has been defined as “the ability of one actor to touch another actor over a distance by means of tactile or kinesthetic feedback technology” (Haans & IJsselsteijn, 2006). Recently, several researchers have expressed their concern over the fact that the use of social touch has decreased in daily life over the course of the last 20 years and suggest that mediated haptics could help to overcome this issue (Jewitt et al. 2021).

Research has shown that mediated social touch can modulate physiological responses, increase trust and affection, help establish bonds between humans, and initiate pro-social behavior (Van Erp & Toet, 2015). In general, humans use, experience, and react to mediated social touch similarly to direct touch (Bailenson & Yee, 2007). Mediated touch can lower the heart rate of participants after they watch a sad video clip (Cabibihan, 2017). It can also increase sympathy and intimacy towards the communication partner when watching a movie together in remote locations (Takahashi et al., 2011). During a remote storytelling experiment, mediated touch increased the sense of connectedness (Wang et al., 2012). Finally, mediated touch can increase pro-social, altruistic behavior, and willingness to comply with a request (Haans & IJsselsteijn, 2009). Thus, virtual touch can be processed like direct touch (Haans et al., 2014). These encouraging findings from different social contexts support the development of remote haptics.

### *Examples of mediated affective and social touch*

Affective haptics (Tsetserukou et al., 2009) is defined as a field that studies and designs haptic systems capable of eliciting, enhancing, or influencing human emotions. The field integrates affective computing, haptic technology, and user experience (Eid & Osman, 2015). However, up to date the design of most haptic interfaces has focused on discriminative touch while potential affective qualities have been neglected (Bianchi et al., 2017). Only recently, the affective qualities of haptics have been integrated as a part of interface design, with varying success (Schneider et al., 2017).

In the following subsections, we discuss affective responses to haptic stimulation and provide insight on the use of haptics to evoke emotions in remote, social communication settings. Most often, affective qualities or dimensions of mediated social touch are measured using the pleasure-arousal-dominance (PAD) emotional state model by Mehrabian and Russell (1974). PAD consists of the dimensions of valence (i.e., from unpleasant to pleasant), arousal (i.e., from calm or relaxed to aroused) which is related to the motivational system of humans, namely activating appetitive and defensing systems (Bradley & Lang, 2000), and dominance. Dominance is less explored in haptics research, but it is equally important from the perspective of the current article since it is related to the social context (Bradley & Lang, 1994).

### *Affective responses to haptic stimulation*

Most of the previous research that explored affective responses to haptic stimulation did not include a specific communicational context but pre-programmed or device-initiated haptic output. Vibrotactile actuators have been integrated in hand-held devices or wearables for pleasant sensations (Seifi & Maclean, 2013; Yoo et al., 2015; Chandra et al., 2018) or to mimic touch gestures tickling and stroking (Knoop & Rossiter, 2015). The timing of the vibrotactile stimulation when manipulating surfaces like a touchscreen can affect the perceived pleasantness (Lylykangas et al., 2011).

When combined with visual (Akshita et al., 2015) or auditory stimulation (Salminen et al., 2012), vibrotactile stimuli contribute to high arousal values. Visual qualities seem to dominate the overall affective qualities of the multimodal stimulation consisting partly of vibrotactile haptic stimuli (Jiao & Xu, 2020) but vibrotactile stimulation is effective in amplifying the emotions experienced (Mazzoni and Bryan-Kinns, 2016a). Unpleasant vibrotactile stimuli are reported as more pleasant in the presence of environmental noise, further suggesting that such stimulation is not effective in creating strong affective responses in the presence of other modality inputs (Salminen et al., 2009; Salminen et al., 2011). Because of the strong interaction between vibrotactile stimuli and other modalities, alternative means of triggering affective responses via haptics need to be considered.

Thermal stimulation is centrally related to the feeling of pleasure and arousal (Wilson et al., 2016). Overall, the previous research shows that stimuli mildly warmer than the human skin temperature (e.g., +2°C) are rated as pleasant; while stimuli aiming to heat the skin more (e.g., +6°C) are rated as unpleasant and arousing even though the stimulation would not reach the thermal pain threshold (Salminen et al., 2011; Salminen et al., 2013). However, as with vibrotactile stimulation, there is initial evidence suggesting that information acquired by other modalities would dominate the perception of pleasantness, while thermal stimulation would dominate the perception of arousal (e.g., Tewell et al., 2017).

