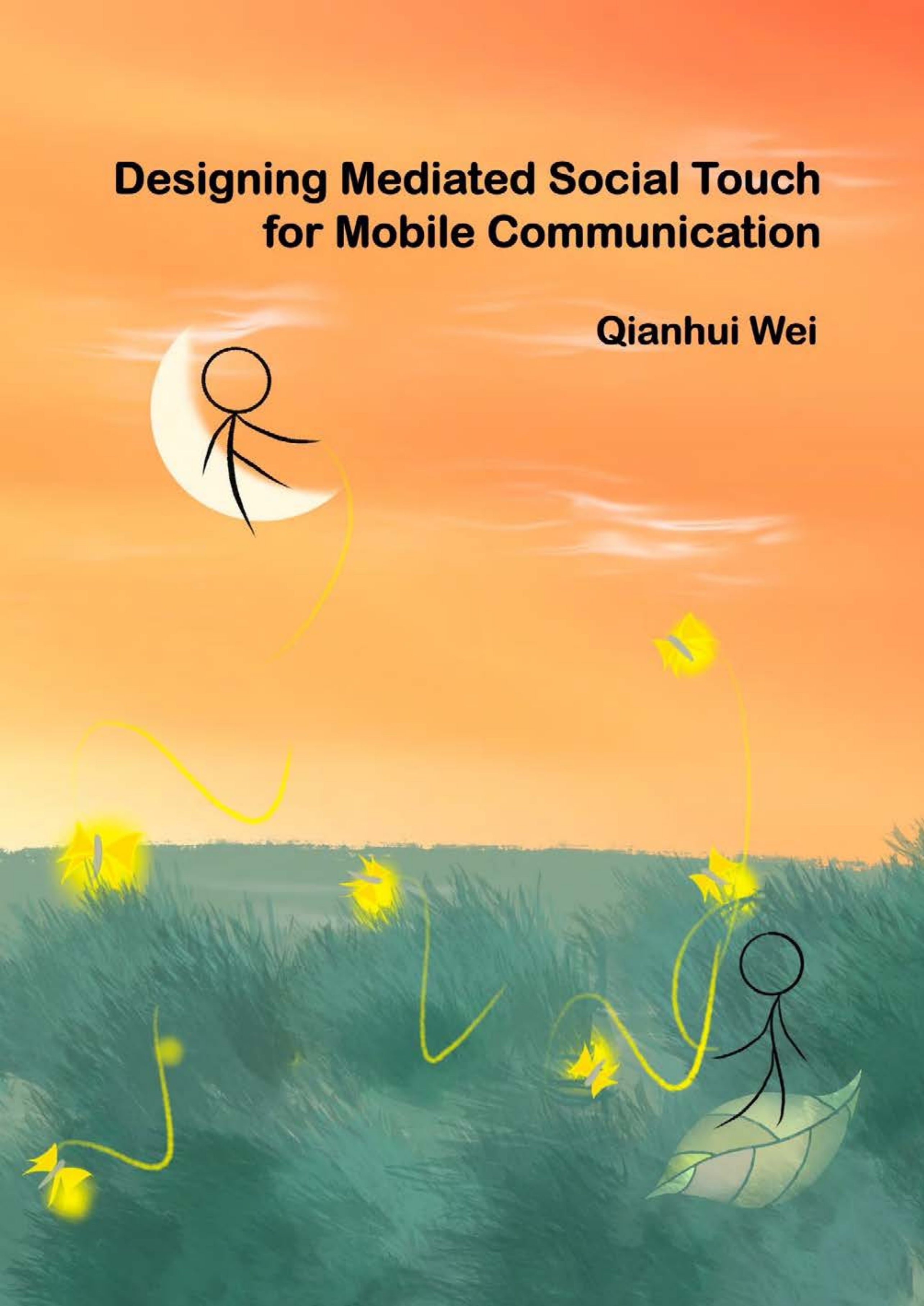
Designing Mediated Social Touch for Mobile Communication

Qianhui Wei



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PROEFONTWERP

ter verkrijging van de graad van doctor aan de Technische Universiteit Eindhoven, op gezag van de rector magnificus prof.dr. S.K. Lenaerts, voor een commissie aangewezen door het College voor Promoties, in het openbaar te verdedigen op dinsdag 28 november 2023 om 11:00 uur

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Qianhui Wei
geboren te Sichuan, China

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Het onderzoek of ontwerp dat in dit proefschrift wordt beschreven is uitgevoerd in overeenstemming met de TU/e Gedragscode Wetenschapsbeoefening.

Summary

Background:
Nowadays, remote communication is very common. In current remote communication, voice and video calls provide clear information. However, non-verbal cues, such as touch, are usually missing. It has been demonstrated that non-verbal cues are important in communicating emotions, sending quick information, and complementing verbal communication.

Touch is one of the non-verbal channels that we could consider in communication. Physiologically, compared to the visual and audio channels, touch can be reached over the whole body since it is mediated by the skin. Information received from touch is also processed fast, especially in evoking emotions.

Mediated social touch (MST) is a new form of communication that can support non-verbal cues and bring richer experiences to remote communication. Many researchers tried to transmit MST signals via different tools, such as mobile devices and haptic wearables.

Recent haptic technologies provide the potential for rendering MST signals. Different haptic actuators can render various haptic stimuli. However, many researchers focused on developing new prototypes to transmit MST signals. There is a lack of a generation method for MST signals.

The key elements of this Ph.D. project:
The key elements are from three aspects: technology, design, and application. From the aspect of technology, we choose the smartphone as a carrier, controlling one linear resonant actuator embedded in the smartphone to present MST signals. Our focus lies in users engaging with smartphones and interacting with touchscreens when designing MST signals.

Regarding design, we study how users perceive vibrotactile stimuli on touchscreens before broadening our focus from human-computer interaction to computer-mediated human-to-human interaction. We present a generation method for MST signals, incorporating key factors such as touch properties (e.g., pressure, duration, etc.). We design a rich set of MST signals.

As for application, we apply MST signals in an online social application to increase the social presence in mobile communication.

Objective:
The research objective is to investigate how MST could be expressed, perceived, and recognized for increasing social presence in mobile communication.

Methods and Results:
We conducted studies as follows to reach the objective:

1) *Literature Review (Chapter 2)*

We conducted a systematic review to comprehensively understand the state of the art of MST designs and evaluations for mobile devices. We explored which actuators, parameters, and prototypes researchers used to express and communicate MST signals with mobile devices and how they evaluated their designs. We also derived guidelines for future work. Based on those findings, we summarized the key elements from the aspects of technology, design, and applications for this Ph.D. research.

2) *Senders Expressing MST Gestures (Chapter 3)*

We conducted an elicitation study to explore how to express MST with hand gestures on a touchscreen. We collected touch properties such as pressure and duration, obtained different hand/finger movements, and resulted in a set of user-defined MST gestures. These findings guide the MST signal design (Chapter 5) and the application design (Chapter 6).

3) *Receivers Perceiving Vibrotactile Stimuli (Chapter 4)*

We present a generation method to instantiate a wide range of vibrotactile stimuli. We generate vibrotactile stimuli with various signal parameters, i.e., frequency, duration, envelope, superposition, and compound waveform composition (CWC). We explored how signal parameters affected the users in perceiving vibrotactile stimuli on touchscreens. We used graphic graphical buttons as the carrier. We conducted a user study to evaluate the perceived depth and roughness of the graphical buttons on the touchscreen, which would be connected to the skin deformation and pressure applied to the skin for MST gestures on touchscreens in Chapter 5.

Research results indicated that the selected frequencies, durations, and the designed CWC forms affected the users in perceiving vibrotactile stimuli. These signal parameters were adjusted for the design of MST signals in Chapter 5.

4) *Receivers Recognizing MST Signals (Chapter 5)*

We present a generation method for MST signals based on the generation method proposed in Chapter 4. We created the vibrotactile stimuli in Chapter 4 with the touch properties presented in Chapter 3 to represent MST gestures. We adjusted the parameters (i.e., frequency, duration, and CWC forms) for MST signals based on the touch properties. The generation method resulted in a set of MST signals. We conducted user studies to explore to which extent users could recognize these MST signals.

The research results showed that around 70% of designed MST signals could be recognized above a precision of 25%, which was two times better than the random recognition rate. These concrete measures gave us insights into designing and applying MST signals on mobile phones for future applications. The generated MST signals were selected for the experiment with online communication in Chapter 6.

5) *MST Communication Between Senders and Receivers (Chapter 6)*

We applied MST signals suggested in Chapter 5 in a mobile communication application for texting and video calls. We conducted a user study to evaluate if social presence could be increased with MST signals in mobile communication.

We found that adding vibrotactile stimuli to MST gestures helped to increase social presence in the aspects of co-presence, perceived behavior interdependence, perceived affective understanding, and perceived emotional interdependence. Adding vibrotactile stimuli to MST gestures caused no significant differences in attentional allocation and message understanding. There was no significant difference between texting and video calling when applying MST signals in mobile communication. The qualitative data analysis showed that participants thought MST gestures with vibrotactile stimuli were interesting, and they were willing to use them in mobile communication, but the application design should be iterated based on their feedback.

In general, this thesis mainly explored how MST can be expressed, perceived, and recognized for increasing social presence in mobile communication. We obtained a user-defined MST gesture set on smartphone touchscreens and collected touch properties to guide MST signal design. We proposed a generation method to design MST signals and apply these signals in mobile communication. We also derived design guidelines and implications, which could guide the future design of MST signals and applications for mobile communication.

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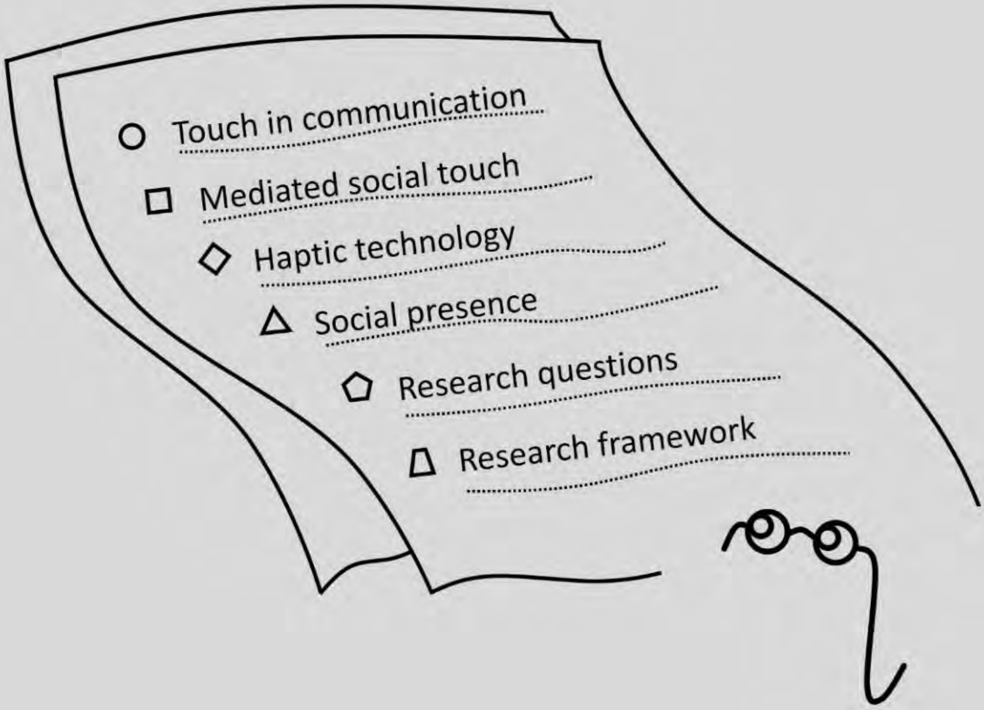
Chapter 1

Introduction



1.1 Background

1.1.1 Touch in remote communication

Nowadays, remote communication is very common. In current remote communication, voice and video calls provide clear information. However, non-verbal cues, such as touch, are usually missing. It has been demonstrated that non-verbal cues are important in communicating emotions [1], [2], [3], [4], sending quick information [5], and complementing verbal communication [5], [6], [7].

Body patterns, facial expressions, and touch are typical non-verbal channels in communication [6]. The advanced webcam telecommunication technology can display body patterns and facial expressions well by video-based telecommunication. The touch channel is still a new and popular research field for remote communication. With the development of haptic technologies, researchers could design haptic stimuli for the touch channel. There are many design opportunities in this field.

In this research, we choose touch as the carrier in remote communication for the following reasons:

- Touch is an important modality for communicating emotions [2], [3], [6], [8], [9] because specific receptors processing affective touch exist in human skin [3].
- Touch processes information fast in evoking emotions. Touch could evoke emotions immediately because of the interceptive quality. It takes more time for the audio and visual cues to evoke emotions because further inferences and embodiment are needed [10].
- Touch can be reached over the entire body [11] since it is mediated by our largest organ – skin [12] while other senses are localized around specific parts of the body [11]. There are many design opportunities when considering different parts of the body for remote touch transmissions.
- There are challenges in face-to-face physical interactions in some contexts. Some researchers find that computer-mediated communication may avoid dysfunctional social-psychological influences in face-to-face interactions and create a forum conducive to public deliberation [13]. Some people with a high level of loneliness prefer smartphone-mediated communication to face-to-face communication [14].

In this research, we consider focusing on touch to complement non-verbal channels and increase social presence in remote communication.

1.1.2 Mediated social touch in mobile communication

Mediated social touch (MST) means ‘the ability of one actor to touch another actor over a distance by means of tactile or kinesthetic feedback technology’ [15], which is a new form of non-verbal cues in remote communication [4], [16]. We choose smartphones as the carrier to transmit MST signals in this Ph.D. research for the following reasons:

1) Smartphones are the most popular non-wearable device people would like to use for MST signal transmission [16].
2) Smartphones can be a platform to provide different asynchronous and synchronous applications such as video calls, voice calls, emails, and text messaging. These applications are difficult to implement with wearables such as gloves and jackets.
3) Physiologically, fingertips have the highest density of receptors, adding up to 250 receptors/cm^2 [17]. Compared to using wearables on whist such as smartwatches, users may perceive richer haptic feedback when using fingers interacting with smartphones.

Researchers have designed various prototypes for mobile devices to transmit MST signals. For example, CheekTouch [18], [19] could share touch patterns such as tapping, sliding back and forth, slapping, kissing, and tickling during a phone call. Teyssier et al. [20] designed MobiLimb, which could be installed on a mobile phone. It could provide some MST gestures, such as stroking and patting the user’s hand or wrist, conveying emotions. ForcePhone [21] helped users express greetings, presence and emotions through tactile messages. Park et al. [22] designed Bendi to provide hand-to-hand interaction with pleasant tactile feelings and movement representations. The haptic interface – KUSUGURI [23] provided a channel for users to tickle each other. Hashimoto et al. [24] designed high-fidelity tactile displays which could send MST signals such as tapping, tickling, pushing, and caressing.

Most researchers designed these prototypes and evaluated the effectiveness of the design, but a generation method for the MST signals needed to be included.

In this Ph.D. research, we aim to provide a generation method for MST signals on smartphones and design a rich set of MST signals.

1.1.3 Haptic technologies in mobile devices

Haptic technology is important in implementing MST signals via smartphones. Researchers used different haptic actuators to render MST signals. Examples of different actuators are as follows:

1) Servo motors can rotate to specific positions [20], [25]. For example, MobiLimb [20] provides stroke, pat, and other touch signals by five servo

motors. Kissenger [26] applies an array of linear servo motors to generate normal forces on the skin surface.

2) Shape memory actuation (SMA) coils can change the shape of a surface. For example, Bendi [22] uses six coil-type SMAs to provide different movements. Researchers use a joystick to control the shape change of this prototype when electrical signals flow on the specific SMAs [22].
3) Linear vibration motors [27], [28], DC motors [29], and eccentric motors [30], [31] are also popular haptic actuators to provide MST signals such as squeezing, tapping, stroking, and flicking. For example, Singhal et al. [27] provide touch feelings by controlling an array of 12 linear resonant actuators and creating a linear sequential vibration pattern.

Most studies apply more than one actuator when presenting MST signals, but it is not practical to embed many actuators in a smartphone. For our research purpose, it would be more convenient if we studied on a smartphone embedded with one haptic actuator rather than adding extra actuators, allowing users to send and receive MST signals.

1.1.4 Social presence

Social touch can elicit the feeling of social presence [4]. Social presence describes the degree to which a user is perceived as real [32], [33], [34] and with access to intelligence, intentions, and sensory impressions [35].

Applying haptic stimuli is a popular and useful way to increase social presence and convey more affective information in mediated social interaction [4], [32], [36] during phone calls, video conferencing, and text messaging [4]. For example, some researchers have applied haptic stimuli for mediated social interaction in a collaborative environment to increase social presence [37], [38], [39], [40], [41].

However, very few studies focused on applying MST signals on smartphones for social presence. In this research, we consider exploring the social presence under a specific context.

1.2 Research questions

In this research, we try to increase social presence in mobile communication by MST signals.

This thesis mainly addresses the following research question: *How could MST be expressed, perceived, and recognized for increasing social presence in mobile communication*? We divide this research question into several specific research questions.

For conveying MST signals through smartphones, we first need to know how users express MST with hand gestures on smartphone touchscreens, and we need to collect related touch properties such as pressure and duration. The research question about expressing MST gestures is as follows:

RQ1: How to express MST with hand gestures on a touchscreen?

As we use the smartphone as the tool and apply a linear resonance actuator to provide vibrotactile stimuli, we need to understand how users would perceive the vibrotactile stimuli and how it would be affected by signal parameters. The research question about perceiving vibrotactile stimuli is as follows:

RQ2: How do signal parameters affect the users in perceiving vibrotactile stimuli on touchscreens?

After understanding how to express MST gestures and perceive vibrotactile stimuli, we start to create vibrotactile stimuli with touch properties. We need a generation method. We try to design vibrotactile stimuli that can represent MST gestures. The research question about designing MST signals is as follows:

RQ3: To which extent could users recognize the designed MST signals?

After designing MST signals, we would apply them in mobile communication to enhance the feeling of social presence. The research question about applying MST signals for mobile communication is as follows:

RQ4: Can MST signals increase social presence in mobile communication?

1.3 Thesis outline

Figure 1.1 describes the detailed thesis outline. In this thesis, we first present a literature review in Chapter 2 to have an overview of the designs and evaluations of MST signals with mobile devices. We explored which actuators, parameters, and prototypes researchers used to express and communicate MST signals with mobile devices and how they evaluated their designs. We also derived guidelines for future work. Based on those findings, we summarized the key elements from the aspects of technology, design, and applications for this Ph.D. research.

Chapters 3 – 6 present the designs and evaluations from four aspects: senders expressing MST gestures, receivers perceiving vibrotactile stimuli, receivers recognizing MST signals, and MST communication between senders and receivers (Figure 1.1).

Chapter 3 addresses RQ1. We conducted an elicitation study to explore the user-defined MST gestures on a touchscreen. We collected touch properties such as pressure and duration of each MST gesture, obtained different hand/finger movements, and resulted in a set of user-defined MST gestures. These findings guided the MST signal design (Chapter 5) and the application design (Chapter 6).

Chapter 4 addresses RQ2. We present a generation method to instantiate a wide range of vibrotactile stimuli. We generate vibrotactile stimuli with various parameters, i.e., frequency, duration, envelope, superposition, and compound waveform composition (CWC). We use a graphical button on the touchscreen as the carrier. We conducted a user study to evaluate the perceived depth and roughness of the graphical buttons on the touchscreen, which would be connected to the skin deformation and pressure applied to the skin for MST gestures on touchscreens in Chapter 5. A user study was conducted to evaluate the designed vibrotactile stimuli. We found that the selected frequencies, durations, and the designed CWC forms affected the users in perceiving vibrotactile stimuli. We will adjust these parameters to design MST signals in Chapter 5.

Chapter 5 addresses RQ3. We provide a generation method for MST signals based on the generation method proposed in Chapter 4. We try to create the vibrotactile stimuli in Chapter 4 with the touch properties presented in Chapter 3 to represent MST gestures. We adjusted the parameters (i.e., frequency, duration, and CWC forms) for MST signals based on the touch properties. The generation method resulted in a set of MST signals. User studies were carried out to evaluate these MST signals. The research results gave us insights into designing and applying MST signals on smartphones for future applications. The MST signals would be selected for the experiment with online communication in Chapter 6.

Chapter 6 addresses RQ4. The MST signals suggested in Chapter 5 were applied in a mobile communication application for text messaging and video calls. We conducted a user study to evaluate the application. The results show that applying MST signals increases the social presence in the aspects of co-presence, perceived behavior interdependence, perceived affective understanding, and perceived emotional interdependence between people in remote communication.

Chapter 7 summarizes the answers to research questions addressed in this research, and discusses the limitations, future work, and contributions.