Mid-air haptics can effectively produce haptic sensations all over the body, and by manipulating the intensity and movement of these stimuli, it is possible to affect the experienced valence, arousal, and dominance (Sato and Ueoka, 2017; Tsalamlal et al., 2015). Further, mid-air haptics can be expressive and successfully mediate complex emotional states such as happiness, sadness, excitedness, or fear (Obrist et al., 2015).

Recently, the CT touch theory has been motivating researchers to use, for example, fabric-based tactile displays. The initial results show that modulating the strength, texture, duration, and velocity of a stroking gesture similar to a caress affected the valence ratings; where fast movements were rated as unpleasant and slow movements were rated as pleasant (Bianchi et al., 2014; Taneja et al., 2021; Toet et al., 2011; Zhu et al., 2020). These fabric-based interfaces, worn usually as sleeves, are effective in modulating the perceived arousal, excited vs. calm, when the pace of the haptic stimulation is varied (Papadopoulou et al., 2019).

Despite the technology used, there is a negative correlation between the rated haptic stimulus pleasantness and its arousal (Salminen et al., 2008; Zheng and Morrell, 2012; Mazzoni & Bryan-Kinns, 2015). Further, there is hardly a conclusion about which parameters of the haptic system can be used to trigger affective experiences via a mediated interface. Schneider et al. (2016) suggest that vibrotactile icons require more research and the use of high-quality analytical tools like crowdsourcing can help reduce the gap.

By combining different haptic technologies like vibrotactile and thermal, the available range of emotions evoked by the haptic stimulation can be enriched (e.g., Wilson & Brewster, 2017). At the moment, combining different haptic technologies like warmth and vibration has been rare, despite the fact that wearable devices which enable touch stimulation via multiple methods have been evaluated positively (Arafsha et al., 2015).

### *Affective haptics in communicational setting*

Mediated social touch has potential in various forms of emotion-related communication such as establishing connectedness between romantic couples (Haans & IJsselsteijn, 2006). In its simplest form, haptic stimulation can be used to create an illusion of physical co-presence while the actual emotions are mediated via visual stimulation (Tsetserukou & Neviarouskaya, 2012). Often, prosocial gestures like hugs (Teh et al., 2009; Tsetserukou, 2010) are mimicked to evoke pleasant affective experiences.

Some of the earliest studies in the area of remote haptic communication were focused on studying what could be communicated using touch alone. Smith and MacLean (2007) instructed their participants to communicate emotions such as anger, delight, calmness, and joy to a partner with a 1-degree of freedom force-feedback knob. The results showed the potential to communicate these emotions with a minimal haptic device with a 54% accuracy. Bailenson et al. (2007) showed that with a 2-degree of freedom force-feedback device the seven universal emotions (disgust, anger, sadness, joy, fear, interest, surprise) can be conveyed at above-chance level. Rantala et al. (2011) further showed that vibrotactile stimulation can effectively mediate unpleasant, pleasant, relaxed, and aroused intentions between two people when a member of a dyad uses input gestures like squeezes and strokes, while the other feels the vibrations in the palm area (Rantala et al., 2013b).

Gestures like pinching, squeezing, and twisting (Simons et al., 2020) or poking (Park et al., 2011) can be successfully mediated to enhance the interaction, with the most popular gesture being stroking. In a series of studies, authors tested a haptic sleeve for remote communication (Huisman et al., 2016; Huisman et al., 2013) and showed that vibrotactile stimulation on the arm can be perceived as a continuous stroking sensation like a gentle touch that activates CT-afferents. Other studies report comparable results where a distant stroke can be perceived as comfortable and like an actual caress (Eichhorn et al., 2008). Creating stroking gestures with vibrotactile actuators shows how CT touch (*see*

*Section 2.2*) can be replicated if characteristics like velocity are considered. For example, studies have shown how strokes at low amplitude are felt as pleasant and those with high amplitude are felt as unpleasant (Israr & Abnousi, 2018). Additional factors such as long duration and a short inter-stimulus-interval maximize the feeling of continuation and pleasantness (Culbertson et al., 2018). To promote the feeling of intimacy, other types of caressing gestures like touching fingers via haptic gloves can be used (e.g., Singhal et al., 2017).

In multimodal settings, touch can easily be used to highlight the emotional content of a story (Wang et al., 2012) or music (Chan et al., 2019). There are also studies indicating people's preferences in using multimodal settings to communicate emotions instead of haptics alone (Mullenbach et al., 2014).

Erk et al. (2015) showed how mediated affective touch can enhance prosocial behavior (e.g., understanding of the partner). Vibrotactile stimulation can facilitate social interactions for the visually impaired when a pattern shape or duration is varied to influence affective responses (e.g., McDaniel et al., 2014). However, although thermal stimulation relates to human emotions, its effects in mediated contexts do not include elevation in prosocial behavior (Willemse et al., 2018).

As noted by Askari et al. (2020), results related to mediated social touch are mixed, and information about contextual factors potentially affecting the perception of mediated social touch and its affective qualities is virtually inexistent. Studies have also shown unambiguous evidence that comprehensive methodologies such as sociotechnical imaginary, which is a future-oriented method to connect social and technological orders (Jewitt et al., 2020a) and research over touch norms especially from gendered and cultural points-of-view (Jewitt et al., 2020b) could enrich designing haptic interfaces supporting interpersonal touch. Furthermore, even though tactile sensations can be associated with different emotions, there are only a few papers addressing comparisons between haptic technologies. Preliminary studies indicate that force feedback is perceived as more natural than vibrotactile touch and has a better ability to express emotions (e.g., Ahmed et al., 2016).

## Discussion

Our vision for the future is that haptics would provide as natural interpersonal haptic communication channel as possible, both in the quality and the range of different stimuli produced. This high-quality haptic communication channel should have low latency to allow real-time haptic communication. We expect this type of haptics to be an essential building block of the metaverse where people would live and work in the future.

In this Section, we first present nine emerging research themes based on the present state of the art. Then, we discuss the societal impact and ethical considerations related to wider availability, acceptance, and utilization of interpersonal haptic communication.

### *Emerging research themes for the future*

The following themes are based on the present state of the art and the authors' views of the future trends in haptics. In each theme, we first describe current challenges from the point of interpersonal haptic communication. Then, the state of the theme is summarized, and the research gap recognized. Finally, we provide key research directions to advance the theme.

#### Theme 1: Mediated touch vs. non-mediated touch

**Challenge**: To adapt mediated social touch technology (Huisman, 2017) to the ways how humans use non-mediated touch in their daily lives. There is not a general understanding of which aspects of non-mediated touch are essential for mediated touch technology.

**State**: Often, the aim of mediated touch (see Section 4) is to mimic human tactile behavior via haptics and to investigate its effects. The identification of the key differences between mediated and non-mediated touch would give fruitful ground for applications, where the remote touch could be designed to better affect human emotions or enhance social bonds. Additional factors affecting the communication setting include, for example, interpersonal distance and social norms (Askari et al., 2020).

**Research gap**: Mediated social touch is typically not recognized as similar to non-mediated touch (van Hattum et al., 2022; Askari et al., 2020). Possible explanations for this include the incapability of current haptic technology to realistically simulate a human touch and the lack of understanding of the wider setting where mediated social touch takes place (Askari et al., 2020). Thus, more research is needed both related to the used technological solutions as well as the social, perceptual, and other factors.

**Key Research Directions**

- Identify the underlying social, perceptual, and technological factors that are essential for a tactile stimulus to be perceived as an interpersonal touch.
- Study the effects of the sender's or receiver's personality or current mood in the context of remote touch.
- Study whether the effects of context are similar when the touch is mediated vs. non-mediated.
- Investigate if social cues function similarly in real and mediated touch settings.

#### Theme 2: Combinations of haptic sub-modalities

**Challenge:** To ensure haptic interpersonal communication can achieve an information transfer rate that is closer to visual and auditory communication, it is important to utilize all available haptic sub-modalities.