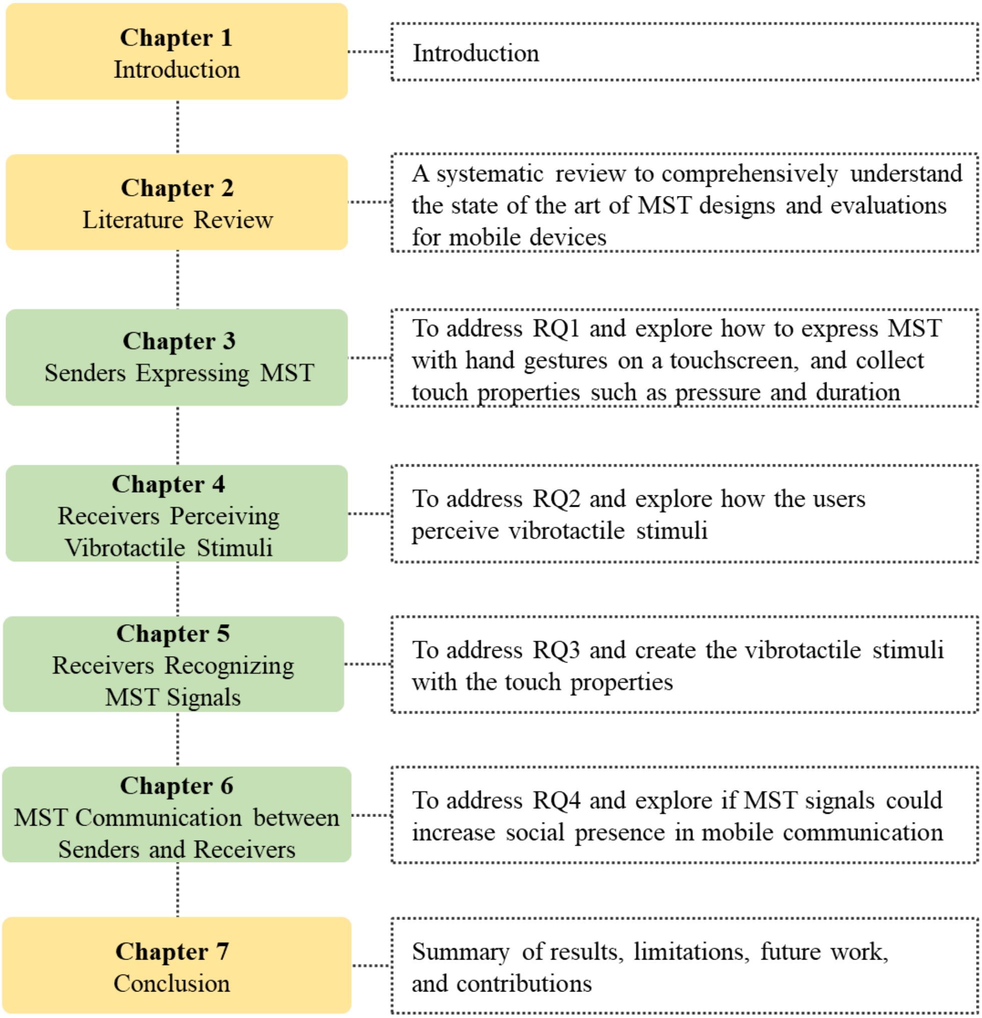
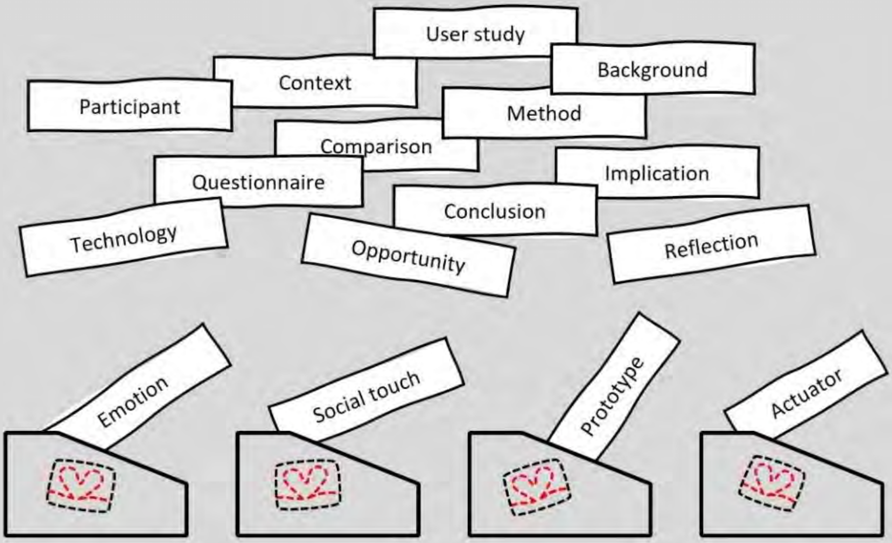


Figure 1.1 The framework of this thesis

Chapter 2

Literature Review



This chapter is based on:
Q. Wei, M. Li, and J. Hu, "Mediated Social Touch with Mobile Devices: A Review of Designs and Evaluations," *IEEE Transactions on Haptics*, pp. 1–20, 2023.

Abstract

Background: Mediated social touch has been widely studied for remote affective communication in the field of human-computer interaction.

Goal: We conducted this literature review to comprehensively understand the state of the art of the designs and evaluations of mediated social touch for mobile devices.

Methods: We selected 52 articles based on related keywords from four main digital libraries, i.e., ACM, IEEE, Springer, and Scopus.

Results: We summarized from these articles how mediated social touch signal is designed, prototyped, and evaluated, and what the main research findings are. Based on the analysis, we identified opportunities for later work.

2.1 Introduction

Mediated social touch (MST) is a new form of remote affective communication [28]. New advanced haptic technologies and new applications make this field flourish. Jarzyna [42] indicated that the explosion of digital media in the recent two decades augments the fulfilment of real relationships with para socialization. Moreover, the COVID-19 quarantine in recent years restricted real socialization [42] and isolated people more [43]. Many researchers have done research to compensate for the lack of real touch in an isolated situation [44].

Advanced touch technologies in new actuators make MST possible. For example, linear resonance actuators (LRA) can help people feel the flexing of the remote partner's finger touch effects by controlling a linear sequential vibration pattern [27]. Piezoelectric actuators [45] can be embedded in a touchscreen to provide friction. Tpad can create the perception of force, shape, and texture on a fingertip [46]. Mullenbach et al. [45] demonstrated that affective communication through this variable-friction Tpad was possible.

The current mobile communication applications (e.g., text, voice calls, video calls, et al.), and remote collaborative tasks for remote users can all be enhanced with the compensation of real touch. Many researchers developed prototypes to transmit MST signals in remote communication. For example, Kissgener [47], [26], CheekTouch [18], [19], KUSUGURI [23], MobiLimb [20], POKE [48], SansTouch [49], and SqueezeBands [37] can create effects of kiss [47], [26], [18], [19], tickle [18], [19], [23], [48], stroke [20], pat [48], poke [48], handshakes [49], and squeeze [37] in daily interpersonal communication and collaborative tasks.

Many researchers have conducted literature reviews in the MST fields. For example, Eid and Osman [50], Huisman [36], and van Erp and Toet [4] reviewed affective haptics and haptic technologies for social touch in human-computer interaction. They summarized the applications for social touch (e.g., affective haptics in social interaction, healthcare, gaming and entertainment, human-robot interaction, etc.), and the effects of social touch (physical, emotional well-being attachment, bonding, behavior changing, etc.). Culbertson et al. [51] studied artificial touch, introduced different haptic interfaces, and discussed integration with virtual and augmented reality.

These reviews have provided a detailed overview of MST in human-computer interaction. We still found most of them discussed mobile devices, wearables, virtual agents, and other haptic devices together. However, the technologies and psychophysics theories could be different when the haptic stimuli work on different body parts.

In this chapter, we focus on mobile devices since Rognon et al. [16] have found that mobile devices (e.g., cell phones and tablets) are popular devices that users use to communicate social touch. We want to explore which actuators, parameters, and prototypes researchers use to express and communicate MST signals with mobile devices and how they have evaluated their designs. We also want to derive guidelines for future work.

2.2 Methods

2.2.1 Literature search

We mainly searched literature from the following databases: ACM digital library, IEEE Explore, SpringerLink, and Scopus because they provided important journal and conference papers in the intersection of social computing and touch technology [52].

We chose keywords for search from three aspects: technology, goal, and carrier (Table 2.1).

Table 2.1 Key Words for Literature Search

Categories	Detailed key words
Technology	Haptic, tactile, vibrotactile, vibration
Goal	Goal 1 (touch): mediated social touch, remote touch, social touch, touch gesture
	Goal 2 (communication): social communication, remote communication
	Goal 3 (emotion): affective communication, emotion
Carrier	Smartphone, touchscreen, mobile device, tablet, phone, mobile surface

For keywords in Goal, as touch communicates emotions [8] and haptic stimuli can be used for remote affective communication [50], we chose three goals: touch, communication, and emotion (Table 2.1).

The detailed Boolean search string is as follows:

("haptic" OR "vibrotactile" OR "tactile" OR "vibration") AND ("mediated social touch" OR "remote touch" OR "social touch" OR "touch gesture" OR "social communication" OR "remote communication" OR "emotion" OR "affective communication") AND ("smartphone" OR "touchscreen" OR "mobile device" OR "tablet" OR "phone" OR "mobile surface").

We followed the PRISMA flow chart [53]. We followed four steps to select articles (Figure 2.1).

In step 1, we used the above-mentioned Boolean search string in each database.

In step 2, we limited the time in the recent 15 years from January 2008 to August 2022, as researchers started to study MST signals and gestures on mobile devices around 2008. We mainly included research articles (journal and conference papers). We excluded reviews, monographs, abstracts, posters, demonstrations, surveys, tutorials, notes, index, introductions, invited talks, keynotes, prefatory, books, reference work entry, reference work entries, protocols, and papers in a non-English language.

In step 3, we conducted title and abstract screening. We chose papers meeting our needs. This means the chosen paper was for at least one of our goals, using touch technology and mobile devices. We also added some papers from other resources.

In step 4, we conducted careful screening. We read the whole paper and made sure the article met our needs.

2.2.2 Article selection

During the careful screening phase, we found many researchers developed new prototypes for mobile communication. We needed to clarify the criteria for these prototypes. The inclusion criteria had the following considerations:

- The prototype should be hand-held. Devices with big sizes are excluded. For example, the balloon-like haptic device in [54] is too big to hold in hand.
- The shape and size are similar to mobile devices [55]. Or the prototype could be imagined as mobile devices [56], [57], [58], [59], [60].
- Although the prototype may not look like a handheld one, the authors mentioned the prototype was developed for mobile communication [25].
- When wearables are used together with the mobile device, the haptic stimuli should present to hands [27], [49], [37] rather than wrists [61], [62] or shoulder [63], or other body parts [64], [65], [66], [67], [68], [69], [70], [71] because the density of tactile sensors in the skin over the entire body is different [72], [73]. We need to limit the research area to the hand to facilitate the later discussion.
- Some studies used computers for video calls and haptic prototypes for remote

touch transmission. These studies could be included because we could use a mobile device to replace the computer for video calls, e.g., Skype for video calls on mobile phones [27], [19]. The results of these studies are meaningful in MST for mobile devices.

We also found two types of studies: computer-mediated human-to-human interaction (HCH), which in our case involved mobile devices, and human-to-computer interaction (HC), also carried out using mobile devices. For HCH studies, researchers mainly tried to transmit MST signals via mobile devices in remote communication. One dyad is needed in the HCH studies. For studies such as [74] and [75], some participants were asked to create emotional expressions on a mobile device, and other participants were asked to recognize user-defined emotional expressions after a while. Although the communication is not real-time, we kept these studies for further analysis since there is an expressing and perceiving process from one dyad.

For HC studies, researchers primarily designed haptic stimuli for emotional expressions and tested the perceiving of haptic stimuli when one participant interacted with the mobile device. Although it seems no dyads were in HC studies, we still included them in this chapter because of the following reasons:

1) Participants interact with the mobile device and perceive the haptic stimuli conveying emotional expressions. It can be assumed that the haptic stimuli are sent by other people. For example, we could assume that the researcher customizes the haptic stimuli with intended expressions and sends them to the participants to perceive.
2) The research results were meaningful for future HCH studies. For example, Yoo et al. [76], and Salminen et al. [77], [78] tested how the designed haptic stimuli represented emotional expressions. These haptic stimuli could be directly applied in an application for social communication. The research field can easily broaden from HC to HCH.

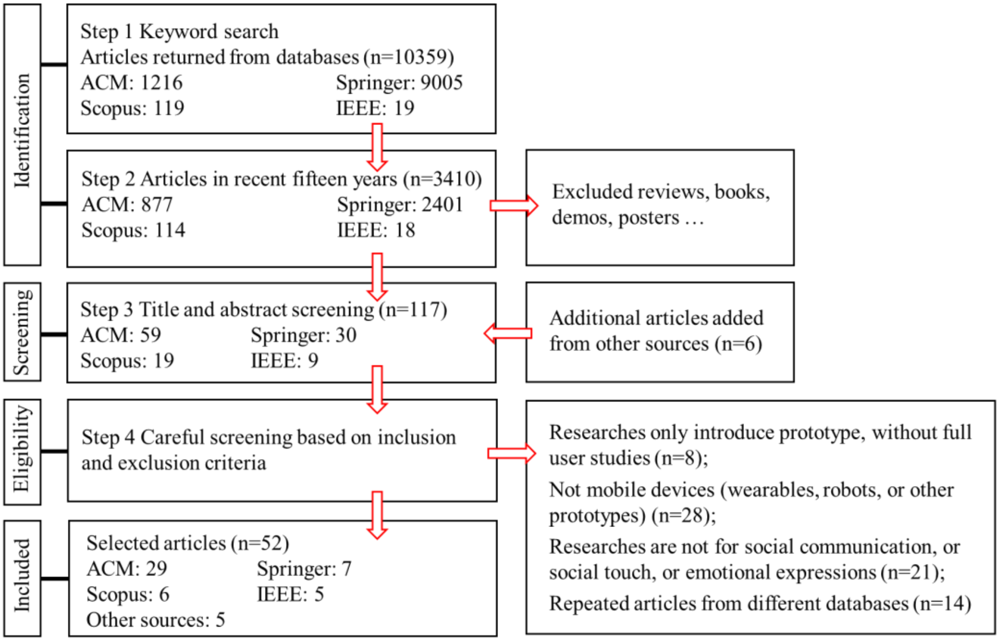


Figure 2.1 The flow chart and detailed steps for literature search

2.3 Results

We selected 52 articles for further analysis. Figure 2.1 shows the search results in each step. The **Appendix** shows detailed information about these selected articles.

2.3.1 Design: from haptic input to haptic output

This section summarizes the typical haptic input and output found in the selected papers. We also study how researchers set parameters for haptic stimuli based on the selected actuators to express certain social touch.

2.3.1.1 Typical haptic input

There are two types of haptic input signals: pre-defined signals and real-time generated signals. Figure 2.2 shows a summary of typical haptic input and output.

Researchers usually set parameters (e.g., frequency, amplitude, envelope shape, envelope frequency, waveform, etc.) for pre-defined signals, and users receive the preset haptic stimuli. For example, Shiraga et al. [55] used 85 pre-defined haptic stimuli with various accelerations, intensities, and voltages and quantified how those haptic stimuli affected users' impressions. Choi et al. [79] defined protruded dots as tactile emoji for visually impaired people to perceive.

The real-time signals can be generated based on the social touch properties (e.g., pressure, duration, gesture patterns, etc.) [80], which means, for example, when one user applies changing pressure during a touch, the other can feel the real-time changing pressure by haptic signals. We summarized four main types of haptic input for the real-time generated signals: touch gestures, shape change, joystick, and graphic user interface (GUI).

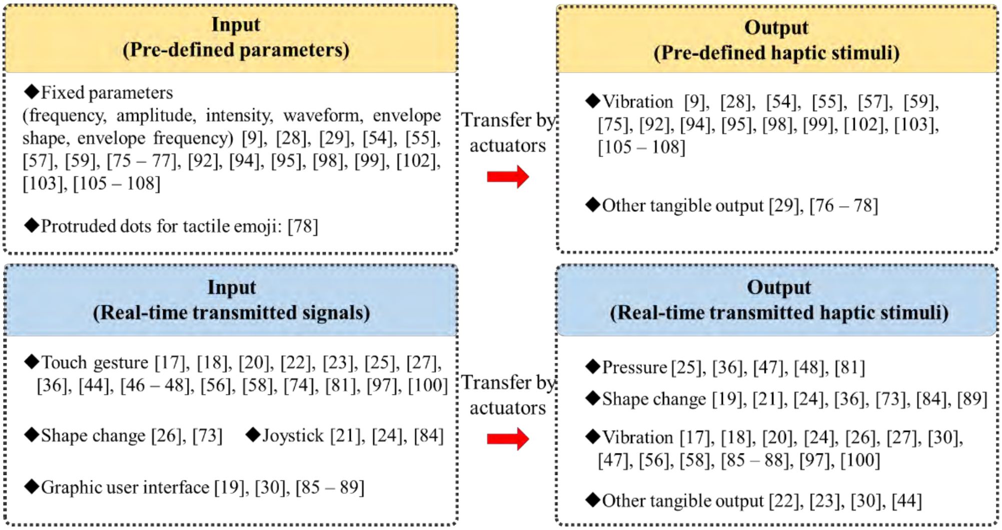


Figure 2.2 Typical haptic input and output

1) Touch gestures

We found that researchers mainly converted collected sensor signals from different sensors to haptic stimuli. Some researchers mainly used force sensor resistors (FSR) to collect the force data and convert it into haptic stimuli via different actuators. For example, Kissenger [47], [26] applied FSR to collect the user's force when kissing, transferred the force data, and presented the force with stepper actuators (Figure 2.3(a)). The converting equations can be found in [81]. Other studies that apply FSR to collect force data are [28], [48], [57], [59], and [21]. Besides FSR, Zhang et al. [49] developed an Android application to detect the movement of touch on the mobile phone and converted the collected data to haptic stimuli. Zhang et al. [82] used a silicon surface with an airbag for social touch input (Figure 2.3(b)). The force applied to the silicon surface is measured by the air pressure change of the airbag [82].

Some researchers converted audio signals to haptic stimuli. For example, Furukawa et al. [23] developed a tactile screen for bidirectional tickling (Figure 2.3(c)). They used an audio signal to provide proportional modification of the velocity of the index finger movement on the screen [23]. Two audio amplifiers were applied to drive the vibrators embedded in the tactile screen. Other examples that convert audio signals to haptic stimuli are [18], [19], [83], and [84].

Other researchers applied more than one type of sensor (e.g., force sensors and acceleration sensors.) to collect various signals and convert them into haptic stimuli. For example, the prototype in [24] has a force sensor and an acceleration sensor. The value of force and acceleration were sent to a control box with a microprocessor and stereo amplifier. This control box converted the collected sensor data into haptic stimuli.

2) Shape change

Researchers usually applied flex sensors embedded in the haptic device to detect the shape parameters, such as the amount of flex. For example, Strohmeier et al. [74] designed a shape-changing interface to communicate emotions (Figure 2.3(d)). The shape parameters of this interface are convexity, angle, radius, axis, granularity, speed, area in motion, and amplitude of motion [74]. Users could create shapes with different shape parameters to express various emotions [74]. Besides, Singhal et al. [27] also converted shape parameters into other haptic stimuli. For example, the Flex glove developed in [27] could provide vibrotactile stimuli by an LRA based on the signals collected from flex sensors.

3) Joystick

Researchers developed haptic devices with joysticks and used the joystick for movement input. The joystick input values could be read, usually through a Bluetooth module [25], [22], [85] connected to a computer. For example, Park et al. designed Wrigglo [85], controlled by joysticks attached to a phone case (Figure 2.3 (e)). Users could manipulate the joystick to control the directions of the other joystick attached to the other user's phone case.

4) GUI

Researchers developed mobile applications in which users could customize the touch signals and send the touch signals to the haptic device [20], [86], [87], [88], [89], [90]. For example, Jowalski et al. [87] developed Cubble with a haptic device and a mobile application. Users could send touch signals such as nudging, tapping, and holding hands to the haptic device from the mobile application (Figure 2.3(f)) [87].