**State:** Numerous actuation technologies (see Section 3) and materials (Biswas and Visell, 2019; Cruz et al., 2018) providing both tactile (Coe et al., 2019; Farooq et al., 2020; Evreinov et al., 2021) and kinesthetic output (Kim and Follmer, 2019; Elvitigala et al., 2022), have been developed for skin stimulation controlled with physical parameters (e.g., displacement, acceleration, electrical current, pressure) (Farooq et al., 2015). The studies that integrated more than one of these technologies into a single haptic interface showed that this can improve social and affective responses to the distant touch (Farooq et al., 2016b, Coe et al., 2019, Ahmed et al., 2016; Arafsha et al., 2015; Wilson & Brewster, 2017; Messerschmidt et al., 2022). Using a combination of technologies, we can ensure the resulting feedback can deliver a wider bandwidth of haptic information (Tan et al., 2010).

**Research gap:** The knowledge of combining haptic sub-modalities is underdeveloped. Currently, the vibrotactile stimulation only creates rudimentary tactile output in the absence of a meaningful feedback loop essentially causing signal integration and attenuation across the entire device. The configuration also rarely accounts for environmental noise. Getting an understanding of how composite haptic information can be designed for the user at the point of contact can maximize information exchange (see Section 2.1).

**Key Research Directions**

- Extend the haptic information channel, focusing on creating a wide range of tactile outputs by combining multiple actuation technologies.
- Bridge the gap between the available sensory bandwidth and the optimum information transfer, by combining different sub-modalities and technologies.
- Ensure haptic communication is as robust and reliable as communication with visual and auditory modalities, across different contexts of use.

**Theme 3: Multisensory communication context**

**Challenge:** To integrate digital touch seamlessly as a part of remote multimodal communication to create positive, socially and emotionally meaningful and real life like experiences for people.

**State:** The perception of affective touch is modulated by simultaneous visual, auditory, olfactory, and gustatory simulation (Spence, 2022). Previous research (see Section 4) has focused on using simple vibrotactile stimulation to amplify emotions evoked by visual or auditory content (Mazzoni and Bryan-Kinns, 2016b). However, people prefer to communicate emotions multimodally (Mullenbach et al., 2014). Still, CT touch (McGlone & Reilly, 2010) is rarely addressed with the present haptic technologies or studied in multisensory context (Toet et al., 2011).

**Research gap:** Currently, there is a lack of understanding of the potential to use haptics in multisensory context beyond amplifying emotions conveyed via other modalities. Contextual factors (Askari et al., 2020), the role of haptic sub-modalities like thermal stimulation (Ahmed et al., 2016; Willemse et al., 2018), and touch norms (Jewitt et al., 2020b) all contribute towards the perception of social or affective haptics in multimodal context.

**Key Research Directions**

- Study the ability to reproduce CT touch (see Section 2.2) via haptic interfaces.
- Study the role and potential of haptic stimulation in multisensory communication where other sensorial information is provided in parallel.
- Compare mediated touch in multisensory context to multisensory communication in real life.

**Theme 4: Wearable haptics and extended reality**

**Challenge:** To emotionally interpret haptic sensations on their body provided by wearable systems, e.g., tickling sensations on their skin. Informative touch in the context of interpersonal communication via wearables should provide emotional connotations besides the physical sensations.

**State:** Wearable haptics such as smart clothes are under active research. The most common body site remains the forearm to simulate caress-like sensations (see Section 2.2). Vibrotactile handheld controllers remain the dominant interaction method in current commercial VR systems. Nonetheless, wearable haptic technologies are actively developed creating new opportunities for research to create haptic systems that deliver sensations on the body. Companies such as HaptX, VRgluv, and more recently Meta Reality Labs have developed glove-based haptic systems that can concurrently provide actuation and tracking. As an alternative to these glove-like exoskeletons, haptic vests and suits (e.g., Teslasuit) that provide haptic stimulation to multiple sites on the user's body can be used to provide minimal and effective haptic feedback (García-Valle et al., 2017; Krogmeier et al., 2019).

**Research gap:** The affective and emotional nature of the sensations depends on the people engaging in the mediated tactile interaction and affects how they are felt on the body (see Section 4). Currently available haptic stimuli have been found not to be able to articulate their meaning or connection to real touch (Jewitt et al., 2021). The experience is often restricted to sensations or a different perceptual experience. Most importantly, the experience is lacking emotional cues (Ziat et al., 2020). A thorough investigation of concurrent or congruent haptic stimulation is necessary to test for such effects.