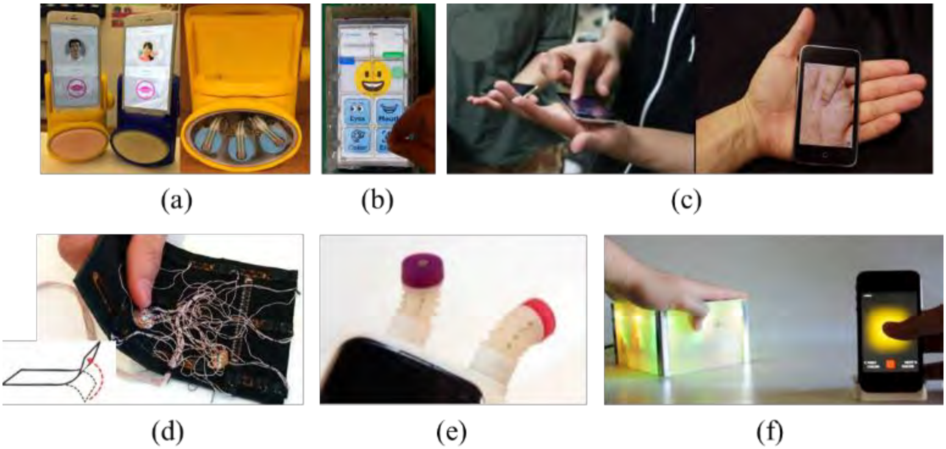


Figure 2.3 (a) Kissgenger with stepper motors [26]; (b) In-Flat with airbags [82]; (c) KUSUGURI [23]; (d) A shape changing interface [74]; (e) Wrigglo with joysticks [85]; (f) Cubble with vibration actuators [87]. Figures are from the corresponding literature.

2.3.1.2 Typical haptic output based on different actuators and parameters

Shape change, pressure, vibration, other tangible output are typical haptic output. We describe how typical actuators can render them in selected papers. The **Appendix** shows actuators and related parameters for presenting social touch.

1) Shape change

The mechanical arm motion of an arm-like haptic device could control shape change. For example, Suzuki et al. [90] controlled a two degrees of freedom (DOF) arm with haptic motors to present stroking and patting (Figure 2.4(a)).

Haptic actuators such as servo motors, allowing specific positions [20], can control the shape change. For example, five servo motors are arranged in MobiLimb to provide 5-DOF [20], for creating social touch such as stroking, patting, and other tactile stimuli on the hand or wrist to convey emotions (Figure 2.4(b)) [20].

The shape memory alloy actuation (SMA) coil can also control the shape change. For SMAs, there are solid-state phase transformations when heated, leading to macro-scale shape changes [37]. For example, Bendi applied six coil-type SMAs [22]. Users can use a joystick to control the shape change of Bendi, which supports bending, tilting, and shrinking movements when electrical signals flow on the specific SMAs (Figure 2.4(c)) [22].

2) Pressure

Stepper motors allow a surface to extend and contract linearly to present the touch and pressure [26]. For example, an array of linear stepper motors in Kissenger [26] can generate normal forces on the skin surface by changing the shape and positions of the Kissgener surface (Figure 2.3 (a)).

Inflatable airbags could generate pressure. For example, Zhang et al. [49] designed SansTouch to reproduce skin-like touch sensations. They applied inflatable airbags in a wearable hand sleeve that can generate touch pressure on the user's hand (Figure 2.4 (d)) [49].

SMAs can also create pressure. It has been demonstrated that forming SMAs into fully-compacted, tightly wound springs can produce significant forces [37], [15]. For example, Yarosh et al. [37] applied SMA compression in wearable gloves such as SqueezeBands to transmit MST signals.

3) Vibration

Vibrations are composed of vibrating components that deliver information through temporal parameters in the signals, such as amplitude, duration, carrier frequency, envelope shapes, frequency of envelope, and waveform compositions [91]. Thus, researchers usually directly choose the parameters of the vibration waveform to provide expected effects. For example, Wei et al. [92], [93] and Zhang et al. [94] applied an LRA, and they chose frequencies, durations, amplitudes, envelope shapes, and other temporal parameters to generate social touch for emotional expressions. An et al. [95] used vibration patterns from VibViz – a vibration library [96] with varying parameters, which could be presented by the Taptic Engine embedded in iPhone to express emotional expressions.

The voice-coil motor is another type of vibration actuator being used frequently. For example, Ju et al. [97] used a TECHTILE toolkit which contained voice-coil vibrators to provide vibrations. MacDonald et al. [60], Yoo et al. [76] (Figure 2.4 (e)), [98], and Wilson and Brewster [99] (Figure 2.4 (f)) applied the Haptuator actuator to the mobile device. Heikkinen et al. [76] (Figure 2.4 (g)) and Seifi et al. [27] applied the C2 actuator to the mobile device, using its audio output through an amplifier and providing vibrations for affective communications.

There are many other types of vibration actuators, such as Minebea Linear Vibration Motors (LVM8 [28], [57], [58], [59], [100]), DC motors [29], Eccentric motors, Eccentric rotating mass vibration motors [31], [30], [101], and other types in [55], [86], [87], [88], [89], [102], [103], [104], [105], [106], [107], [108]. The most common way to create a certain social touch in these studies is to control the temporal parameters.

4) Other tangible output

Various haptic systems and actuators, such as electrotactile systems, ultrasonic systems, and linear electro-mechanical actuators, provide other tangible outputs for touch sensations.

The electrotactile system can generate touch sensations by passing a small electric current through the skin [91]. Usually, researchers control the current and voltage of the related piezoelectric and electromagnetic actuators, to produce certain social touch (e.g., tickling [23]) for emotional expressions [77], [78].

The ultrasonic system can also provide tactile sensation. For example, Hashimoto et al. [24] choose the frequency and the amplitude of the waveform to control the suction or pushing pressure of social touch gestures, which can transmit tickling, tapping, pushing, and caressing on their palms from the air (Figure 2.4(h)).

Linear electro-mechanical actuators can also provide tactile sensation. For example, the table version of EnPower [31] applied this actuator to provide a specific tactile pattern following the Braille protocol for the deafblind (Figure 2.4(i)).

Figure 2.4 (a) A haptic device presenting stroking and petting [90]; (b) MobiLimb with servo motors [20]; (c) Bendi with SMAs [22]; (d) SansTouch with inflatable airbags [49]; (e) A mobile phone with a voice-coil motor [76]; (f) Multi-moji, a mobile phone with a Haptuator [99]; (g) A haptic device with C2 actuators [76]. (h) A tactile display with ultrasonic system [24]; (i) EnPower table version with linear electro-mechanical actuators [31]. Figures are from the corresponding literature.

2.3.1.3 Mediated social touch

We summarize the MST gestures from the selected articles in Figure 2.5. For some studies designed with more than one touch gesture, we listed every social touch gesture in the corresponding category. For example, Brown et al. [30] designed stroke, tap, flick, and twist. We list them separately in Figure 2.5.

There are two types of social touch gestures: specific and non-specific. Specific touch gestures usually have names and definitions, such as “Tickle” and “Stroke”. Non-specific touch gestures do not have a specific name or definition. Researchers usually described the finger or hand motion [45] for non-specific touch gesture. For example, Mullenbach et al. [45] used the TPad tablet and developed Haptic Virtual Touch to make users see and feel the real-time finger path of the other user (Figure 2.6). They used ‘a haptic rendering of their partner’s finger’ to describe the non-specific tough gestures [45].

Figure 2.6 The TPad tablet [45].This figure is from [45].

We found that many studies designed touch signals for ‘Tap’, ‘Kiss’, and ‘Stroke’. The reason could be that users frequently used those social touch gestures in mobile communication. Another reason could be that those social touch signals are easy to design.

Some social touch gestures were less studied. For example, ‘Shake’ and ‘Flick’ were only studied by [100] and [30], respectively. One reason could be that users may seldom use these social touch gestures. Another reason could be technical limitations. For example, on the one hand, it is not easy for researchers to design ‘hold a finger’ since the mobile device is like a brick rather than a finger. On the other hand, if researchers only have vibration technology, it is not easy to use only vibration to express ‘hold a finger’.

Figure 2.5 also shows that researchers studied more specific touch gestures with haptic stimuli on mobile devices than the non-specific ones.

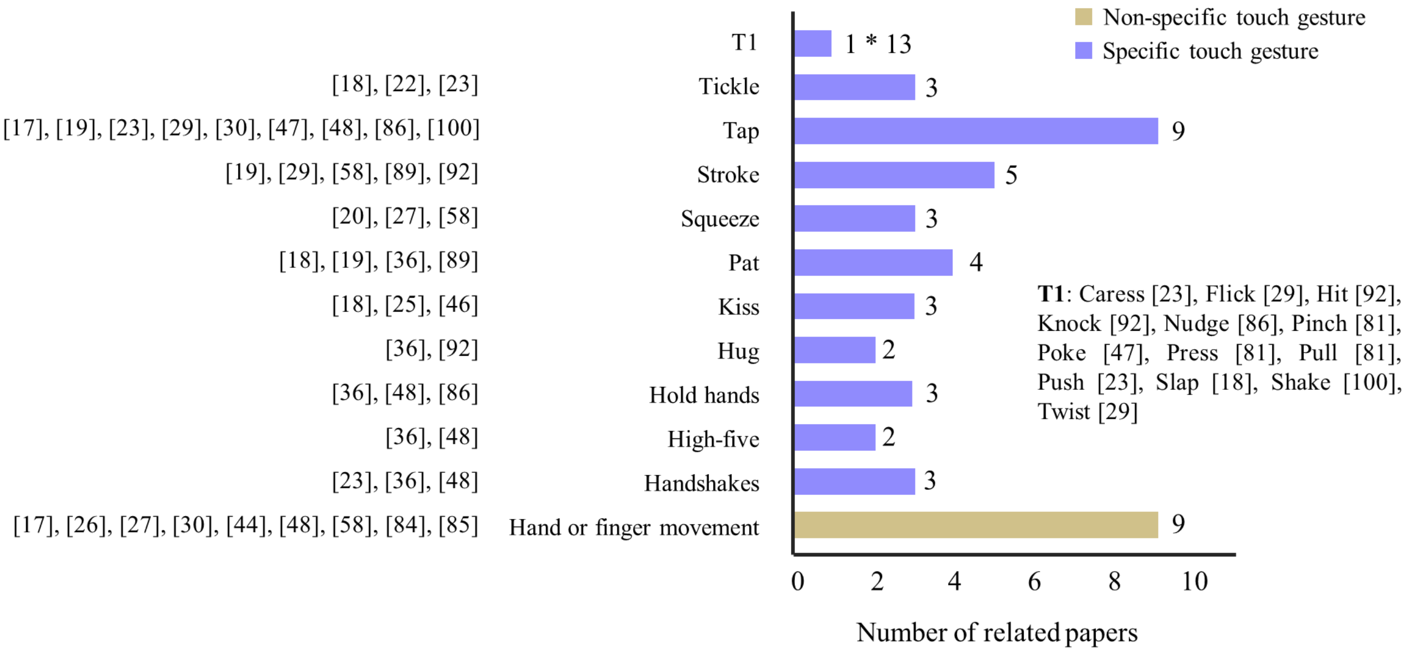


Figure 2.5 Overview of mediated social touch gestures studied in the selected papers. Thirteen MST gestures categorized as T1 were exclusively studied once across the relevant papers.

2.3.1.4 Emotion that social touch communicates

Hertenstein et al. [8], [9] have demonstrated that touch communicates emotion. MST gestures by haptic stimuli could also communicate emotion [28], [50]. For example, Ju et al. [97] developed a haptic prototype. They asked participants to perform different social touch gestures (e.g., tap, rub, press, etc.) to express emotions such as joy, anger, sadness, and relaxation.

We summarize the emotions that social touch communicates in Figure 2.7. For studies that use social touch to communicate more than one emotion, we listed every emotion in the corresponding category. For example, Réhman and Liu [29] tested Normal, Happiness, Surprise, and Sadness. We listed them separately in Figure 2.7.

We summarize the following two types of emotions that social touch communicates:

Dimensions. Many researchers designed MST signals to communicate emotions. But they did not refer to a specific emotion. Instead, they use the dimensions of emotion. These dimensions are arousal, valence, and dominance [109], approachability [110], agitation, liveliness, and strangeness [111].

Specific emotion. Some researchers directly design haptic stimuli to communicate a specific emotion. For example, Strohmeier et al. [74] and Ju et al. [97] specifically mentioned they design haptic stimuli for anger.

For emotion dimensions, there are several terms representing similar dimensions. Barrett and Russell [112] show the various sets of terms for the two-dimensional structure of affect. We need to integrate similar terms to simplify Figure 2.7. We integrated similar terms into one. We integrated the pleasantness and unpleasantness [28], [58], [77], [78], [102], positive and negative [22], [86], active pleasure and inactive pleasure [106] into the valence dimension based on [109], [113], [114], [115]. We integrated the calm [102] into the arousal dimension based on [115]. We integrated the weak and strong emotions [22] into the dominance dimension based on [116].

Figure 2.7 shows that most researchers used the emotion dimensions to describe an emotional feeling when the emotion is difficult to describe. The emotion dimension coordinate [109], [112] could clearly show what the haptic stimuli could communicate. For example, Yoo et al. [76] connected the parameters of haptic stimuli with emotional expressions so that they could quickly choose the parameters for haptic stimuli to communicate the targeted emotion.

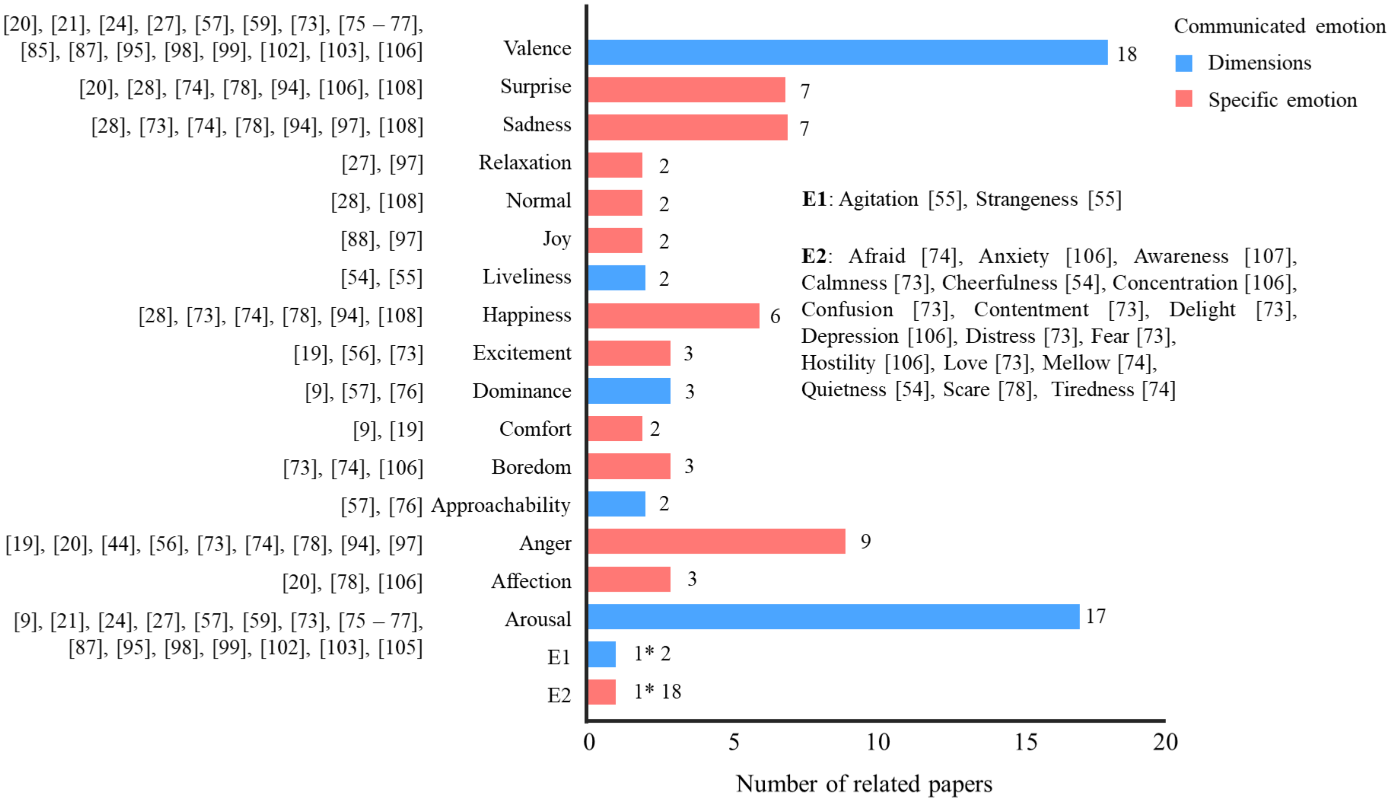


Figure 2.7 Overview of emotions that social touch communicates studied in the selected papers. Two emotions, categorized as E1, belong to the dimension category, while eighteen emotions categorized as E2, representing specific emotions, were each exclusively studied once across the relevant papers.

2.3.2 Prototypes

This section presents an overview of the prototypes that researchers developed to transmit and present MST signals as described in the selected papers. We summarize three prototype categories: integrated actuators, accessories, and connected devices (C1-C3).

2.3.2.1 Integrated actuators (C1)

In C1, researchers try to attach the actuators to a mobile device [18], [19], or make use of embedded actuators in the mobile device [45], [21], [95], [103] to present MST signals. Figure 2.8 shows typical examples of C1.

Related prototypes in C1 include Kissenger [47], CheekTouch (Figure 2.8 (a)) [18], [19], KUSUGURI (Figure 2.3(c)) [23], Multi-moji (Figure 2.4 (f)) [99], VibEmoji (Figure 2.8 (b)) [95], Haptic Empathy [97], PDA [106], CoupleVIBE [107], Shake2Talk [30], [101], iFeeling [29], [108], Pressages [21], TPad [45], emoji icons [92], [94], Nokia tablet [77], [78], Vivitouch [102], Nexus One (Figure 2.8 (c)) [103], PalmScape (Figure 2.8 (d)) [105], Bendi (Figure 2.4 (c)) [22], a haptic device expressing emotional intensity by gestures [75], a smartphone with a vibrotactile actuator [89], [98], a Pad-like touchscreen [76], [117], a mouse-like haptic device (Figure 2.8 (e)) [58], a shape changing device [74], a haptic device presenting protruded emoji for visually impaired people [79], and other handheld haptic devices (Figure 2.8 (f)) [55], [60].

The advantages of this type are as follows:

- The research results of the above-mentioned prototypes can be directly applied to future mobile phones when the technology is mature. The research results in these studies will also be meaningful at that time. For example, Yoo et al. [76] attached the vibration actuators on the back of the mobile phone (Figure 2.4 (e)), and they studied how the vibration parameters affect the emotional expressions of vibrotactile stimuli. Park et al. [18], [19] placed vibration actuators on a thin acrylic panel (Figure 2.8 (a)). The thin acrylic panel was attached to the mobile phone, which did not change the shape and the use of the mobile phone (Figure 2.8 (a)).
- Developing these prototypes is convenient and cheap because no accessories or connected devices are needed. If the mobile application enters the market, the user does not need to pay an extra fee for additional products.

Figure 2.8 Typical examples of C1. (a) CheekTouch with attached actuators [18], [19]; (b) An iPhone with an embedded Taptic Engine for VibEmoji [95]; (c) The Google developer phone Nexus One with an embedded vibration actuator [103]; (d) PalmScape with four vibration actuators [105]; (e) a mouse-like haptic device with vibration actuators [28], [57], [58], [59], and [100]; (f) a handheld haptic device with a vibration actuator [55]; Figures are from the corresponding literature.

2.3.2.2 Accessories (C2)

In C2, researchers designed accessories and attached them to the mobile device. Figure 2.9 shows typical examples of C2. Usually, the mobile device is used for verbal communication, such as voice calls and video calls, while the attached accessory is used to present social touch. For example, Zhang and Cheok [26] developed Kissenger and attached it to the mobile phone. Users use the mobile phone for voice or video calling when sending kisses by the attached Kissenger (Figure 2.3 (a)).

Related prototypes in C2 include Kissenger [26], MobiLimb [20], POKE [48], In-Flat [82], and Wrigglo [85].

There are differences between C1 and C2. The attached actuator in C1 could be embedded in the mobile device when the technology is mature. However, the accessories in C2 are not easy to embed in the mobile device, especially when the accessories are used to produce movements. For example, Teyssier et al. [20] developed MobiLimb and attached it to the mobile phone to produce certain movements (Figure 2.4 (b)). It is not easy to embed MobiLimb [20] in mobile phones.

The advantages of the attached prototype are as follows:

- These accessories are usually developed to be compatible with existing mobile phones. They could provide richer touch effects without changing the main body, the existing sensors, or the actuators of the mobile phone.

For example, POKE [48] can provide vibrations and force feedback by inflatable surfaces with air bumps (Figure 2.9). The force feedback cannot be presented by the mobile phone itself without the air bumps.

- Researchers could design various shapes and movements and choose suitable materials for the accessories to transmit MST signals. For example, the Kissenger [26], [81] was attached to the mobile phone. Users can send and perceive kissing via the attached Kissenge. The shape and materials of Kissenger make it more acceptable to touch the lips than a mobile phone. MobiLimb [20] is a small limb-like accessory which can be attached to a mobile phone. Users can modify the shapes and movements of the limb by controlling the angular position of servo motors to touch the user's hands or wrists. In-Flat [82] is an inflatable skin-like silicon overlay for smartphones, which consists of airbags (Figure 2.3 (b)). It could present various shapes of airbags and skin-like touch sensations with several complicity levels of the surface. Wrigglo [85] is an accessory attached to a mobile phone case (Figure 2.3 (e)). Users can manipulate the joystick of the phone case and make the Wrigglo shrink or bend in different directions.