**Key Research Directions**

- Determine the most suitable actuation technologies and methods for integrating them into wearable devices and clothes.
- Investigate socially acceptable body sites for remote touch in different contexts.
- Design emotionally expressive haptic stimuli for wearables.

**Theme 5: The role of the sender in haptic communication**

**Challenge**: To understand when, why, and how the senders want to initiate mediated social touch (see Section 4.3.2). The situation of initiating a mediated touch is different than using touch in a shared space with another person.

**State**: Gestural input and its related haptic output do not often match real touch. Research should focus on interaction methods where haptic inputs match remote gestures triggered by another person (e.g., a haptic sleeve activated by remote stroking gestures). The sender's role is often missing in remote communication studies even though it is easy to envision how initiating touch is related to positive affect and social experiences. Even in robotic interaction, humans use actual, tactile gestures with robots (Yohanan et al., 2005; Yohanan & MacLean, 2012). This suggests a need for developing more expressive and realistic means for distant touch input instead of limiting the initiation of touch to the use of a surface, e.g., a touchscreen.

**Research gap**: There is a gap in understanding how different input devices affect the sender's perception of initiated touch. There are studies where touch-sensitive clothes or pieces of fabric (e.g., Huisman et al., 2013) have been used as the platform for initiating touches. Additional studies could focus on the role of artificial skin sensors in the use of mediated social touch. Further research possibilities lie in studying how the person initiating mediated touches perceives the communication setting. For example, when is it appropriate to initiate touch contact so that the person receiving the touch does not get startled or surprised (van Hattum et al., 2022)? Contextual factors (e.g., facial and verbal cues) can likely affect when and how touch is initiated.

**Key Research Directions**

- Explore the role of different touch sensing technologies on how mediated social touch is initiated.
- Study the contextual and multisensory factors affecting the initiation of mediated social touch.
- Investigate the sender's social and emotional responses during the communication and initiating touch.

**Theme 6: Haptic illusions**

**Challenge:** To make haptic communication more expressive by using haptic illusions. This would contribute towards the potential to use common vibrotactile actuators in affective and social communication (see Section 4).

**State:** Haptic illusions (Lederman & Jones, 2011) are still underutilized even though a growing body of research points towards the potential of creating motion-based sensations and distinguishing certain haptic sensations as continuous or discontinuous to trigger some affective responses (Ziat & Raisamo, 2017; Ziat et al., 2018). Special interest has been given to suppression phenomena (Ziat et al., 2010) such as apparent motion (Israr and Poupyrev, 2011) or the cutaneous-rabbit illusion, CRI (Gerald and Sherrick, 1972). Two subsequent tactile stimuli in two separate locations on the skin can be either felt as a continuous or a discontinuous motion. If both stimuli vibrate simultaneously, it can lead to a phenomenon known as tactile suppression where one stimulus is masked by another. Stimulus parameters such as duration, frequency, and amplitude (Raisamo et al., 2013) are a key combination for effective haptic illusions.

**Research gap:** The research is limited to specific applications determining stimulus features to classify the motion-like illusions into categories (e.g., apparent motion, saltation, suppression), with few studies exploring the affective aspects of illusions. The pleasure dimension for tactile stimulation is often offset by visual stimulation while arousal and dominance can be modulated by the tactile stimulation (Ziat et al., 2020). Further investigations are required to understand the affective multimodal integration and how it could be applied.

**Key Research Directions**

- Study the effect of stimulus parameters with haptic illusions to support social and emotional remote touch.
- Define mapping and standardization of the parameters for each haptic illusion to allow using them with different communication equipment.
- Investigate multimodal illusions involving haptics.

### Theme 7: Adaptive Haptic Mediation

**Challenge:** To ensure that the encoded haptic signals are mediated to the point of contact with minimal degradation. Haptic signals for interpersonal communication can suffer from signal attenuation and integration depending on environmental noise. This would not only guarantee high information transfer rate (Tan et al., 2010) but also provide much needed reliability and intimacy.

**State:** Tactile or kinesthetic feedback (see Section 3) is commonly one component within a multimodal system (Laput et. al., 2015; Kim et. al., 2012). It is important to make all modalities of the system work effectively with each other (Zhaoyuan et. al., 2015). Instead of simply emphasizing on improving the efficiency of the actuation source (Hayward et al., 2008) or enhancing the perceptual outcome of the created signal (Umetani et al., 2016), current research (Farooq, 2017) focuses on improving the entire haptic feedback loop: 1. how the source of the feedback generates the intended signal (Evreinov et al., 2021), 2. How it is mediated within the device (Farooq et al., 2020, Coe et al., 2019), and 3. How to ensure signal integrity at the point of contact (Evreinov et al., 2017; Pantera and Hudin, 2019) within the tactile sensitivity range.

**Research gap:** There are three key challenges with the current approaches of providing haptic feedback: 1) inefficient delivery of the signal, 2) static actuation, and 3) the lack of dynamic adjustment within the system. Generated haptic signals are intended to propagate uniformly, distributing the vibration energy across the entire device equally, but virtually no effort is made to ensure this (Basdogan et al., 2020; Evreinov et al., 2017; Farooq et al., 2016a). Actuators and driving mechanisms are coupled using performance parameters (i.e., resonance frequency and displacement) rather than using the overall system capabilities, especially in multi-actuation setups (Dhiab and Hudin, 2019). The lack of a viable feedback loop within the system means that standardized haptic signals cannot be implemented across different devices (Hudin et al., 2015).

**Key Research Directions**

- Actively adjust the output of multiple actuation components with respect to environmental noise and propagation inefficiencies.
- Study the use of different surface materials to create more capable haptic systems.
- Use artificial intelligence methods to model interaction contexts and to modify haptic feedback parameters, creating a more robust end-to-end haptic communication channel.

### Theme 8: Contactless touch

**Challenge:** To deliver expressive haptic information without physically touching a system. Contactless touch (see Section 3.4) is already available, but much is still unknown of how to make it as expressive as other actuation technologies.

**State:** Potential solutions exist, such as mid-air ultrasound haptics (Obrist et al., 2015), pneumatic haptics (Sodhi et al., 2013), magnetic haptic effects (Ge et al., 2019), and thermal haptics (Salminen et al., 2013). Despite existing technological obstacles, contactless haptic stimulation has been found to be effective in conveying social and emotional content (e.g., Obrist et al., 2015). It is necessary to investigate these technologies as a part of multimodal communication scenarios and to study behavioral and emotional experiences related to stimulus perception.

**Research gap:** Existing solutions have technological limitations: Resolution of thermal and mid-air haptics is often low, meaning that providing accurate stimulation to a certain location of interaction is difficult. Mid-air haptic devices typically require a stable distance between the user and the device, while controlling the temperature changes in a thermal device has a low temporal resolution (e.g., Salminen et al., 2011) and a magnetic device has a low spatial resolution.

**Key Research Directions**

- Increase the spatial and temporal resolution with the current technologies.
- Create interaction methods that best suit for touchless haptic interaction.
- Investigate combinations of different contactless touch technologies (e.g., ultrasound and thermal haptics).

### Theme 9: Artificial skin

**Challenge:** Human-like skin mesh can enhance communication in social interaction. Current embedded sensors require a trade-off between technical capabilities, realistic interactive output, and the cost associated with covering a large surface area of interaction.

**State:** There is a wide range of approaches for designing artificial skin (Silvera-Tawil et al., 2015, Tiwana et al., 2012). Force-sensing resistors are commonly used to sense touch (Akhtar et al., 2017) because of their accessibility and cost (Yeung et al., 1994). Resistive (Klimaszewski, et al., 2019) or piezo-resistive (Canavese et al., 2014) skin structures have also been under development (Asfour et al., 2006; Mukai et al., 2008). The latter are commonly ridged and create brittle texture when embedded into artificial skin (Ulmen and Cutkosky, 2010; Honnet et al., 2020), resulting in a complex fabrication process with unnatural texture. One way to avoid this issue is to embed a soft cushion layer (Fritzsche et al., 2011), or cover the sensing elements with textile (Tomo et al., 2018). Other sensors covered with silicone-based materials give a more “pleasant” and human-like feel (Shirado et al., 2006; Minato et al., 2007; Schmitz et al., 2011). Most of these techniques render the sensor mesh less efficient and in turn require forced touch, to register even subtle contact.