Figure 2.9 Typical examples of C2: POKE attached to a mobile phone [48]; Figures are from the corresponding literature.

2.3.2.3 Connected devices (C3)

Researchers designed haptic devices that connected to mobile devices in C3. Mobile devices are generally for verbal communication [24], [22], [90] or customizing MST signals [86], [87], [31], while the connected devices are for presenting MST signals. Figure 2.10 shows typical examples of C3.

Related prototypes in C3 include Sphero mini (Figure 2.10 (a)) [86], little hands (Figure 2.10 (b)) [90], Cubble (Figure 2.3 (f)) [87], a ball-shaped device [24], Kissenger [47], a ring-shaped device (Figure 2.10 (c)) [88], EnPower [31], Flex-N-Feel [27], SansTouch (Figure 2.4 (d)) [49], SqueezeBands [37], and EMO [25].

There are differences between C3 and C2. The accessories need to be attached to a mobile phone in C2. However, it is not necessary to attach connected devices in C3 to a mobile device.

The advantages of connected devices are as follows:

- Researchers and designers have more opportunities to design a more anthropomorphic touch. For example, in [90], researchers directly develop a hand model (Figure 2.10 (b)) to send stroke and pat, which is very similar to real hands. SansTouch [49] and SqueezeBands [37] can provide the force of holding hands and handshaking. Flex-N-Feel [27] can make people feel the flexing of the remote partners' fingers.
- Connected devices can adapt to more mobile devices. For example, accessories such as the attached Kissenger [26] were limited to the smartphone because of its shape. It was no longer be helpful if users used a tablet with a bigger screen. However, the connected Cubble [87] can adapt to both smartphones and tablets (Figure 2.3 (f)).
- It can be applied to more target user groups. It is generally difficult for visually impaired people to contact others by mobile phone. Researchers could design various haptic devices based on their demands to touch others remotely and connect those haptic devices to mobile devices. For example, EnPower is designed for visually impaired people [31]. A special tablet and a wearable were designed and connected to a mobile phone for them to touch others remotely.

(a) (b) (c)

Figure 2.10 Typical examples of C3. (a) Sphero mini with a mobile phone [86]; (b) Two little hands with a tablet [90]; (c) a ring-shaped device with a mobile phone. Figures are from the corresponding literature.

2.3.3 Evaluation

We summarize the evaluation parts of the selected papers in terms of participants, experiment design, and data collection. Detailed information is in the **Appendix**.

2.3.3.1 Participants

There are four types of relationships among participants in the selected papers:

- Close relations (couples [28], [45], [47], [26], [18], [48], [21], [22], [87], [89],

[30] or friends [28], [27], [37], [85], [89], or family members [37])

- Strangers [45], [26], [23], [49], [37]
- Participant interacting with researchers [19], [55], [56], [57], [58], [60], [76], [77], [78], [79], [88], [90], [31], [97], [98], [99], [100], [29], [102], [103], [105], [106], [108], [117]
- Participant interacting with virtual agents [20], [59], [92], [94]

There are some notes when categorizing the relationship of participants. If the researchers mentioned the participants were couples or friends, we regarded them as close relations. If researchers did not mention those participants were known to each other, we regarded them as strangers.

For participants interacting with researchers, there are two types: 1) the researchers and the participants were engaged in real-time communication, such as [88], [90], [31]; 2) The researchers created haptic stimuli and participants perceived them.

2.3.3.2 Experiment design

We summarized five types of experiment design and test methods as follows:

With and without touch + other variables. In this type, researchers usually designed haptic stimuli for MST gestures and tested if adding the MST signals was beneficial for users. Besides the existence of MST signals [49], [95], researchers also considered other variables, such as gender [26], [90], emotion contexts [37], communication partner [45], temperature [99], environment [103], physical parameters [78], device types [26], multimodal feedbacks [19], [57], [78], [21], [88], [98] (study 3), and communication mode [47]. Usually, researchers used a mixed experiment design.

With touch + other variables. In this type, the haptic stimuli were presented to participants, and researchers tested other variables such as communication concept [87], emotion state [89], emotional intensity [75], gesture and role [28], gesture, actuators, and scenarios, preset haptic stimuli and communicated emotion (dimension) [97], [98], [29], [105], [106], [108], impressions [55], emoji [92], [94], meaning [60], design foundation [58], and message intention recognition [79].

Field study + interviews. In this type, participants usually joined a field study to try the new prototype for a longer term. After the field study, an interview was needed to express their experiences. For example, in Bales et al. [107] studied how couples use CoupleVIBE in their daily lives by inviting seven couples into a 4-week field study. Three couples used ForcePhone for Pressages for one month [21]. In [18], couples had a phone call using CheekTouch for 20 minutes per day for five consecutive days. Seven couples used Bendi to communicate for three days in the coffeehouse [22]. Three couples used POKE for one month [48]. Other examples are five days in [89], a four-week trial [95], a six-week trial in [26], and two weeks in [30].

Interviews. In this type, participants usually used the prototype during the user study and gave feedback about the user experiences. For example, participants in [57], [21], [85], [86], and [31] expressed their overall impressions and their points of view on the interaction about the new prototype. Free comments were also welcome during the interview in [28], [23], [20], [48], [49], [59], [82], [24], [22], [94], [107].

Semi-structured interviews were also popular. For example, in [27], besides the preference and emotions when using the glove, participants also answered how they would like to use the glove in their relationship. In [28], the sender was asked to choose which touch gesture was suitable for expressing each emotional intention. Other examples are [26], [87], and [100].

Varying parameters and corresponding haptic effects. In this type, researchers usually vary the parameters and test how participants perceive haptic stimuli changes. For example, Yoo et al. [76] set five amplitudes, five carrier frequencies, six durations, and six envelope frequencies for haptic stimuli. They explored how those parameters affect the affective ratings in the emotion model [76]. Besides, Salminen et al. [77] tested amplitude, rise time, and burst number of haptic stimuli. They explored if perceiving these haptic stimuli was significantly different in different contexts such as laboratory and bus travel [77]. Furthermore, Strohmeier et al. [74] tested how the shape parameters, such as the amount of bend or flex, affected the affective ratings in the emotion model. Other examples are [56], [60], [102], [117]. Those studies tested how parameters, such as frequency, amplitude, duration, waveform, duty ratio, and rhythms, affected the affective ratings in the emotion model.

2.3.3.3 Data collection

There are two types of data: objective data and subjective data. We summarize and list the collected data as follows:

There are three types of objective data:

- **Observation results**: behavior analysis [47], [23], speech turns – temporal structure of the dialogue, and touch behaviors – occurrence and duration [86], touch gestures [28], [100], [18], [49], shape gesture [74], haptic messages created by participants (gesture patterns) [59], verbal content [86], facial expressions [23], [29], [108] number of actions [90], attempted touch [37], and number of places tagged [107].
- **Recorded objective data**: working time [90], task speed [21], presage log [21], logged graphs and audio recorded data [48], logged content of each message (meaning type, color, and if applicable the tap pattern) [87], how many, when and by whom the message was sent [87], which device was used

[87], location of the contact area and intensity of the gesture [25], action, velocity and abruptness (gesture) [25], usage minute [48], gesture length [75], pressure [75], and speed message [75], reaction time [29], delay time [108], effectiveness (the success to failure ratio for task completion) [29], and movements (accelerometer, magnetometer, gyroscope) [100].

- **Calculated data**: error rate [21], [108], recognition accuracy [75], [74], [79], [108], and winning rate in games [26].

There are five types of subjective data:

- **Likert scale**:
  - ***Five-point Likert scale***: ease of use [45], fun [45], self-expression [45], understand partner [45], and how similar it was to the real touch [49]. Intimacy [27], emotional connection [27], closeness [87], appropriateness (doesn't fit at all and fits very well) [103], score the touch [19], feels like the specific touch [92], enhance the effect of text / stickers [92], and impressions [55].
  - ***Seven-point Likert scale***: enjoyment, boringness, and willingness to friendliness, trust, and authority [90], preference [20], useful [20], amusing [20], affectivity [47], co-presence[47], lively [56], agitating [56], strange [56], satisfaction (comfort and acceptability) [29], [108], easiness [100], understandability [100], reasonability [100], and general experiences [95].
  - ***Other Likert scales***: acceptance [89], scored how strongly the vibrations evoked each emotion or sensation on a scale of 0 to 6 [106], difficulty rating survey (how difficult to determine each emotion conveyed by vibration, scale 1-5) [97], usefulness, easiness-to-use, efficiency, pleasurability, and willingness to use [25].
- **Bipolar rating scales and semantic differential questionnaire**: friendly and co-operative/hostile and competitive, intense/superficial, socioemotional/task-oriented, informal/formal, ranging from -4 to +4 [57]; pleasantness (unpleasant/pleasant), arousability (calm/arousing), approachability (avoidable/ approachable), dominance (I was in control/The stimulus was in control), ranging from -4 to +4 [77]; relaxing/arousing for the message, aroused/relaxed for the sender felt, ranging from -4 to +4 [28]; three sensory (week/strong, smooth/rough, non-rhythmic/rhythmic) and two affective (calm/alarming, unpleasant/pleasant), ranging from -2 to +2 [102]; applicability (inapplicable/applicable), easiness (difficult/easy), pleasantness (unpleasant/pleasant), expressiveness (weak/strong), and reasonability (unreasonable/reasonable), ranging from -4 to +4 [59], arousal, comfort, preference, familiarity, and dominance, ranging from -3 to + 3 [117].

- **Ranking**: Pleasantness [78].
- **Verified questionnaire**: NASA task index (NASA-TLX) [37], Networked minds measure of social presence NMMSP [37], SAM [58], [60], [74], [76], [88], [98], [99], [103], [105], the Russell's circumplex model of affect [97], SEA scake (Subjektiv Erlebte Anstrengung) [103], Hassenzahl's AttrakDiff questionnaire [26], 18-item Semantic Differential Scale by Mehrabian and Russell (from [118]), [26], an 18-item rapport questionnaire [21], satisfaction: 7-item Relationship Assessment Scale (from [119]) [26], and perceived stress: the 10-item Perceived Stress Scale (PSS) (from [120]) [26].
- **Interview**: semi-structured interview [28], [27], [26], [87], [100], and free comments [28], [23], [20], [48], [49], [57], [59], [25], [21], [82], [24], [22], [85], [86], [94], [31], [107].

Based on the above, we found researchers mainly collected data in four aspects: user's behavior, biological data of user behavior, subjective ratings, and personal comments. It suggests that applying both quantitative and qualitative analysis can provide comprehensive insights when developing MST signals on the mobile device. Still, researchers could choose the most efficient ways based on their needs.

2.3.4 Research findings of selected papers

We reviewed the selected papers and summarized the research findings in this section.

2.3.4.1 Signal design

1) Pre-defined signals with temporal parameters

Researchers have found that parameters such as amplitude [76], [106], [117], carrier frequency [76], [102], envelope shapes [78], [106], envelope frequency or rhythm [55], [76], [102], [103], [106], [117], duration [76], and intensity [55] significantly affect affective responses [117] of haptic icons [76], affective ratings [102], affect impressions of haptic stimuli [55], [103]. We summarized the parameters and perceiving of haptic stimuli from the following aspects:

- **Amplitude**. Amplitude has been found positively affects arousal [76], [77], [117] and dominance [77], [117]. However, it has also been demonstrated that amplitude has a negative impact on several other dimensions, including pleasantness [77], comfort [117], preference [117], and familiarity [117].
- **Carrier frequency**. The carrier frequency of vibrations positively affects the perceived valence [76] of the haptic stimuli. Specifically, low-frequency vibrations may incur negative feelings, such as unpleasantness and roughness, while high frequency vibrations are associated with positive ones, such as pleasantness and smoothness [76]. Additionally, the carrier frequency also

significantly influences the ratings of calmness or alarm, indicating a main effect of frequency on these dimensions [102].

- **Envelope shape**. Haptic stimuli with long rise time are perceived as more pleasant [78], [106] and arousing [78]. Additionally, vibration patterns with waveforms falling near the end lead to 'inactive pleasure' [106].
- **Envelope frequency and rhythm**. The envelope frequency negatively affects arousal [117], valence [76], dominance [117], pleasantness [103], and effectiveness [117], particularly in the low-frequency range of 0 to 16Hz [76].
- **Duration**. Longer durations of haptic stimuli increase arousal [76], [103]. The very short and subtle haptic stimuli are the most pleasant and least arousing [103].
- **Intensity**. Stronger vibrations are perceived as more alarming [102], more arousing [103], and more powerful [55]. Haptic stimuli with some suspension intervals are rated as more powerful, while those with gradual intensity changes but no suspension intervals induced a heavier impression [55].

We found that most studies evaluate how temporal parameters of haptic stimuli affect emotional expressions, but few focus on the design and evaluation of individual pre-defined MST signals. Future designs could consider the detailed temporal parameters as a helpful guideline for designing MST signals.

2) Real-time generated signal

In the evaluation of real-time generated signals, Strohmeier et al. [74] and Hannan et al. [75] evaluated how well users could recognize the emotional expressions defined by other users via mobile devices. Hannan et al. [75] asked participants to draw on the touchscreen to express different emotional intensities, and after a week, they were asked to recognize the emotional intensity they had previously drawn. It was found that participants could recognize more emotional intensities at extreme ends and could achieve higher recognition accuracy for their own gestures than others' gestures [75]. Size and pressure were two factors that could be interpreted more, while it was not easy to differentiate the speed [75]. Strohmeier et al. [74] asked participants to express emotion by the curve surface. For example, most participants use concave U shape to express delight and happiness. And other participants were asked to recognize those curve surface patterns. The recognition results showed that shape parameters affected the positive-negative dimension of emotion [74], while related movement parameters affected arousal level [74].

Salminen et al. [58] introduced different generation methods for real-time generated signals. They compared two methods of extracting tactile signals for real-time generated signals: one is extracting from concurrent speech samples, while the other one is extracting from separate speech samples with static vibrations. The results showed that using static vibrations alongside speech resulted in higher ratings of pleasantness and approachability compared to the other method. [58].

We did not find many studies evaluating the generation methods of the real-time touch in mobile communication. In contrast, most studies prefer evaluating the application of real-time generated signals in mobile communication. However, evaluating the generation methods could provide deeper insight into MST signals and make them better match related MST gestures. Thus, studying the generation methods could be a research direction.

2.3.4.2 Multimodal stimuli

Researchers usually design multimodal stimuli for mobile communication and evaluate the effects of different types of stimuli, including haptic, auditory, or visual, as well as different combinations of these stimuli. We summarized the following types:

- **Visual + haptic stimuli**. The added haptic stimuli help to increase the expressiveness of visual information [94], prime the emotion of a text message [88], and enrich the visual perceptions [82].
- **Visual + haptic + thermal stimuli**. The combined multi-modal stimuli increase the available range of emotional states [99].
- **Speech + haptic stimuli**. Adding haptic stimuli to speech is more arousing and dominant than the speech-only stimuli [58]. Haptic stimuli can resolve conversations smoothly by replacing words, making people concentrate more on phone conversations [48].
- **Haptic + auditory stimuli**. Park et al. [19] compared multimodal stimuli when transmitting MST signals such as pat through CheekTouch. The results indicated that using haptic stimuli combined with sound was the most effective way to deliver a pat [19].

We found many studies had demonstrated that multimodal stimuli could enhance mobile communication. However, these studies mainly evaluated the difference between multimodal and single-modal stimuli. They did not evaluate the stimuli effectiveness of different modalities.

For future research, multimodal stimuli are still a promising research direction. Making the different modalities well match each other is also important in design.

2.3.4.3 Evaluation of gestures

Evaluating gestures is an active area of research in the field of mobile communication. One popular way of generating haptic stimuli is by performing gestures on a mobile device [121]. Users often have their preferred gestures when interacting with haptic devices. For example, Rantala et al. [59] designed a new touch prototype. The user study revealed that participants preferred squeezing and stroking when interacting with the device [59]. Heikkinen et al. [100] used the same prototype as [59] and indicated shaking, smoothing, and tapping were the most popular gestures.

Users often have their preferred gestures when expressing intended information. For example, Rantala et al. [59] found using squeezing gestures was a quick way to create haptic messages, while stroking gestures helped express more detailed ones. Similarly, Heikkinen et al. [100] showed that users could apply spatiality in haptic messages, using the forward-backward gesture to indicate agreement. Participants particularly appreciated the spatial haptic output when utilizing stroking gestures [59]. Furthermore, Rantala et al. [28] applied the same prototype and explored how different gestures could be used to communicate various emotions. The results indicated that participants preferred using squeezing gestures to communicate unpleasant and aroused emotional intentions [28]. On the other hand, they thought using finger touch gestures was better in communicating pleasant and relaxed emotional intentions [28].

We found that researchers mainly focused on identifying users' preferred gestures when interacting with mobile devices to convey the intended information. The intended information was often limited to the emotional dimension. However, there is a need for more comprehensive research on gestures in mobile communication since Jung et al. [122], [123] have demonstrated that a detailed investigation of gestures can establish foundational principles for MST gesture design and enable automatic detection and recognition.

2.3.4.4 MST signals in mobile applications

MST signals can be useful in collaborative tasks. Researchers developed various prototypes to transmit MST signals, which helps to decrease boredom [90] in tasks, increase users' feeling of friendliness [90], strengthen emotions in life storytelling and collaborative remembering tasks [86], and provide a higher chance of winning the game tasks [26].

Adding MST signals in remote communication positively affects intimate communication. With different prototypes, couples can stay in sync [107], feel closer [48] and more concentrated [48]. MST signals help increase relationship satisfaction [26] and emotional engagement through the physical interaction with the partner [47], [26]. Meanwhile, it decreases perceived stress for long relationship couples [26].

In remote greetings, users prefer experiencing MST signals to mid-air gestures. Zhang et al. [49] designed SansTouch to exchange greetings, and they found that participants prefer using SansTouch over mid-air gestures when exchanging greetings face-to-face with colleagues [49].

MST signals also positively affect other interpersonal communications. Haptic prototypes, such as CheekTouch [18], MobiLimb [20], Wrigglo [85], ForcePhone [21], Bendi [22], a mood vector [89], and Shake2Talk [30], could help to persuade [18], communicate emotion [18], [21], [85], [89], communicate information [18], emphasize important information [18], be playful [18], [30], stimulate curiosity and engagement [20], reflect users' presence [21], [85], express greetings [21], experience rich haptic expressions [24], [22], and coordinate events for action, awareness, reassurance, and social touch [30] in mobile communication.

2.3.4.5 Communication concepts

People have different preferences in communication concepts when they transmit MST signals in mobile communication. For example, Kowalski et al. [87] compared three setups: mobile-only, semi-hybrid (mobile only and mobile + hardware), and hybrid (mobile + hardware). They found that users preferred the hybrid communication concept, as it enhanced their intimate communication by providing emotional closeness [87].

2.3.4.6 Contexts

Different contexts may cause different perceptions of haptic stimuli for people. For example, Salminen et al. [77] compared the affective ratings of haptic stimuli in laboratory and bus environments. The results showed that the haptic stimuli were rated as more pleasant, less arousing, and less dominant in the bus compared to the laboratory setting [77]. Similarly, Seebode et al. [103] compared the perceiving of haptic stimuli in a working context versus a leisure time situation. No significant effects were found in the context when rating the affective impression of Tactons designed in [103].

2.3.4.7 Special users

Haptic devices could help special users, such as deafblind or visually impaired users, to have a better experience in mobile communication. For example, Ranasinghe et al. [31] provided the deafblind people with a haptic device to communicate textual information. The system can translate visual and audio information into haptic stimuli [31]. Similarly, Choi et al. [79] designed image-based tactile emoji, which can improve visual impaired people's texting experience and help them express emotion through tactile imagery. Additionally, Réhman and Liu [29], [108] provided approaches to extracting emotional information and coding and rendering vibrotactile stimuli. The user study indicated touch could enrich the communication on mobile devices and help visually impaired people sense the emotional expressions of other people [29], [108].

2.4 Discussion

In this part, we discuss the design concerns, the advantages, the disadvantages, possible solutions, implications, and future work for MST on mobile devices from different aspects.

2.4.1 Design for target users, age groups, and special users

We summarized users' demands from selected papers. We found some guidelines for target users, age groups, and special users.

For target users, the relationship and familiarity between users are very important when developing prototypes for MST signals. For example, some prototypes are designed for couples in a romantic relationship, such as Kissgenger [47], [26]. This prototype may not be effective for strangers or colleagues. Besides, other relationships between users, such as parent–children or grandparent–grandchildren [16], could also be considered.

For age groups, broadening the age group could be future research. Most studies focused on adults aged 18 [75] to 60 [57]. And most participants studied or worked at the university. Those participants covered a large range of active users for the mobile device. However, not too many researchers considered young people under 18 or older adults above 60. They may have other demands when using mobile devices to transmit MST signals.