**Research Gap:** There is a need (Youssefi et al., 2014; Teyssier et al., 2021) for artificial skin designs to follow the tradition of human-friendly artificial skin (O’Neill et al., 2018) and adopt specific requirements for sensor implementation. Artificial skin and relevant sensor arrays can be implemented by replicating the three main layers of the human skin: epidermis, hypodermis, and dermis. Each layer should use sensor fusion to provide the necessary sensory input for tactile interaction.

**Key Research Directions**

- Develop high enough tactile acuity to detect complex yet subtle tactile information.
- Make artificial skin soft, deformable, and comfortable to touch having similar properties to human skin (see Section 2).
- Design geometry and materials of the artificial skin mesh compliant with the requirements of the application area.
- Next, we discuss the impact and ethical considerations that the next-level interpersonal haptic communication technologies could have in the society and everyday living. As with any technology, the impact can be both positive and negative depending on how this is applied and how people finally make use of it. We must be prepared for both the opportunities and threats that interpersonal haptic communication may bring when it is widely available.

### *Societal impact*

The importance of social touch goes beyond simple interactions by providing emotional and psychological stability to humans (Dominian, 1971; Fisher et al., 1976). For people suffering from dementia, whose hearing and visual abilities have been diminished, touch remains the only bond to the external world by providing comfort and connections during a disorienting or agitated behavior (Kim and Buschmann, 1999; Viggo Hansen et al., 2006; Wu et al., 2017).

Interpersonal haptic communication systems are particularly beneficial for users with special needs, such as visual or hearing impairments. For example, deafblind users rely heavily on touch in their communication, and mediating touch over a distance would enable remote communication for them. In fact, early research in the field of haptics was largely focused on sensory substitution systems for individuals with visual and/or hearing impairment. Systems such as Tadoma (Reed et al., 1996), Teletactor (Gault, 1927), Vibratese (Geldard, 1957), Optacon (Linvill & Bliss, 1966), TVSS (White et al., 1970), and Tactuator (Tan & Rabinowitz, 1996) coded alphabetical and numerical information typically received via the visual and auditory modalities to haptic stimulation. Due to the recent developments in wearable technologies, mobile haptic aids can become more widely available.

Examples of recent research include work on sound-to-touch sensory substitution systems that are designed to convert audio recorded from the environment to vibrotactile stimulation presented with a vest (Novich & Eagleman, 2015). Neosensory Buzz is a commercial product that uses the same principle to present audio from the environment to a haptic band worn on the wrist.

In addition, the relationship to the toucher, cultural context, and other factors affecting tactile social interaction such as body area, gender, age and environments. To our knowledge, there has not been a thorough study related to touch throughout development from infancy to adulthood, passing through childhood and adolescence. Touch plays a vital role in child development (Frank, 1957). That said, there is a universal consensus that the older the child, the more funneled the tactile contact becomes with relatively small age variations based on the culture (Jones & Yarbrough, 1985). Kinships affect this dynamic even more, determining the area on the body considered acceptable for touch (Suvilehto et al., 2015). In adulthood, touching the whole body is considered off-limits to most kinships, including parents. Touch by mothers extends to larger body areas than fathers are allowed to touch, while touch by a stranger is only limited to handshakes. Overall, the social bond correlated highly with the total body area being touched. The stronger the bond the larger the area on the body (Suvilehto et al., 2015). Even between partners, touch dynamics change whether they are in a private or public space. These known limitations for the use of touch are important also from a remote touch point of view: understanding the context and the relationship between the sender and receiver of the touch is essential in order to evoke positive social experiences.