For special users, paying more attention to them could be a future direction. Several studies focused on people such as visually impaired people [79], [29], [31], [108]. Mobile devices could be essential in their daily lives [124]. Tactile and vibrotactile displays have been used for them to interact with the mobile touchscreen, such as texting [125], and function manipulation like 'zooming of graphical information' [126] or input and scrolling [127]. To further enhance the user experience for special users, researchers could explore a deeper understanding of the difficulties they face, their specific touch requirements, and the social demands in transmitting MST signals through mobile devices [128], [129].

2.4.2 MST signal design for mobile devices

We summarized the MST types based on selected studies. We found some implications for future design, as follows:

- The context matters when designing MST signals. Some studies have no context in the user study, such as [74] and [75]. There was only a recognition test of social touch. Participants indeed can provide some advice about the MST signals and the communicated emotion. However, some new variables may emerge when adding context to the user studies. The scenarios or the partner's attitude may also affect the perception of haptic stimuli. Thus, adding specific context to the test can improve the research results.

- Designing for the frequently used MST gestures is more efficient. Figure 2.5 shows that some MST gestures are more popular than others. The reason could be that users may prefer to use those specific MST gestures in remote communication. Similarly, Wei et al. [80] found that users prefer expressing happy or sad expressions rather than neutral emotions in remote communication. Furthermore, the survey in [16] also showed that users preferred social touch gestures that they wanted to use in remote communication. Thus, frequently used MST gestures are important for future design.
- Creating a social touch set is efficient in design. Many researchers have already chosen different social touch gestures to design with various technologies. But there is not a comprehensive analysis of the social touch set. Future studies could consider generating a social touch set based on a touch dictionary such as [130] to organize the touch design.

2.4.3 User-centered design methods in MST signals

We found some user-centered design methods in MST signals based on the selected papers that could be interesting for future design, as follows:

- Collect users' social touch properties (e.g., pressure and duration) and design MST signals based on collected data. For example, Park et al. [19] asked participants first to perform social touch (e.g., pat, slap, tickle, and kiss) to find the representative gesture patterns. They design vibrotactile stimuli based on the collected multi-touch input and touch coordinates [19].
- Let users define and create MST signals by themselves and ask them to recognize their design of MST signals. For example, Strohmeier et al. [74] asked participants to express emotions by changing the shapes of a shape-changing interface. They also investigated if other participants could recognize the emotions generated by the shape changes. Similarly, Hannan et al. [75] asked participants to express and recognize the emotional intensities generated by gestures on touchscreens. They found the recognition of emotional intensities was significantly affected by the gesture's size and pressure [75]. Additionally, Shiraga et al. [104] asked participants to generate vibration patterns to express impressions, such as ordinary, uncomfortable, cheerful, etc. They found a relationship between vibration patterns and impressions [104].

- Provide different choices to users and ask them to choose what they want in a specific context. For example, users in [28] preferred using squeezing gestures to communicate unpleasant emotions.

In general, considering users demands in designing MST signals is important in haptic design.

2.4.4 From HC to HCH

We found two main research fields (HC and HCH) from selected papers. The test in the HC field is usually without real communication. Users interact with the mobile device and perceive the haptic stimuli, which can be assumed to be sent by other people such as the experimenter. In comparison, the test in the HCH field is usually with real communication. Users communicate with each other via mobile devices.

We do not think the two fields are separated. These two fields have both advantages and disadvantages. On the one hand, only considering HC can provide a large set of haptic stimuli quickly, but those haptic stimuli may not all be effective when taking them into the HCH applications. The intended expressions may not be perceived correctly without any context in communication [131], [132]. On the other hand, only considering HCH helps increase design efficiency as researchers can directly integrate the haptic stimuli with the existing mobile applications. However, the problem could be that the number of haptic stimuli may be limited.

Based on the above, we need to confirm whether many or several haptic stimuli are required and choose the generation methods that suit us.

We could also consider these two situations together in future design. For example, we can follow two steps in design. Starting from the HC field, researchers could generate a large set of haptic stimuli and have a thorough understanding of the effect of haptic stimuli through a user study. Then, researchers could screen and select the appropriate haptic stimuli and bring them into the HCH study. Researchers then test the effectiveness of selected haptic stimuli under specific contexts during remote communication.

2.4.5 Applying different types of haptic stimuli for one MST gesture

We found that one MST gesture could be presented by different types of haptic stimuli. For example, the stroking gesture can be achieved by movements [20] and vibrotactile stimuli [27]. Using different haptic stimuli to present MST gesture could present richer effects, but there are more issues to be considered.

One major limitation is the technical constraint. Currently, there is no simple and low-cost mass-produced actuator that can achieve multiple types of haptic stimuli. This means that using different types of haptic stimuli for a single MST gesture would require multiple actuators, which can increase product costs.

The workload on users can increase when there are too many types of haptic stimuli, particularly in remote communication where visual and audio channels are typically main channels. Touch is often considered supplementary in such scenarios [16]. For example, Marc et al. [133] indicate that the visual and haptic channels play dominant roles in different situations. Therefore, researchers should balance various channels to avoid unnecessary design of stimuli, considering that the visual channel is dominant in sensation within a certain context.

When designing haptic stimuli for mobile devices, a common limitation is that popular devices like smartphones or tablets usually have a single actuator. This makes it difficult to provide different types of haptic stimuli, such as movements and vibrations, simultaneously, as shown in previous studies like [25].

Future research could develop actuators to present different types of haptic stimuli together. But for now, the most efficient way to meet users' needs is to use the actuators that are getting widely used in mobile phones, such as the LRA. And consider visual and audio modalities together with touch to provide rich effects.

2.4.6 User demands for products and consumer demands in the market

We found developing accessories and connected devices for the mobile device is a popular way to transmit MST signals in current studies. There are many advantages to doing this. For example, the accessories of MobiLimb [20] can provide richer touch effects while the SansTouch [49] can provide real touch effects.

However, several issues should be considered: (1) maybe users do not want to buy accessories or connected devices due to the high cost associated with it, as well as an inadequate motivation [134]; (2) Extra maintenance may be unmanageable [135]; (3) Usage frequency may be low since additional effort is required from users, such as remembering to use it and occasionally recharging it [134]. Thus, if researchers want to develop accessories and connected devices, they should consider factors from design and market aspects together.

From the design aspect, researchers should consider target users, user demands, and contexts. Or the device may not be helpful. For example, in [25], many participants found using emojis on the phone easier and more efficient to express their emotional states than the connected device – EMO. Also, some participants thought the prototype was for children since it looked like a toy [25]. Thus, the shape, the interaction, the target group, and the context are all important when designing accessories and connected devices.

From the market aspect, consumers may have more considerations in the purchase. We take the wearable as an example. Jung et al. [136] show that besides the display shape, size, and standalone communication, brand and price are also important factors that need to be considered for wearables such as smartwatches. Yang et al.

[137] show that besides the perceived usefulness and enjoyment, social image is also important in customers' perceived value of wearable devices.

In general, to develop accessories and connected devices for transmitting MST signals, considering both the user demands from the design aspect and the consumer demands from the market aspect is important.

2.4.7 New forms of MST signals

Most studies provided MST signals through haptic stimuli by actuators such as motors. We still found some new forms of MST signals, as follows:

- *Applying new material*. Teyssier et al. [138] developed an artificial skin as a skin-on interface. They conducted three user studies to choose a better material to reproduce the look and feel of the human skin [138]. Meanwhile, Weigel et al. [139] explored how the gestures input on the skin could be transformed on this new interface. This skin-on interface can be used as a phone cover, a smartwatch cover, or a touchpad with artificial skin, which is a possible way to transmit real social touch on a mobile device [139].
- *Applying flexible surfaces*. Mobile devices usually have a rigid screen. The shape-changing of screens could present effects that hard screens cannot achieve. Although we do not have a mass-produced flexible screen for mobile devices at present, some researchers have already tried to explore the possibility of using it. For example, Bendi [22] is a phone-sized and phone-shaped prototype that can provide shape-changing movement during a phone call. Lahey et al. [140] provided PaperPhone and evaluated the effectiveness of bend gestures in conducting tasks with a flexible display. Strohmeier et al. [74] created a 2D flexible surface and explored the possibility of conveying emotions through this new flexible surface. The sensor's dimensionality and 2D form factor have the potential to be developed as a circuit sandwiched behind a flexible display, which makes it possible to make the flexible display in a flexible smartphone in the future [74].

Based on the above, technology is a significant barrier to new forms of MST signals. But researchers can still simulate new forms with some simplified prototypes and explore the potential of MST signals.

2.4.8 Design for new mobile application

Adding MST signals to traditional mobile communication, such as texting [88] and voice calling [18], [19], [48], was common in haptic design. However, the newly developed smart mobile devices provide more possibilities in haptic design for mobile communication. We need to consider the new mobile applications when designing MST signals, as follows:

- Considering the change in the use of mobile devices in mobile communication. For example, users usually put their mobile phones on their ears during a phone call in the past. So, POKE [48] and CheekTouch [18], [19] focused on presenting haptic stimuli on users' faces and cheeks during a phone call. Nowadays, smartphones are more and more popular. Headphones are easy to connect with the smartphone, so users do not need to put the phone on their ear during a phone call. New forms of MST signals during a phone call need to be explored.
- Generating MST signals for video calls could be a popular trend because, with the development of smartphones, video calls are becoming popular on mobile devices. Rognon et al. [16] found that users prefer to use MST gestures during a video call. Many researchers have already tried to develop MST signals for video calls [27], [26], [20], [81], and [89].
- Developing haptic stimuli for existing icons conveying emotion is also popular. Online chatting applications, such as WhatsApp and WeChat, can present emojis and stickers. Many researchers have studied haptic stimuli for these emojis and stickers [62], [92], [94], [95], [99].

In general, new forms of MST signals are based on the latest mobile technology and applications. Future designs about MST signals for mobile communication could consider new mobile applications (e.g., TikTok and mobile augmented games) and technologies (e.g., new actuators, virtual reality displays, and metaverse).

2.5 Limitations

There are some limitations to this chapter. Firstly, we excluded prototypes with wearables that did not provide haptic stimuli on users' hands, but some of these studies are valuable for future remote communication on mobile devices. For example, Wang et al. [70], [71] created a phone cover for people to squeeze, transmitting the squeezing pressure to an armband. The phone cover is a possible and acceptable way for users as many people like using a phone cover to decorate or protect smartphones. Israr et al. [62] and Graham et al. [61] provided haptic stimuli to users' wrists with smartwatches. Smartwatches are also widely used by many people, which can be used for potential research direction when designing MST signals.

We excluded studies without complete user studies on social touch, but some concepts have a good potential for future application. For example, Hemmert et al. [141] created three concepts of transmitting grasping, kissing, and whispering on the mobile device. Teyssier et al. [138] experimented with a skin-on interface to send social touch or other notice on the mobile device, smartwatches, and touchpads.

We only considered research articles in four main digital libraries (ACM digital library, IEEE Explore, Springer, and Scopus) in English. However, some short articles, posters, or exhibitions may not achieve a full research level at present, but the new concepts they bring are valuable for future design and research. Other digital libraries, languages, and literature types other than research articles could also be considered.

2.6 Conclusion

This chapter presents an overview of MST designs and evaluations on mobile devices based on selected 52 articles.

From the perspective of MST design, we summarize the following:

- Typical haptic input. There are two typical haptic input types: pre-defined signals and real-time generated signals. There are four types of real-time generated signals (i.e., touch gestures, shape change, joystick, and GUI.
- Typical haptic output based on different actuators and parameters. There are four types (i.e., shape change, pressure, vibration, and other tangible output).
- Mediated social touch. There are two types – specific and non-specific.
- Emotions that social touch communicates. There are two types: specific emotion and emotion dimensions.

We also find that actuators, accessories, and connected devices are currently three typical prototypes researchers developed for MST gestures and signals.

We summarize the evaluation of MST research from the perspective of participants, experiment design, and data collection. We have learned what conclusions benefit future research, especially in the aspects of signal design, multimodal stimuli, gesture evaluation, MST signals in the application, communication concepts, contexts, and special users.

We also discuss possible solutions for the found issues and suggest directions for future MST design and research. The main issues that designers and researchers could consider in future design are: (1) consider target users, age groups, and special users; (2) Design frequently used MST signals for specific context; (3) Apply user-centered design methods and choose an efficient generation method; (4) Consider the user demands of products and consumer demands in the market together in the development; (5) Consider new forms of MST signals; (6) Design for new mobile applications and technologies.

2.7 Summary for key elements of this Ph.D. research

Based on the literature review, we found some space for further study: (1) Many studies applied more than one actuator to provide MST signals. However, only one actuator is usually embedded in most mobile devices, such as smartphones; (2) Many studies mainly developed prototypes for MST signals transmission. They did not bring about a systematic generation method for MST signals; (3) Some studies provided vibrotactile stimuli for MST gestures based on researchers' experiences. Before design, there was no comprehensive study on the social touch properties (e.g., pressure and duration); (4) Only a limited number of MST signals were considered.

We summarize the key elements of this Ph.D. research, considering the aspects of technology, design, and application. Figure 2.11 shows the details.

From the aspect of technology, we choose the smartphone as a carrier, controlling one linear resonant actuator embedded in the smartphone to present MST signals. Our focus lies in users engaging with smartphones and interacting with touchscreens when designing MST signals.

Regarding design, we study how users perceive vibrotactile stimuli on touchscreens before broadening our focus from human-computer interaction to computer-mediated human-to-human interaction. We present a generation method for MST signals, incorporating key factors such as touch properties (e.g., pressure, duration, etc.). We design a rich set of MST signals.

As for application, we apply MST signals in an online social application to increase the social presence in mobile communication.

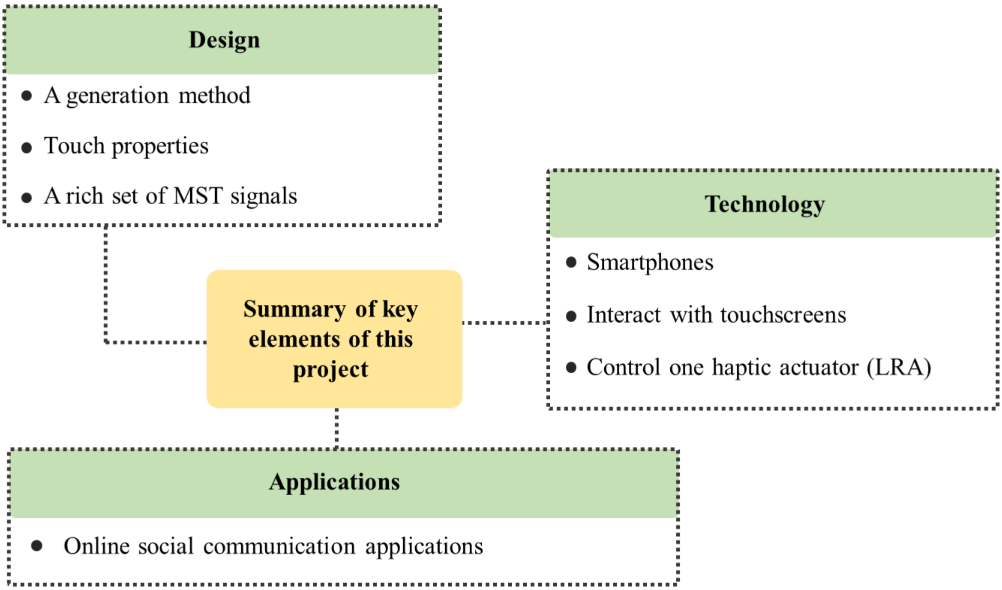


Figure 2.11 Summary of key elements of this Ph.D. research

Chapter 3

Senders Expressing Mediated Social Touch

This chapter is based on:
Wei, J. Hu, and M. Li, "User-defined gestures for mediated social touch on touchscreens," *Personal and Ubiquitous Computing*, vol. 27, no. 2, pp. 271–286, 2023.

Abstract
As we will use the smartphone to transmit mediated social touch (MST) signals, we need to know how users would express MST with hand gestures on smartphone touchscreens. Therefore, this chapter mainly explores how to express MST with gestures and collect touch properties such as pressure and duration.

Background: MST is a new form of remote communication. Researchers have designed prototypes to deliver MST signals for mobile devices. However, a comprehensive analysis of the user-defined MST gestures on smartphone touchscreens is lacking.

Methods: We conducted an elicitation study for 24 social touch gestures on smartphone touchscreens and recorded pressure and duration.

Results: We developed a user-defined MST gesture set considering touch properties and context. We provided classifications based on the hand/finger movement. We found that social touch gestures with shorter duration were easier for participants to perform; participants were inclined to use social touch with an easier hand/finger movement more often. Based on the findings, we discuss the implications for MST technology and its application on touchscreens.

3.1 Introduction

Remote communication between people is popular. Rantala et al. [28] mention that visual and audio are the main channels for traditional remote communication. Besides these two channels, mediated social touch would be a new form of remote communication [28].

Mediated social touch (MST) means ‘the ability of one actor to touch another actor over a distance by means of tactile or kinesthetic feedback technology’ [15]. As advanced haptic actuators are embedded in most mobile devices [142], there is a possibility to make MST signals more active in interaction with mobile devices and in remote communication [28]. For example, the Taptic Engine in iPhones (since iPhone 7) could provide various physical effects with haptic feedback [143].

Some MST signals have been designed for mobile devices. Researchers have designed prototypes (i.e., POKE [48], CheekTouch [18], [19], and ForcePhone [21]) for mobile devices to deliver MST signals (e.g., poke, pat, slap, tickle, and kiss) via vibrations. Hemmert et al. [141] designed three mobile phone-shaped and -sized prototypes with sensors and actuators to deliver grasping, kissing, and whispering. Furukawa et al. [23] proposed a ‘Shared Tactile Interface’ (KUSUGURI) to send a bidirectional tickling sensation. Rantala et al. [28] designed a mobile device and demonstrated that vibrotactile stimulations that imitate human touch could convey intended emotions in remote communication.

However, these studies [48], [18], [19], [21] mainly focused on the context of phone calls (with phones on the ear). There is a lack of research addressing the context of having a with phone in the hands for texting and video calling. In the context of texting or video calling, users would hold the phone in their hands in front of them. Moreover, these studies mainly provided novel prototypes [28], [48], [18], [19], [21], [141], [23] without an understanding of touch properties [130] of MST gestures, such as pressure and duration. Yohanan and MacLean [130] mentioned touch properties included common points of contact as well as duration and intensity of gestures. Touch properties are essential for applying tactile or kinesthetic feedback technology. For example, suppose we deliver MST signals via tactile feedback. In that case, the perceived intensity and duration of tactile feedback could be designed based on the pressure and duration of specific MST gestures [21], [144].

To address this gap, this study aims to provide guidelines to design MST signals based on user-defined MST gestures and related data of touch properties in the context of texting or video calling.

To get a comprehensive understanding of MST gestures, we choose 24 social touch gestures from the Touch Dictionary [130]. This Touch Dictionary was extracted from human-animal interaction, human-human touch, and human-human affective touch [130]. Gestures from different sources frequently overlapped in kind, but not name [130]. This Touch Dictionary [130] presented a relatively complete picture of the social touch that could exist between humans. So, it was efficient to choose social touch gestures from this Touch Dictionary [130].

We focus on the mediated interaction between humans via touchscreens of mobile devices because the context in remote communication we consider is with mobile devices on hands (e.g., texting or video calling). We explore the user-defined MST gestures on the touchscreen and related touch properties.

We apply an elicitation study [145] to explore the user-defined MST gestures on the smartphone touchscreen and capture related touch properties. The elicitation study is beneficial for exploring surface gestures that people make in natural interactions [146], because gesture-based natural interactions provide a higher likelihood to design interfaces that are easy to perform and remember [147]. Many researchers have conducted the elicitation study to explore related gesture sets on smartphone touchscreens ([145], [147], [148], [149], [150], [151], [152], [153], [154]).

The research question in this chapter is how to express MST with hand gestures on a touchscreen. Additionally, to guide the MST signal design in the following chapters, a comprehensive understanding of the touch properties of these MST gestures is essential.

3.2 Related work

3.2.1 Elicitation studies for touchscreens of mobile device

As many sensors have been embedded in mobile devices, gesture recognition on mobile devices to invoke commands has become possible [148]. User-defined gestures are important in the mobile computing paradigm [148].

Many researchers have applied elicitation studies to explore user-defined gestures for touchscreens of mobile devices. Wobbrock et al. [145] conducted an elicitation study to design tabletop gestures. They demonstrated that consensus existed on parameters of movements and mappings of motion gestures onto commands for surface computing [145]. They also developed a taxonomy for motion gestures to specify a user-defined gesture set. Tu et al. [149] explored user-defined gestures to perform interactive tasks in three common tablet-holding postures, and they compared the effects in different holding postures. Findlater et al. [150] provided a gesture set that included multi-touch and single-touch gestures for commonly used non-alphanumeric text input. They found that using gestures for non-alphanumeric inputs was no slower than using keys. Kurdyukova et al. [151] explored iPad gestures that users naturally performed for data transfer. Examples of transfers were: two iPads, an iPad and a tabletop, and an iPad and a public display. Three modalities were checked: multi-touch gestures, spatial gestures, and direct contact gestures. They indicated how the user would choose modalities and gesture types in a different context [151].