Finally, environmental, and cultural factors play a role in proxemic behavior. People living in cold areas such as Canada tend to have a larger personal space than those living in warm areas such as the South America. Dense populations such as India have lower expectations of personal space (Duby, 1992). Additionally, Hall made a distinction between high-contact cultures and noncontact cultures (Hall, 1966; Lustig and Koester, 1996). High-contact cultures are Latin American, Middle Eastern and southern European, where hugging and kissing are often daily interactions during conversations. These tactile demonstrations are less common or inexistent between North Americans, Northern Europeans, and Asians during conversations (Mazur, 1977; Høgh-Olesen, 2008) often limited to a handshake or a bowing. Such cultural differences will affect the uptake of different remote haptic technologies and should be considered while designing haptic systems.

### *Ethical Considerations*

Ethical considerations related to emerging technologies is a hot topic especially in the context of VR, cybernetics, and AI. With haptics, the discussion is almost nonexistent. As Boothroyd (2009) indicates, the ethical attention to our digital and cyber spaces is focused mainly on the visual dimension. The optimistic cheer for the potential of improving human lives while the pessimistic worry that these technological enhancements would lead to invasive situations on both privacy and psychological levels. Moreover, due to their cost, access to emerging technologies would only be limited to an elite audience increasing hence the gap of inequality within the society (Brenner, 2013). Haptic technology faces the same challenges and considerations as other emerging technologies.

Privacy remains one of the most important values for humans when it comes to technology. Similar to a webcam that can be activated at distance without the user's knowledge, a haptic device could be subject to hacking if it is connected through the internet. For instance, a device can trigger vibrations or pressure when they are not needed or desired, or without the knowledge of the person being touched. Our phones already vibrate, when we do not expect this, providing us with notifications. We accept those vibrations and we do not consider them as a privacy invasion. The context would be different if someone hacked your phone at a distance and triggered its vibrations without your consent. The context used would be completely different if someone were controlling a wearable haptic device on a part of your body. Birnbaum (2020) used the term “haptic spam” for situations where someone activates a haptic device without your permission. The worst-case situation would be a rape per deception, where a person can forcibly control a sex toy at distance (Sparrow & Karas, 2020).

The invasive nature of some external devices to extend or modify temporarily or permanently the human body begets some ethical, philosophical, and legal aspects about the nature of the invasion itself. The legal terminology is blurred as pointed out in a case study by MacDonald Glenn (2012), where an airline caused damage to a mobility assistive device (MAD) of an individual dependent on such system. The case was solved by a compensation agreement where the passenger and the MAD were perceived as a merged person. Despite being mostly out of the scope of the present article, similar problems will become more common if haptic technologies become interchangeable parts of the human communication abilities via human augmentation (Raisamo et al., 2019). Sensory restrictions enforced by the biomechanical structure of our skin and the mechanoreceptors therein may not be a limiting factor in the evolution of social touch. Concepts like cognitive touch, where the brain is artificially stimulated to allow physical and virtual interaction may become a future paradigm for tactile communication.

Although haptic technology will provide us with new ways of communicating with each other, these shared experiences are highly dependent on the social contexts and can provide a framework for the ethical issues raised above. The launch of the Metaverse space, where escapism (Han et al., 2022), harassment, and virtual groping (Falchuk, Loeb, & Neff, 2018) are growing, requires more research to establish digital ethics guidelines.

## Conclusions

The development of technology will allow better replication of real touch which will improve the quality of mediated social touch. This will enable focus on finer details of interpersonal communication and make it possible to reach a deeper understanding of mediated social touch. The emerging themes presented are expected to have an impact on advancing this field. Humans frequently use the sense of touch in their daily lives to promote prosocial behavior, intimacy, and social bonding. Consequently, mediating social touch over a distance has gained a lot of interest in the research community, but traditional vibrotactile stimulation methods are not optimal to convey either distinct, social, or affective qualities of touch.

A growing body of research suggests that humans benefit from the use of mediated touch in social and emotional contexts. Our elaboration of emerging research themes helps provide directions for researchers interested in emotional and social aspects of mediated touch or the latest technological developments of simulated touch. Still, the societal acceptability and accessibility of these technologies as well as ethical considerations related to privacy and social equality need to be considered. Within a few years, mediated social touch will be on the verge of becoming universally available, so research on this topic is timely and necessary.

## CRediT authorship contribution statement

**Roope Raisamo:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Katri Salminen:** Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing, Funding acquisition. **Jussi Rantala:** Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Ahmed Farooq:** Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing, Visualization. **Mounia Ziat:** Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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