Researchers have also studied user-defined gestures for more than the front screen of mobile devices. Shimon et al. [152] applied an elicitation study to explore user-defined gestures for smartphone commands and identify their criteria for using back-of-device gestures. Wu and Yang [153] explored user-defined multi-finger gestures for game tasks on a dual-screen mobile device (both front and rear screens). Liang et al. [154] explored user-defined gestures to provide information to users through a dual-surface device (with both front and back surfaces). They indicated that a consensus existed among gestures for choice of sensory, multi-touch, and dual surface input.

Other researchers compared the user-defined gestures among different age groups. Rust et al. [155] studied user-defined gestures from children for touchscreen tabletop interaction. They compared the difference between adults and children. The results showed that adults and children created similar gestures. The results provided a basis for future user-defined gesture studies with children.

From above, we found that the following two points were important for consideration:

1) *Function*. There is a gap in exploring user-defined gestures for social context.

Most gestures were defined for manipulating mobile devices, such as commands for interaction with touchscreens. However, since social communication is, after all, among humans, not between a human and a computer, the guideline for user-defined gestures for social context may differ from that of function commands. We should consider the characteristics of human communication when exploring user-defined MST gestures.

2) *Context*. Different contexts may lead to different user-defined gestures. For example, Tu et al. [149] compared user-defined gestures in three holding postures of a tablet. For some commands, user-defined gestures were significantly different between different holding postures. We should not mix different contexts when exploring user-defined gestures.

3.2.2 Mediated social touch on mobile devices

User-defined touch gestures for MST can be used as input on mobile devices. MST signals have been explored in different applications.

Researchers developed prototypes to create a real-time MST signal on mobile devices. Park et al. [48] presented Poke - a prototype used a remote touch technique through an inflatable surface. The inflatable surface was attached to a mobile device. It was designed for delivering pleasant emotional touches over interpersonal mobile communications. The study found that it was possible to send 'poke', 'shake', and 'pat' through this inflatable surface during a typical phone call. Park et al. [18], [19] also designed a pair of CheekTouch prototypes. Each prototype had a multi-touch screen. Users could deliver touch through the vibrotactile display. Hemmert et al. [141] designed three mobile-phone like prototypes embedded with sensors and actuators to deliver grasping, kissing and whispering for mobile phones. Hoggan et al. [21] designed ForcePhone – a mobile synchronous haptic communication system. Users could squeeze the side of the device during phone calls. The pressure would be transferred to the mapping vibrations on another user's device. Furukawa et al. [23] proposed a method of 'Shared Tactile Interface' (KUSUGURI), which could send a bidirectional tickling sensation. Rantala et al. [28] designed a mobile device to show that vibrotactile stimulation imitated human touch could convey intended emotions from one person to another.

From above, we found that the following three points were important for considering:

1) Context. So far, the context of the work was during a phone call (with the phone on the ear). It is underexplored in the context of the phone on the hand for texting or video calling.
2) Touch types. A limited number of social touch gestures were considered in the above studies. Researchers developed prototypes to deliver several simple

touch gestures for mobile devices. It would be interesting to consider more social touch gestures in remote communication.

3) Touch properties. The touch properties of MST gestures were underexplored. Most researchers designed prototypes to send real-time touch. For example, Rantala et al. [28] and Hoggan et al. [21] delivered touch via vibrotactile stimuli, which were transferred by input pressure. Users could feel the emotion or feelings by the vibrotactile stimuli. However, users may not recognize the intended social touch. It would be interesting to explore the touch properties of specific social touch.

In summary, the points that we would like to highlight in this study were:

- We will consider more social touch gestures. We will choose 24 social touch gestures from Touch Dictionary [130].
- The context will be having remote communication with mobile devices on the hand (e.g., texting or video calling), not on the ear.
- We will explore user-defined MST gestures on the smartphone touchscreen and explore related touch properties.

3.3 Methods

This section presents an experiment conducted based on the elicitation study [145] to explore user-defined MST gestures on smartphone touchscreens and obtain related touch properties. This study was approved by the Ethical Review Board from Eindhoven University of Technology with the approval number ERB2020ID4.

3.3.1 Participants

We recruited 20 participants (7 males and 13 females) aged from 23 to 35 to perform social touch on a smartphone touchscreen. Based on [156], a sample size of 20 participants is efficient in related elicitation studies [145], [148]. We randomly recruited participants from the TU/e campus. Participants' majors included Civil Engineering, Industrial Design, Industrial Engineering, Petroleum Engineering, Supply Chain Management, Traffic Planning and Management. All participants have experience of using smartphones and social media.

3.3.2 Selection of referents

We chose 24 social touch gestures (Grab, Hit, Hug, Kiss, Lift, Massage, Nuzzle, Pat, Pinch, Poke, Press, Pull, Push, Rock, Rub, Scratch, Shake, Slap, Squeeze, Stroke, Tap, Tickle, Toss and Tremble) from the Touch Dictionary [130]. As mentioned earlier, this Touch Dictionary presented a relatively complete picture of social touch that could exist between humans [130]. So, it was efficient to choose social touch gestures from this Touch Dictionary [130].

3.3.3 Apparatus

To reduce the visual bias of the graphical display and prevent smartphone feedback because of gestures [157], touch was performed on a pressure sensor (The FlexiForce™ A502, sensing area: 50.8 mm x 50.8 mm) attached to a powered-off smartphone (Figure 3.1). The smartphone was only used for its form factor. The sensing area was efficient for the active regions defined by the thumb sweep of the radius [158]. The pressure sensor was connected to a computer through an Arduino microcontroller to read the value of pressure. A Processing program was used to read and store the pressure values from Arduino's serial port. The pressure was read every 50ms.

A video camera was mounted on a tripod, positioned in front of participants to record the gestures performed by them. For privacy, only the hands of the participants were video recorded during the experiment.

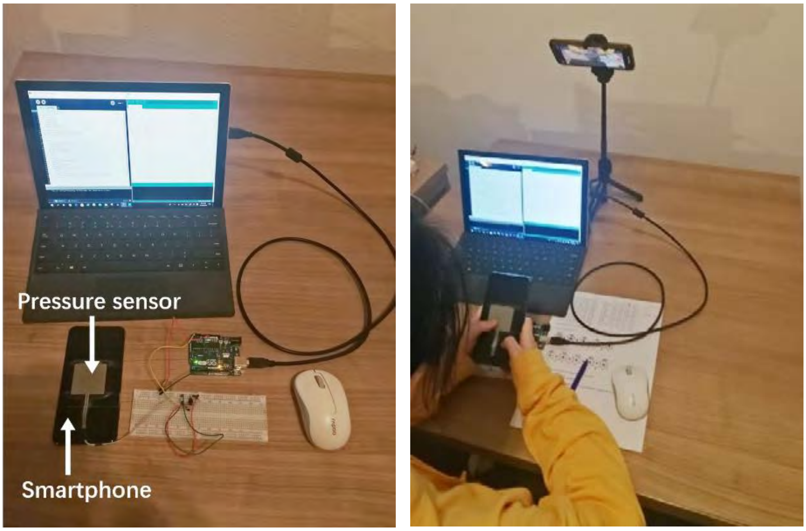


Figure 3.1 Experiment setup. Left: installation. Right: test environment

3.3.4 Procedure

We conducted an elicitation study based on [145]. First, the participant was briefly introduced to the purpose of the study. Questionnaires and consent forms were delivered to each participant before the experiment.

There were three main tasks in the study: performing social touch on the touchscreen, explaining the social touch they performed, and filling out the questionnaires.

Participants were asked to perform social touch on the touchscreen and try not to use the smartphone's movement for this purpose. Tilting, rotating, panning, and shaking the smartphone to represent social touch were not considered in this study. We only considered the 2D touchscreen because the target context in this study was sending MST signals with a phone in the hand for texting or video calling.

We recorded the pressure and duration of the touch gestures for exploring user-defined MST gestures considering touch properties and context.

Participants were given the chosen social touch from Touch Dictionary [130]. Participants were asked to imagine that another person was in the 2D touchscreen and perform the social touch gestures. For example, in 'Shake', participants were asked to imagine how to shake someone on the touchscreen. Participants performed social touch on the pressure sensor's sensing area on the test device for recording physical data. The order of the social touch gestures was randomized. The randomized order was obtained using the random function in Python and was presented to each participant on the paper questionnaire. During the experiment, each social touch was performed five times. When finished with one social touch, participants were asked to explain why they performed the social touch gesture like that and fill out the questionnaire about the social touch.

It could be inconvenient for users to perform a difficult gesture in a real application. So, we wanted to find how easy it is to perform a given gesture to guide future design and application. A 7-point Likert scale was applied to report the subjective ratings of ease of performing ('I feel it is easy to perform this touch gestures on the touchscreen' from 'strongly disagree' to 'strongly agree') [148].

We also wanted to find out how often users would like to use a given gesture. A 7-point Likert scale was applied to report the subjective ratings of usage frequency ('I would often use this social touch if it existed in online social communication apps' from 'never' to 'very often') [148].

3.4 Results

Our results included gesture classifications based on nature, cardinality, hand/finger movement, duration, and pressure of all collected gestures, a user-defined MST gesture set considering context and touch properties, and subjective ratings.

3.4.1 Gesture classifications on all collected gestures

We classified collected gestures according to two dimensions: nature and cardinality (Table 3.1, Figure 3.2 (a)). The nature dimension was from [145]. This dimension has been applied in many gesture elicitation studies [145], [146], [148], [149]. The cardinality dimension was from [149], where it was proposed to explore users' kinematic aspects for gesture interaction [149].

Table 3.1 Classifications of tablet gesture

Nature	Physical		Gesture acts physically on objects
	Metaphorical		Gesture indicates a metaphor.
	Symbolic		Gesture visually depicts a symbol.
	Abstract		Gesture-referent mapping is arbitrary.
Cardinality	Fingers	Atomic	Gesture is performed by one finger on one hand.
		Compound	Gesture is performed by multi-fingers on one hand.
		Parallel	Gesture is performed by multi-fingers on two hands.
	Palm		Gesture is performed by the palm.
	Fist		Gesture is performed by the fist.

This table was adapted from [145] and [149].

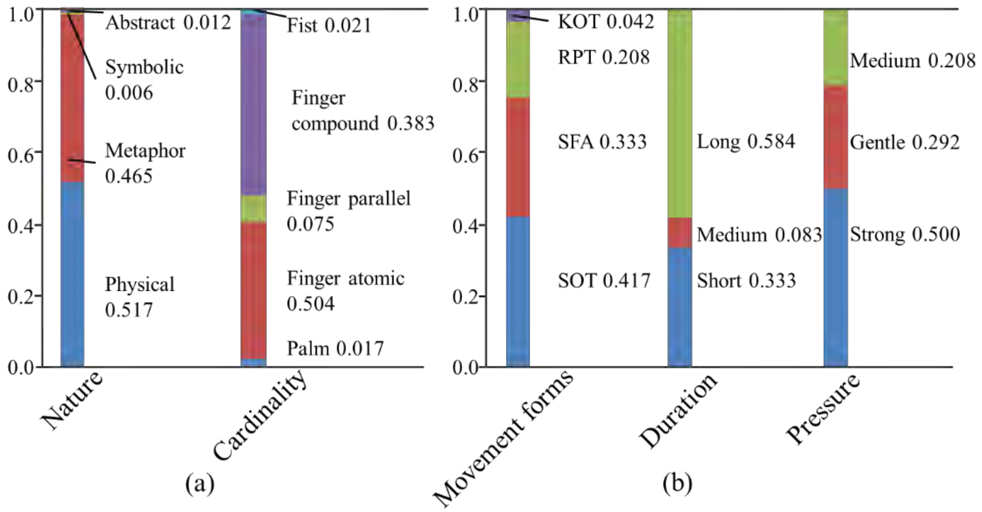


Figure 3.2 (a) gesture classifications based on nature and cardinality; (b) gesture classifications based on hand/finger movement, duration, and pressure of all 480 collected gestures

In the nature dimension, there are four types of gestures, namely physical, metaphorical, symbolic, and abstract gestures [145], [149].

Physical gestures would be the same when interacting with people in the real world (in 3D space) and interacting with touchscreens (on 2D touchscreens), because Tu et al. [149] indicate that physical gestures are meant to interact in the same way using a physical motion on the object. The touchscreen could be regarded as the other user when performing physical gestures. Those social touch movements could be described similarly to those in the Touch Dictionary [130]. For example, in 'Poke', 19 out of 20 participants prodded the touchscreen with one fingertip.

Metaphorical gestures describe actions using something else to represent them [149]. For social touch, the metaphor has two dimensions: direction and movement. For direction, on the touchscreen, the upper area represents the further distance or higher location. The lower area represents the closer distance or lower location. For example, in ‘Pull’, 14 out of 20 participants ‘Pull’ someone on the touchscreen by swiping their fingers down. Nineteen participants swiped their fingers up to represent ‘Lift’ someone. For ‘Hug’, 11 out of 20 participants moved two thumbs close together to represent two arms’ movement embracing the other one. Participants used similar gestures on the touchscreen to represent ‘shake’ (19 out of 20), ‘rock’ (16 out of 20), and ‘tremble’ (19 out of 20). They moved their fingers on the touchscreen back and forth to represent the body movements.

Symbolic gestures are visual depictions [145], [149]. For example, P13 drew a heart shape to represent ‘Kiss’ to show love.

Wobbrock et al. [145] described abstract gestures as ‘gesture-referent mapping is arbitrary’. For example, P12 used the right thumb to point to the touchscreen once as a ‘Stroke.’

In the cardinality dimension, there are three types of finger gestures, namely atomic gestures, compound gestures, and parallel gestures [149]. Atomic gestures were performed with one finger, compound gestures were performed with multi-fingers of one hand, and parallel gestures were performed with two hands [149]. In this study, we added the palm and fist because some participants used the palm or the fist to perform some gestures without using fingers (Table 3.1).

3.4.2 User-defined MST gestures on smartphone touchscreens

We firstly developed a user-defined MST gesture set according to [145]. The largest groups of identical gestures for each referent were assigned to represent the referent [145]. Then we considered context and touch properties in user-defined MST gestures.

3.4.2.1 Agreement rate

We analyzed the recorded video of participants’ gestures from the kinetic aspects. Sequences of kinetic gestures were mainly used to describe the interaction between the user and a designed product [159]. In this study, we observed how users would interact with the touchscreen when performing social touch gestures. Some examples of the kinetic gesture analysis are in Table 3.2.

We chose six aspects to describe a collected gesture – namely trajectory and dynamics [160], movement description, contact location of fingers, palm direction, cardinality dimension, and description of cardinality and trajectory (Table 3.2).

Table 3.2 Some Examples of Kinetic Gesture Analysis

Social touch gestures	Participant	Trajectory and dynamics [160]	Movement description	Contact location of fingers	Palm direction	Cardinality dimension [149]	Description of cardinality and trajectory
Poke	P2	Straight	Starts from the air, stops on the touchscreen	Fingertips	Palm down	Atomic gestures: Index finger, right hand	One finger points one time
Tap	P3	Straight	Starts from the air, stops on the touchscreen	Knuckle	Palm up	Atomic gestures: Index finger, right hand	One finger knuckle points one time with the palm up
Scratch	P4	Straight	Moves on the touchscreen	Fingernails	Palm down	Compound gestures: Index, middle and ring finger, right hand	Three fingernails from one hand move on the touchscreen
Hit	P1	Straight	Starts from the air, stops on the touchscreen	Knuckle	Palm down	Fist, right hand	One fist hit one time
Squeeze	P3	Straight	Moves on the touchscreen	Fingertips	Palm down	Parallel gestures: Thumbs, both hands	Two thumbs from two hands are approaching
Shake	P6	Repetitive	Moves on the touchscreen repetitively	Fingertips	Palm down	Compound gestures: Index and middle finger, right hand	Two fingers from one hand move side to side together
Massage	P6	Kneading	Kneads on the touchscreen repetitively	Fingertips	Palm down	Atomic gestures: Thumb, right hand	One thumb kneads
Tickle	P13	Straight	Starts from the air, stops on the touchscreen	Fingertips	Palm down	Compound gestures: Index and middle finger, right hand	Two fingers move a little from upper to lower two times

We adopted the trajectory and dynamics from [160] for kinetic gesture coding. From the aspect of trajectory and dynamics, a straight gesture is from a resting or an active position directly, with a straight trajectory, to the final position [160]. A repetitive gesture has repetitions that result in a metrical or rhythmical movement [160].

The two participants' gestures could be regarded as identical when the six aspects (Table 3.2) of the social touch gesture were the same. Identical gestures were used for calculating the agreement rate (AR) [156].

We generated a user-defined MST gesture set (Figure 3.3). Identical gestures of one social touch were grouped. The group with the largest size was then chosen to represent the user-defined MST gesture set [145].

To evaluate the degree of consensus among our participants, we adopted the process of calculating an agreement rate [156] for each referent. Vatavu and Wobbrock [156] proposed a mathematical calculation for the agreement rate, where:

$$\mathrm{AR}(r) = \frac{|P|}{|P|-1} \sum_{P_i \subseteq P} \left(\frac{|P_i|}{|P|}\right)^2 - \frac{1}{|P|-1} \qquad (3-1)$$

In Equation (3 – 1), r is the referent, $|P|$ is the proposals collected for a given referent r. P_i represents subsets of participants from group P that are in agreement over r, $|P_i|$ donates the cardinality of subset P_i [149], [160], [161].

We applied AGATE tool (Agreement Analysis Toolkit) to compute agreement rates [156]. Figure 3.4 illustrates the agreement rates. The mean agreement rate was 0.215. There was a significant effect of referent type on agreement rates [156] ($V_{rd(23,N=480)}$=1312.305, p=0.001).

There were six referents whose agreement rate was less than 0.1, namely 'Massage' (AR=0.02), 'Nuzzle' (AR=0.05), 'Stroke' (AR=0.06), 'Push' (AR=0.07), 'Shake' (AR=0.08), and 'Rock' (AR=0.09). There were significant effects of referent type on agreement rate for these six referents ($V_{rd(5,N=120)}$=38.020, p=0.001).

These referents had low agreement rates because most of these collected gestures belonged to metaphorical gestures (except for 'Stroke'). Wobbrock et al. [145] has indicated that complex gestures are more likely to result in metaphorical gestures. It was normal that complex gestures had low agreement rates since each participant had their own understanding of a metaphor.

For 'Stroke', most collected gestures were physical gestures, but 'Stroke' still had a low agreement rate. The reason was that the 'Stroke' between humans demanded no directions or exact fingers. However, participants moved different fingers in different directions on touchscreens, which resulted in a low agreement rate.

The agreement rate of ‘Massage’ was the only one that was not significantly greater than zero ($V_{rd(1,N=20)}$=4.000, p=0.050). So, there was almost no consensus on a gesture for “Massage”. The reason was that users had their own massage habits and massage techniques.

Referents with a higher agreement rate (AR > mean 0.215) included ‘Poke’ (AR=0.90), ‘Pinch’ (AR=0.81), ‘Slap’ (AR=0.55), ‘Press’ (AR=0.32), ‘Pat’ (AR=0.30), and ‘Scratch’ (AR=0.22). There were significant effects of referent type on agreement rate for these six referents ($V_{rd(5,N=120)}$=295.283, p=0.001).

These referents with a higher agreement rate belonged to physical gestures. Wobbrock et al. [145] has indicated that simple gestures are more likely to result in physical gestures. It was normal that simple gestures had higher agreement rates.

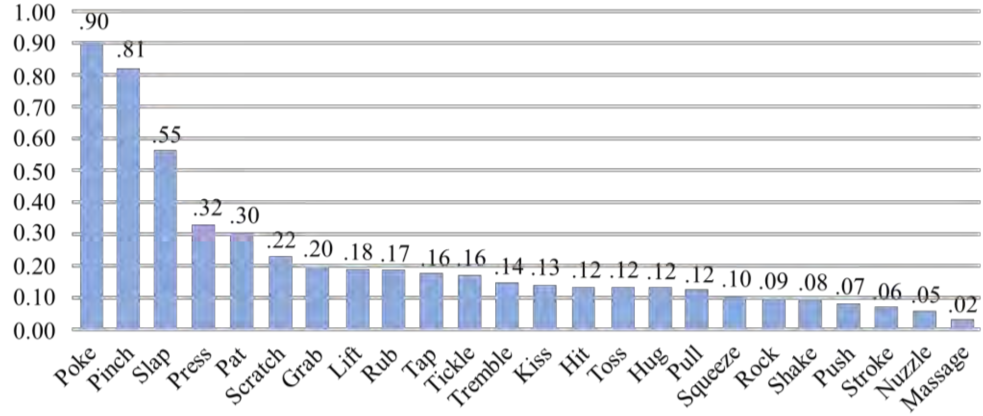


Figure 3.4 Agreement rate

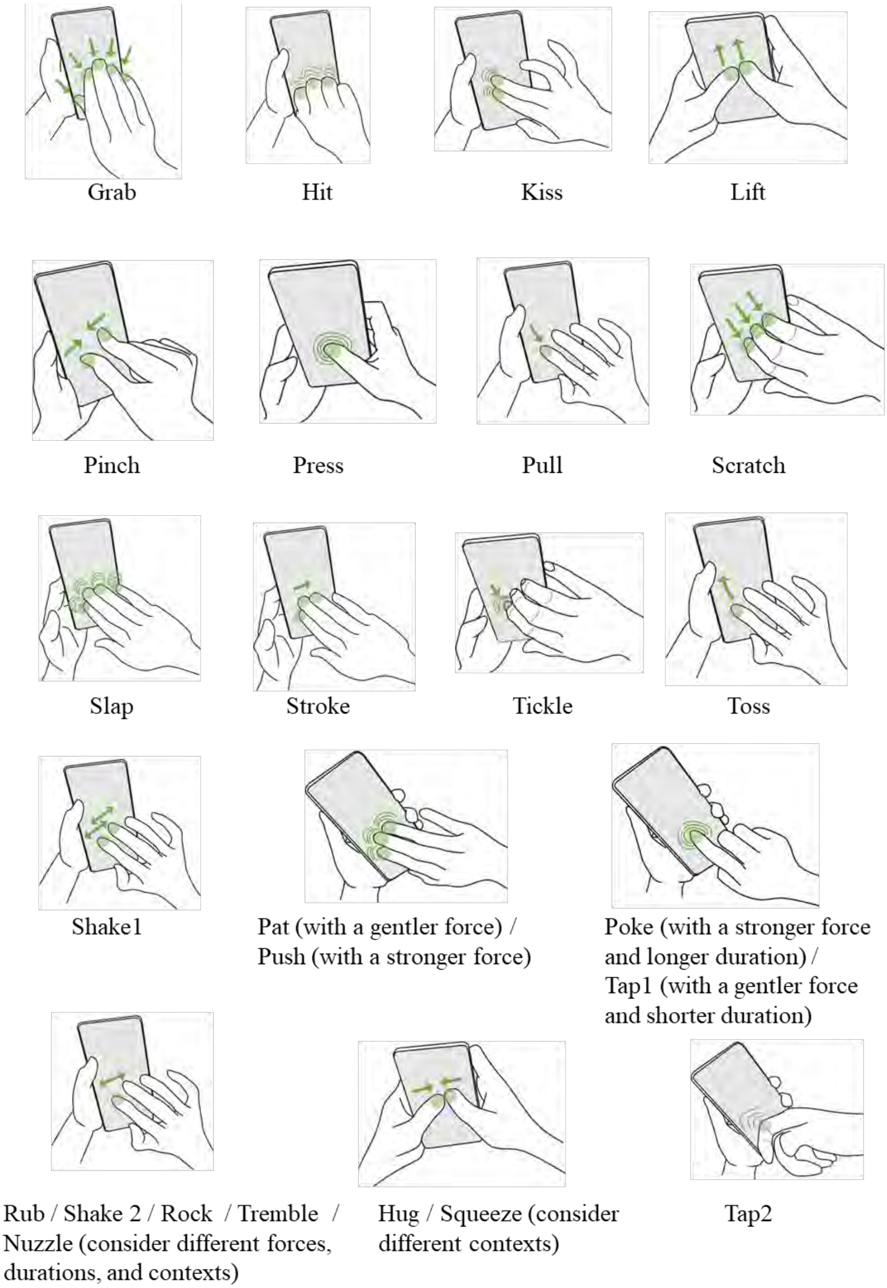


Figure 3.3 User-defined MST gestures on the smartphone touchscreen

3.4.2.2 Considering touch properties and context in user-defined touch gestures

In Figure 3.3, some user-defined MST gestures represent more than one social touch. For example, the user-defined MST gesture for ‘Hug’ and ‘Squeeze’ are the same. Woodblock et al. [145] mentioned that the same gesture was used to perform different commands, and a conflict occurred because one gesture cannot result in different outcomes. To resolve this, the referent with the largest group won the gesture [145].

However, we think there is a possibility to accept that one touch gesture could represent different meanings in MST gestures.

1) From the aspect of the definition, some social touch gestures indeed have similar kinetic features. Definitions of those conflicting social touch gestures from the Touch Dictionary [130] are in Table 3.3. For example, ‘Rub’, ‘Tremble’, ‘Shake’, ‘Nuzzle’ and ‘Rock’ have the same user-defined gesture (Figure 3.3). The definitions of these social touch gestures include descriptions like ‘back and forth’ (‘Rub’ and ‘Rock’), ‘move side to side’ (‘Shake’), ‘shake against’ (‘Tremble’), ‘rub against’ (‘Nuzzle’). These descriptions belong to similar kinetic features. For ‘Poke’ and ‘Tap’, ‘Poke’ means jab or prod with one finger, ‘Tap’ means strike with one finger. The movements of these social touch gestures are similar, just with different forces and different rhythms. It is acceptable that the obtained user-defined gestures are the same since the movements in the gesture definition are similar. Different forces and rhythms could help to differentiate.
2) From the aspect of context, MST gestures are not like commands for mobile devices. It highly depends on context. Some verbal and non-verbal expressions accompany a touching action, and whom we touch, when, and in what manner is regulated through social and personal norms [162]. It is important to take contextual factors into account [162]. As touch communicates emotion [130], it has been proved that a single touch gesture can be used to communicate various emotions [8], [9]. For example, Yohanan and MacLean [130] showed the mean likelihood of touch gestures that would be used to communicate given emotions. For ‘Rub’, the users’ rates of ‘Depressed’ and ‘Sleepy’ were the same. What the user exactly wants to communicate depends highly on a specific context. It is thus possible that one touch gesture could represent different types of social touch. If we consider different contexts, we could understand the different meanings of the same touch gesture [149].

To differentiate gestures with the same movements, we could take the following aspects into account:

1) Taking touch properties such as pressure and duration into consideration. Villarreal-Narvaez et al. [163] indicate that a secondary sense could serve for eliciting new ranges of symbols. The recorded pressure values of conflict gestures like ‘Poke’ and ‘Tap’ were different (Table 3.3). For the definition, ‘Poke’ means ‘jab with the finger’, which refers to a sudden strong movement, while ‘Tap’ means ‘a light blow’ [130] (Table 3.3). So, pressure is a significant factor in differentiating touch gestures on touchscreens. Duration is also helpful. The recorded durations were different for conflict gestures like ‘Shake’ and ‘Rock’ (Table 3.3). For the definition, ‘Shake’ means rapid and forceful movements, while ‘Rock’ means gentle movements [130] (Table 3.3). Most mobile devices have built-in sensors to compute pressure and contact duration [164]. Built-in sensors in mobile devices could help to differentiate these gestures [149].
2) Taking context into consideration. Tu et al. [149] indicate that although assigning one gesture to multi-commands would cause a conflict, there should be no problem if the context is considered. For example, the touch gestures of ‘Hug’ and ‘Squeeze’ were the same (Figure 3.3). There was no significant difference in recorded durations and pressures (Table 3.3), but different contexts could help to differentiate social touch with the same user-defined gesture. For example, in the context of comforting others, people may ‘Hug’ rather than ‘Squeeze’.
3) Taking other modalities into account when developing applications. MST signals could present interpersonal touch over a distance through haptic or tactile displays [162]. Villarreal-Narvaez et al. [163] mentioned that among primary human senses, vision and audition are covered much more than tactition, probably because our human brain filters signals so that the visual, auditory, and tactile channels respectively occupy 80%, 10%, and 5% of the total bandwidth [163]. The haptic or tactile stimuli could be a compensation for visual and audio information. So other channels could help to differentiate MST signals when the touch gestures come the same.

Table 3.3 Conflicting user-defined MST gestures and recorded average maximum pressure and duration

Social touch gestures	Gesture definition from [130]	Average pressure *	Average duration (s)
Pat	Gently and quickly touch the recipient with the flat of your hand.	404	0.10
Push	Exert force on the recipient with your hand in order to move it away from yourself.	898	0.60
Poke	Jab or prod the recipient with your finger.	647	0.30
Tap	Strike the recipient with a quick light blow or blows using one or more fingers.	446	0.08
Hug	Squeeze the recipient tightly in your arms. Hold the recipient closely or tightly around or against part of your body.	827	1.00
Squeeze	Firmly press the recipient between your fingers or both hands.	818	0.80
Rub	Move your hand repeatedly back and forth on the fur of the recipient with firm pressure.	353** – 605***	0.25****
Tremble	Shake against the recipient with a slight rapid motion.	275** – 508***	0.12****
Rock	Move the recipient gently back and forth or from side to side.	362** – 418***	0.20****
Shake	Move the recipient up and down or side to side with rapid, forceful, jerky movements.	365** – 627***	0.12****
Nuzzle	Gently rub or push against the recipient with your nose or mouth.	191** – 407***	0.20****

* We used Arduino to collect pressure. The pressure was a relative value, ranging from 0–1023.

Recorded pressure of repetitive gestures (explained in 4.3.1) fluctuated in a wavy pattern. The average pressure of the troughs** and the crests*** were applied here.

**** The average duration of repetitive gestures in this table was the duration between two adjacent troughs.

3.4.3 Hand/finger movement and touch properties

We provide hand/finger movement to describe trajectory features for gesture interaction. The touch properties mainly refer to pressure and duration in this study.

3.4.3.1 Hand/finger movement

Hand/finger movement indicate the trajectory and dynamics [160]. It also describes the spatial relations between the hand/finger and the touchscreen. The hand/finger movement has the following aspects:

1) The classifications based on the hand/finger movement consider gestures with general characteristics. The general taxonomy of gesture is based on all collected gestures [145], [148], [149]. However, not all collected gestures for one social touch have general characteristics. We need to screen all collected gestures first to exclude those without general characteristics. For example, the definition of 'Stroke' is moving the hand over with gentle pressure over the subject [130]. We collected 20 gestures of 'Stroke', 19 out of 20 participants moved their fingers on the touchscreen, and only one participant pointed to the touchscreen without touching the screen one time. We excluded this gesture for further analysis.
2) *The hand/finger movement of social touch does not consider the exact fingers*. The user-defined gesture comes from a group of identical gestures [145]. These identical gestures may be performed with different fingers. However, social touch is not like function commands. People have a preference when touching someone. There is no need to demand specific fingers. For example, 'Scratch' means rub the subject with your fingernails [130]. The definition mention fingernails, not the exact fingers. The recorded videos also showed that nine participants moved fingernails of the index, middle and ring fingers from up to down, five participants moved fingernails of the index finger from up to down, and three participants moved fingernails of the index and middle fingers from up to down on the touchscreen. Although the used fingers were not the same for all participants, the meaning participants wanted to express was the same.
3) *The hand/finger movement of social touch considers spatial relations between the hands/fingers and the touchscreen*. The original form proposed in [145] included aspects of hand poses, paths, and figures. This form described whether the hand pose was static or dynamic and whether the hands moved. However, it did not describe how the hands moved or what the specific path was. In this study, we regarded the touchscreen as the other person. Thus, it is important to consider spatial relations between the hands/fingers and the touchscreen.

We classified touch gestures based on hand/finger movement. We considered hand/finger movement and ignored the specific use of fingers when classifying the same gestures. For example, some participants 'Pat' on the touchscreen with two fingers, while some used three or four fingers. These gestures were different, but these were classified as the same type based on the hand/finger movement.

Table 3.4 Gesture classification based on hand/finger movement, duration, and pressure

Dimension	Types	Description	Social touch gestures
Hand/finger movement	SFA	SFA gestures move from the air with a straight trajectory to one point on the touchscreen, with a quick contact with the touchscreen.	Hit, Kiss, Pat, Poke, Press, Slap, Tap, Tickle
	SOT	SOT gestures move from a resting position on the touchscreen with a straight trajectory to another position	Scratch, Stroke, Lift, Pull, Push, Toss, Grab, Hug, Pinch, Squeeze
	RPT	RPT gestures move on the same trajectory repetitively.	Rock, Nuzzle, Rub, Shake, Tremble
	KOT	KOT gestures knead on the touchscreen repetitively.	Massage
Duration	Short	It took less than 0.3s.	Hit, Kiss, Pat, Poke, Slap, Tap, Tickle
	Medium	It took between 0.3s and 0.6s.	Press, Toss, Grab, Scratch, Stroke
	Long	It took more than 0.6s	Lift, Pull, Push, Hug, Pinch, Squeeze, Rock, Nuzzle, Rub, Shake, Tremble and Massage
Pressure*	Gentle	The recorded pressures were less than 500*.	Pat, Stroke, Rock, Tap, Tickle, Scratch, Nuzzle
	Medium	The medium pressure was between 500* and 700*.	Toss, Poke, Rub, Shake, Tremble
	Strong	The recorded pressures were more than 700*.	Squeeze, Slap, Hit, Hug, Pinch, Kiss, Press, Grab, Lift, Pull, Push, Massage

* We used Arduino to collect pressure; the pressure was a relative value, and the pressure range was from 0–1023.

Four categories of social touch (Figure 3.2(b), Table 3.4) on the touchscreen based on hand/finger movement were extracted – including straight gestures on the touchscreen (SOT), straight gestures from the air (SFA), repetitive gestures (RPT) on the touchscreen, and kneading gestures on the touchscreen (KOT). These four categories were adapted from [160]:

- SOT gestures move from a resting position on the touchscreen with a straight trajectory to another position (so-called phasic gestures in [160]). Examples of SOT gestures are 'Scratch', 'Stroke', 'Lift', 'Pull', 'Push', 'Toss', 'Grab', 'Hug', 'Pinch' and 'Squeeze'.
- SFA gestures move from the air with a straight trajectory to one point on the touchscreen, with a quick contact with the touchscreen. Examples are 'Hit', 'Kiss', 'Pat', 'Poke', 'Press', 'Slap', 'Tap', and 'Tickle'.
- RPT gestures on the touchscreen have repetitive movements on the touchscreen. As shown in [160], repetitive gestures involve repetitive movements, resulting in metrical or rhythmical movements [160]. For example, in 'Rock', 'Nuzzle', 'Rub', 'Shake' and 'Tremble', participants moved their fingers up–down–up–down on the touchscreen.
- KOT gestures stay on the touchscreen with a kneading movement repetitively. These gestures refer to social touch expressing changing force primarily, such as 'Massage'.

3.4.3.2 Duration

The duration refers to the contact time that fingers touch the touchscreen. We did not consider the time when the hands/fingers were in the air.

To explore the characteristics of social touch based on the largest consensus, we considered the mean duration of each gesture in the same hand/finger movement. We excluded gestures that had no general characteristics with others because these gestures may be extreme cases, and their characters may not contribute to the description of the specific social touch.

Short-duration gestures included single taps on the touchscreen [146], which belong to the SFA group. They took less than 0.3s in the SFA group based on our recorded duration. Gestures in the SFA group ('Hit', 'Kiss', 'Pat', 'Poke', 'Slap', 'Tap', 'Tickle') were all categorized in the short-duration group.

Medium-duration gestures included 'Press', 'Scratch', 'Stroke', 'Toss' and 'Grab'. They belonged to the SFA group and the SOT group. 'Toss' and 'Grab' were two gestures that involved gesture movements in the air and took between 0.3 and 0.6s. The duration of the other gestures within the SOT group was longer than that of the SFA group, exceeding 0.6s in the SOT group.

Gestures categorized as long in duration included the rest of the gestures in the SOT group (‘Lift’, ‘Pull’, ‘Push’, ‘Hug’, ‘Pinch’ and ‘Squeeze’), RPT gestures (‘Rock’, ‘Nuzzle’, ‘Rub’, ‘Shake’ and ‘Tremble’) and KOT gestures(‘Massage’). They were all categorized in the long-duration group for more than 0.6s (Table 3.4).

3.4.3.3 Pressure

We considered the mean maximum pressure of each social touch in the same hand/finger movement. Although the pressure was changing on the touchscreen, the maximum pressure could be the main characteristic when describing a social touch [122]. We used the relative pressure recorded by Arduino, ranging from 0 to 1023.

Gentle pressure touch included ‘Pat’, ‘Nuzzle’, ‘Stroke’, ‘Rock’, ‘Tap’, and ‘Tickle’. The definitions of these social touch gestures included words like ‘gentle’ or ‘light’ [130]. The recorded pressure values were less than 500. According to recorded pressure, other gentle pressure touch included ‘Scratch’.

Strong pressure touch included ‘Squeeze’, ‘Slap’, ‘Hit’, ‘Hug’, and ‘Pinch’ because they were described using words like ‘firmly’, ‘sharply’, ‘tightly’, or ‘forcible’ [130]. The recorded pressure values were more than 700. According to recorded pressure, other strong pressure touch gestures included ‘Kiss’, ‘Press’, ‘Grab’, ‘Lift’, ‘Pull’, ‘Push’, and ‘Massage’.

Medium pressure touch included ‘Toss’, ‘Poke’, ‘Rub’, ‘Shake’ and ‘Tremble’. The medium pressure was between 500 and 700 (Table 3.4).

3.4.4 Subjective ratings

3.4.4.1 Ease of performing

A Friedman test indicated a significant effect of referent type on ease of performing (χ^2 (20)=154.589, p<0.001). The top eight (mean≥5.5) referents were ‘Pat’, ‘Press’, ‘Poke’, ‘Slap’, ‘Scratch’, ‘Tap’, ‘Stroke’ and ‘Tickle’. These social touch gestures had higher scores because the user-defined gestures on the smartphone touchscreen were the same as the social touch in real human-human interaction. Social touch gestures with lower ratings (mean≤4.5) were ‘Hug’, ‘Pull’, ‘Tremble’, ‘Grab’, ‘Lift’, ‘Kiss’, ‘Nuzzle’, ‘Rock’, ‘Toss’ and ‘Squeeze’. The user-defined gestures for these social touch gestures on the touchscreen were a metaphor of the social touch in real human-human interaction.

We also conducted the Spearman correlation analysis on ease of performing and agreement rate. We found a positive correlation between the agreement rate and ease of performing ($r_{(N=24)}$=0.430, p=0.036 (two-tailed)). This result indicated that gestures which were easier to perform had a larger consensus (Figure 3.5).

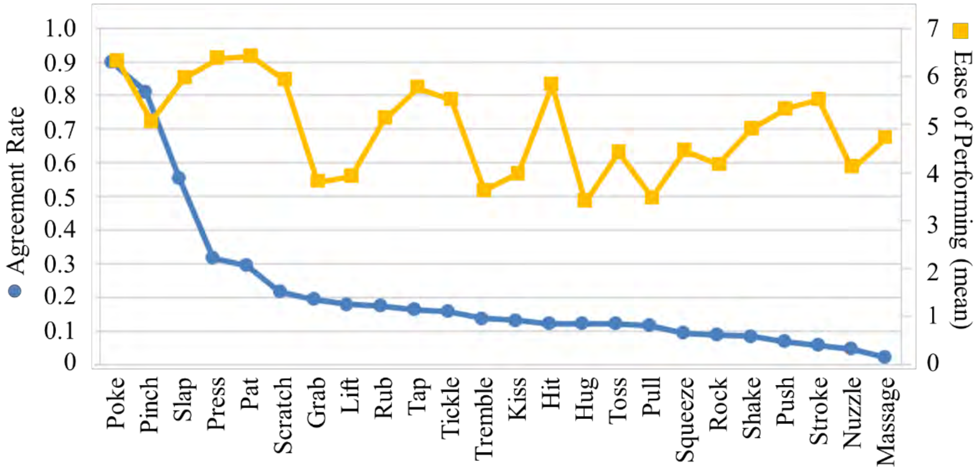


Figure 3.5 Correlation between agreement rate and ease of performing, Spearman's $r_{(N=24)}=0.430$, $p=0.036$ (two-tailed)

3.4.4.2 Usage frequency

A Friedman test indicated a significant effect of referent type on usage frequency (χ^2 (20)=122.655, p<0.001). Users were more likely to use social touch like 'Kiss', 'Poke', 'Stroke', 'Hug', 'Pat' and 'Tickle' (mean≥5). Users were less likely to use social touch such as 'Pull', 'Rub', 'Lift', 'Squeeze', 'Massage', 'Tremble', 'Rock' and 'Scratch' (mean≤3.5).

3.4.4.3 Relationship among ease of performing, usage frequency and touch properties

To find out if there were some correlations among ease of performing, usage frequency, and touch properties, we conducted the Spearman correlation analysis among these factors as follows (Figure 3.6):

1) *Ease of performing and usage frequency*. With 24 social touch gestures chosen from Touch Dictionary [130], there was a positive correlation between the ease of performing and the usage frequency ($r_{(N=24)}=+0.410$, $p=0.046$ (two-tailed)). People were inclined to use easier social touch more often. As [146] showed, the participants preferred simple user-defined gestures and believed that simple gestures were easier to perform and remember.
2) *Duration and ease of performing.* A negative correlation was observed between the duration and ease of performing ($r_{(N=24)}=-0.494$, $p=0.014$ (two-tailed)). Social touch gestures with shorter duration were easier to perform

because those short-duration gestures were mainly simple gestures, like 'tap' and 'poke', which were examples of simple gestures [146].

3) *Duration and usage frequency.* A negative correlation was observed between the duration and usage frequency ($r_{(N=24)}$=-0.483, p=0.017 (two-tailed)). As mentioned above, short-duration gestures were mainly simple gestures [146], such as 'tap' and 'poke'. Users were more likely to use these gestures often on smartphone touchscreens.
4) *Pressure, duration, ease of performing and usage frequency.* No significant correlations were observed between pressure and duration (p=0.105), pressure and ease of performing (p=0.231), pressure and usage frequency (p=0.271).

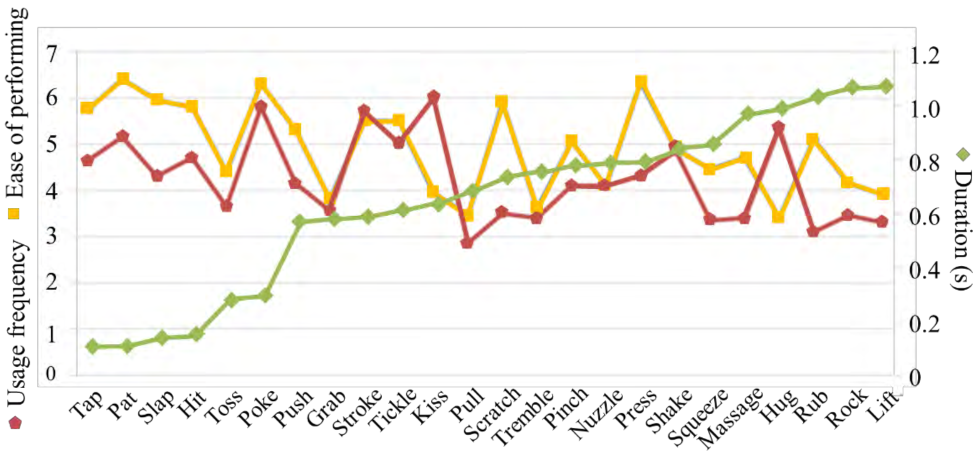


Figure 3.6 Correlation between duration and ease of performing, Spearman's $r_{(N=24)}$=-0.494, p=0.014 (two-tailed), and between duration and usage frequency, Spearman's $r_{(N=24)}$=-0.483, p=0.017 (two-tailed)

3.4.4.4 Hand/finger movement, ease of frequency and usage frequency

We explored if the hand/finger movement of social touch affected ease of performing and usage frequency. The values of the Likert scale from participants whose touch gestures were in the same hand/finger movement for each social touch were averaged and combined into one data set [161]. We excluded "Massage" (KOT group) because there was only one social touch in the KOT group.

1) *Hand/finger movement and ease of performing*. There were significant differences in the ease of performing in different hand/finger movements (F(2,22)=6.647, p=0.006). Post-hoc analysis (LSD) showed that significant differences were observed between the SFA group and the SOT group (p=0.004) and between the SFA group and the RPT group (p=0.007). No significant differences were observed between the SOT group and the RPT

group (p=0.746). The result showed that the SFA gestures were easier to perform because they were simple gestures and had a shorter duration and gentler pressure. These social touch gestures were easier to perform. Social touch gestures in POT and RPT groups were mostly metaphorical, and they were considered not easy to perform.

2) *Hand/finger movement and usage frequency*. There were significant differences in the usage frequency in different hand/finger movements (F(2,22)=5.137, p=0.016). Post-hoc analysis (LSD) showed that significant differences were observed between the SFA group and the SOT group (p=0.011) and between the SFA group and the RPT group (p=0.014). No significant differences were observed between the POT gestures and the RPT gestures (p=0.697). The result showed that the SFA gestures were considered to be used more often. This result was connected with the above results. Social touch in the SFA group (Table 3.4) were simple gestures. Simple gestures were considered to be used more often for touchscreen interaction (mentioned in 4.2.2).

3.5 Discussion and Limitations

In this study, we conducted an elicitation study. We obtained user-defined MST gestures on smartphone touchscreen considering touch properties and context. The user-defined MST gestures conform to the context of holding a smartphone in hand (e.g., text or video calling). We also collected pressure and duration of user-defined MST gestures. Based on these results, we discuss the limitations of the study and the implications for the design and application of our results in the field of MST signals.

3.5.1 Implications for user-defined MST gestures considering touch properties and context

Touch properties could expand the space for gesture differences. Wobbrock et al. [145] indicated that the same gesture might cause conflicts to invoke commands, so the referent with the largest group won the gesture. But sometimes, it was not possible to discard any referents since both referents would be used frequently. In this case, touch properties could help to differentiate social touch. For example, 'Rock' and 'Shake' could use the same user-defined gesture (Figure 3.3) with the pressures differed. Adding pressure to the gesture could help differentiate them.

Context could help to differentiate social touch when the touch gestures were the same and the pressures were similar. For example, 'Hug' and 'Squeeze' had the same gesture (Figure 3.3) and similar pressure (Table 3.3). Suppose one couple expressed love for each other with this gesture, so they may want to 'Hug' with each other rather than ‘Squeeze’, since ‘Squeeze’ sometimes could represent an emotion of anger or fear [9].

Based on the above, designers or researchers could take the context into consideration of design and take advantage of the unique touch properties and contexts in design for the differentiation. It is important to ensure that there are no conflicts in the MST gestures, which may confuse the users. For example, if we design vibrations to reflect MST gestures. ‘Shake’ should have a stronger intensity than ‘Rock’, since ‘Shake’ has a higher recoreded pressure than ‘Rock’.

3.5.2 Implications for gesture recognition of mediated social touch

Jung et al. [122] provided the Corpus of Social Touch and demonstrated that it was possible to recognize MST gestures. The primary data collected for gesture recognition in [122] were pressure (mean/maximum pressure variability/ per column/per row, and peak count), duration, and trajectory (contact area and displacement). We collected pressure, duration, and trajectory data. Designers or researchers could first confirm if the MST signals are for real-time transmission or not. If real-time transmission is needed, gesture recognition of MST may be needed.

3.5.3 Implications of hand/finger movement applications

Hand/finger movement may help simplify the MST signal design on a large scale. Social touch in the same hand/finger movement has similar touch properties. We could design MST signals on a macro-aspect first. For example, if we design MST signals with haptic stimuli, the vibration signal could be a short pulse in the SFA group because the contact time with the touchscreen is very short. In contrast, in the SOT group, the vibration signal could be long because the contact time in this group was mainly long. Then, within each group, pressure could be the factor that differentiates the social touch. Different amplitudes in vibration signals could control different pressures of the social touch.

Based on the above, designers or researchers could consider the type of MST signals for design, especially when many MST signals need to be considered. It is efficient to apply the common characteristics of MST gestures to simplify the design.

3.5.4 Implications from subjective ratings

The subjective ratings (ease of performing and usage frequency) could provide insights for MST signal design.

The main correlation results were: 1. Social touch with short duration was often easier to perform, 2. Social touch with easier hand/finger movement was usually used more often.

In design, we could design more forms for frequently used social touch and emotions. Designing more forms for frequently used features is commonly used in the application of current social networking. For example, smileys are used very frequently for emojis, so there are many types of emojis that express smileys, such as grinning face, beaming face with smiling eyes, and rolling on the floor laughing [165]. If we design through haptic stimuli, we could provide different vibration types for one social touch, as [76] showed a different combination of frequency, amplitude, duration, and envelope could present a similar emotional expression.

In the design of gestures that are not easy to perform, we may apply multimodal modalities to present MST signals (e.g., a combination of visual, audio, and tactile information). Multimodal modalities may provide an opportunity to simplify the gestures that users should perform physically. For example, we could design stickers or Gifs to visualize the gestures. Users just need to press the touchscreen to trigger the visual gestures, so they do not need to perform it physically.

Based on the above, designers or researchers could consider the needs of the application first. This entails checking if more types of stimuli of MST signals are needed for users and identifying what kind of stimuli and modalities that users prefer in different contexts to make the design more efficient and meet users' demands.

3.5.5 Implications for design abstract mediated social touch

The communication of emotion through touch could be another design space for MST signals. It has been demonstrated that touch communicates emotion [8], [29], [144]. Sometimes, there is no need to know the specific touch when expressing emotion, as many social touch gestures could express a similar emotion. This aspect could help simplify the design.

Based on the above, designers or researchers could consider if their target users need the precise MST signals or abstract emotion expressions. This may lead to different design methods.

3.5.6 Limitations

We only considered the smartphone touchscreen and ignored the spatial dimension of the smartphone (e.g., tilting, panning, and shaking the smartphone were not considered). For repetitive gestures such as 'Shake', 'Tremble' and 'Rock', some users asked if shaking the smartphone was possible during the experiment. This means that considering spatial dimension may be needed. In the future, we could consider the spatial dimension and compare the differences between two conditions (i.e., considering spatial dimension vs. ignoring spatial dimension). This consideration could provide a more comprehensive understanding of delivering MST signals via smartphones.

There are some limitations due to the age group of participants. We mainly recruited participants from the campus. We did not consider the age group under 23 or over 35. Teenagers or older people may have a different insight of performing MST gestures on touchscreens. However, participants we recruited were also active users of social media, and they could still cover a specific spectrum.

3.6 Conclusion and future work

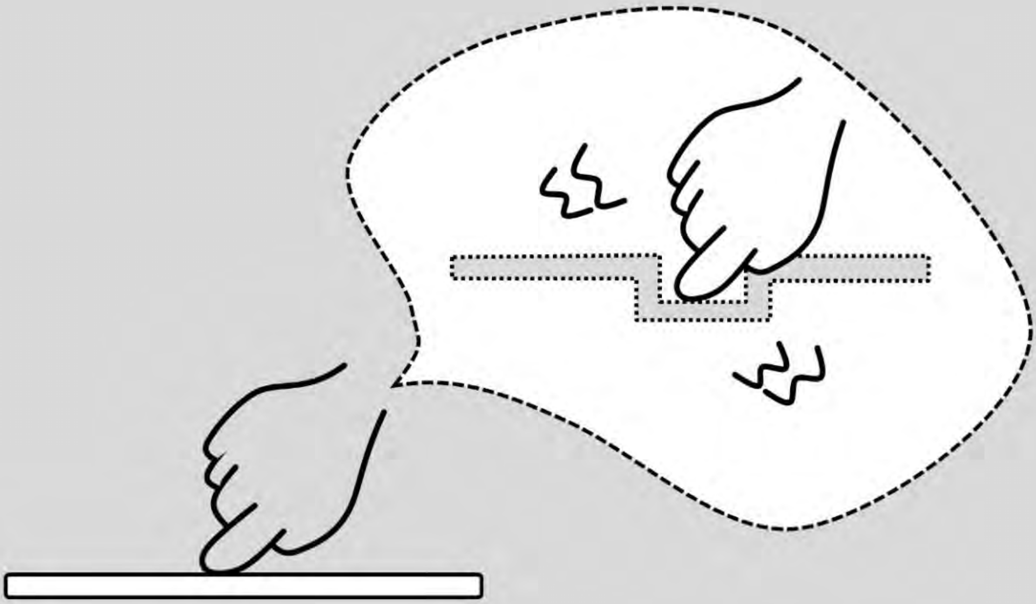
We conducted an elicitation study to explore MST gestures on the touchscreen of smartphones. Our main contributions are as follows:

- Quantitative and qualitative characterization of MST gestures.
- Gesture classifications based on nature, cardinality, hand/finger movement, duration, and pressure of all gestures.
- A user-defined MST gesture set on smartphone touchscreens considering touch properties and context.
- Implications for MST technology and its application.

In Chapter 5, we will try to apply the user-defined MST gestures and related data of touch properties (pressure and duration) collected in this chapter to design MST signals.

Chapter 4

Receivers Perceiving Vibrotactile Stimuli



This chapter is based on:
Q. Wei, M. Li, J. Hu, and L. M. G. Feijs, "Perceived depth and roughness of virtual buttons with touchscreens," *IEEE Transactions on Haptics*, vol. 15, no. 2, pp. 315–327, 2021.

Abstract
As most smartphones apply a linear resonance actuator to provide vibrotactile stimuli, we need to understand how users would perceive the vibrotactile stimuli and how it would be affected by signal parameters. This chapter mainly explores how signal parameters affect the users in perceiving vibrotactile stimuli on touchscreens.

Background: We choose graphical buttons as the carrier to present vibrotactile stimuli in this chapter. With the rapidly increasing penetration of touchscreens in various application sectors, sophisticated and configurable haptic effects can be rendered on touchscreens.

Methods: We present a generation method to instantiate a wide range of vibrotactile stimuli for rendering various graphical buttons on touchscreens. We generated and selected drive signals to render vibrotactile stimuli for graphical buttons through varying envelope shapes, superposition methods, compound waveform composition forms, durations, and frequencies. We study the perceived depth and roughness of rendered graphical buttons, which would be connected to the skin deformation and pressure applied to the skin for mediated social touch on touchscreens in Chapter 5.

Results: We find that the selected frequencies, durations, and the designed compound waveform composition forms significantly affect the users perceiving in vibrotactile stimuli. The results also show the perceived depth and roughness of graphical buttons increase when the frequency approaches the resonant frequency. Perceived depth and roughness decrease when the frequency moves away from the resonant frequency. A longer duration of vibrotactile stimuli and adding the number of pulses could increase the perceived depth and roughness. Perceived depth and roughness have a similar trend with varying frequencies at a fixed duration.

4.1 Introduction

Recently, touchscreens have been widely used on mobile devices. The simple mechanical structure, attractive look, and rich potential for visual rendering make touchscreens popular [166]. Recent technologies allow touchscreens to replace the physical keypads on mobile devices [166]. However, lacking haptic feedback from the machine would make users not confident in interacting with the touchscreens, which might increase input delays and errors [166]. Haptic feedback could help solve the problem.

With the advancement of the transducer and haptic technologies, haptic feedback combined with touchscreens is gaining momentum in various sectors. Most smartphones have embedded advanced haptic actuators [142] to provide haptic feedback. For example, the Taptic Engine in recent generations of iPhones (since iPhone 7) can provide haptic feedback to emulate various physical effects [143].

Taptic Engine is a typical wideband Linear Resonant Actuator (LRA), which not only has high energy conversion efficiency at the resonant frequency but also can render a relatively wider bandwidth when compared to traditional LRAs (such as the 0832 LRAs used in Samsung/LG/Huawei phones and 0815 LRAs used in HTC and Google phones) that have large Q values (the ratio of energy stored in the resonator to the energy dissipated per cycle [167]), although the frequency response at higher frequencies is still significantly lower than the resonant frequency. The industry confirms this is a promising field, given the richer capability to render more complex haptic effects.

We study graphical buttons in this chapter for the following reasons:

1) Graphical buttons play a crucial role in touchscreen-based systems as they are one of the essential mechanical elements that have been long used for human-machine interaction. Incorporating haptic feedback enhances users' input and interactive experience, making touchscreens with haptic feedback even more efficient than traditional mechanical buttons [142]. The key reason is that, although touchscreens usually have a non-deformable (or nearly rigid) surface, haptic feedback can potentially render a wide range of configurable sensations for various scenarios. In comparison, traditional mechanical buttons can only render a fixed and predefined sensation. Hence, it is crucial to understand how various sensations can be rendered.
2) Graphical buttons could be the carrier in presenting mediated social touch signals in the following chapters. We first use buttons when testing how users perceive vibrotactile stimuli because we want to build a design foundation from the perspective of human-computer interaction. Then we extend our study from human-computer interaction to computer-mediated human-to-human interaction.

For mimicking physical buttons on touchscreens with haptic stimuli, Liu et al. [168] mentioned that it was possible to emulate the feel of a button or key with 1-2 mm travel. Tan et al. [169] estimated human fingertip position resolution to be 2.2 mm during active free movements from a series of finger joint-angle discrimination thresholds. When the index finger presses on a solid surface, the fingertip tissues can yield up to about 2 mm [169]. Since humans cannot sense such a position change at the fingertip during active moments in free space, it might be possible to create the illusion of a virtual key yielding 1-2 mm under the fingertip instead of the fingertip being compressed by the same amount [168].

According to this perceptual cue, some researchers also tried to mimic the real effect of physical buttons on touchscreens. Kim and Lee [170] and Sadia et al. [171] designed haptic stimuli for graphical buttons on touchscreens. The research showed that the designed graphical buttons with haptic stimuli were realistic and distinctive.

Participants were able to associate different graphical buttons with their physical counterparts. These studies demonstrate that providing a realistic response of a physical button on the touchscreen with haptic feedback is possible. To be more specific, like physical buttons, users can feel an illusion of vertical travel when pressing a graphical button with specific haptic feedback on touchscreens.

In this chapter, we present graphical buttons on touchscreens with visual information and vibrotactile stimuli together. When users press the graphical buttons on the touchscreen, vision and touch both provide information for estimating the graphical buttons [133]. Visual information is helpful when judging size, shape, or position [133]. In this chapter, the gray squares (default settings of buttons from Android Studio) on the touchscreen help show a button-like image that could present an illusion of a button at first sight. We amplify the high-frequency tactile sensation using vibratory actuators to make the perception clearly affected by haptics.

We choose perceived depth and roughness in this chapter for the following reasons:

1) *Perceptual dimensions of vertical key clicks*. Liu et al. [168] have found that '***shallow – deep***' and '***rough – smooth***' are two perceptual dimensions of manual button clicks when focusing the tactile sensation associated with the vertical travel of the buttons and keys. Meanwhile, Sadia et al. [171] also revealed that 'rough – smooth' was a key perceptual dimension when participants rated the virtual push button with vibrotactile stimuli similar to its physical counterpart. Based on this understanding, we apply these two perceptual dimensions for exploring how users perceive vibrotactile stimuli when interacting with buttons.
2) *Skin deformation and pressure assumption*. We assume there are similarities between pressing a graphical button on touchscreens and pressing on human skin. If we think of the touchscreen as our skin, a deeper button press can be seen as causing more skin deformation. Similarly, when a graphical button feels rough, we tend to apply more pressure vertically, as if pressing harder on the skin.

In this chapter, we first generated drive signals for graphical buttons through varying envelope shapes, superposition methods, and compound waveform composition (CWC) forms. By comparing, analyzing, and selecting the vibrotactile stimuli, we determined signal parameters and their values significantly impacting the perceived differences between graphical buttons. Then, we evaluated graphical buttons with varying frequencies, durations, and CWC forms. We explored how these signal parameters affect the perceived depth and roughness of graphical buttons.

4.2 Related work

4.2.1 Application context of graphical buttons on touchscreens with vibrotactile stimuli

One typical application area is the mobile device. Users' performance when interacting with a touchscreen with haptic feedback has been explored for mobile devices. For the text entry task on the touchscreen [172], [173], [174], and the task path-finding task [142], users' input accuracy has improved with tactile feedback. Meanwhile, the tactile feedback makes the sensation of graphical buttons close to that of a real physical button [172]. Part et al. [166] and Pakkanen et al. [175] evaluated the users' preference of graphical buttons with haptic stimuli. They revealed design guidelines for realistic and favorable graphical buttons with tactile feedback.

4.2.2 Design methods of haptic stimuli for graphical buttons on touchscreens

A common way to generate haptic stimuli for graphical buttons is to set parameters of haptic stimuli according to a "feels like" sensation. Brewster et al. [173] and Okamoto et al. [176] directly modulated frequency, duration, and envelope shapes of haptic signals for a touchdown event as a feeling of pressing a button. Others [172] modulated frequency and envelope shapes for a button's pushing and releasing stage separately to create a "click" sensation on the touchscreen similar to a physical button.

Another way is to record objective signals when pressing a physical button and then modulate haptic signals according to the recorded signals to give users a similar sensation when pressing a graphical button. Kim and Lee [170] provided a design of graphical buttons with haptic feedback based on the force-displacement curves of a physical button. They recorded the Jump, Slope, and Bottom-out sections of a displacement curve. They mapped the displacement with vibrotactile stimuli by implementing a similar friction grain model. Park et al. [166] measured the accelerations of real button clicks to collect the time and vibration magnitude of the pushing and releasing stages. And they got an intrinsic frequency through Fast Fourier Transformation, which transformed the time-domain accelerations into the frequency domain [166]. The vibrotactile stimuli of graphical buttons were rendered on touchscreens according to the recorded signals of real button clicks. Sadia et al. [171] recorded and analyzed the force, acceleration, and voltage data of three types of physical buttons: latch, toggle, and push-buttons. Vibrotactile stimuli were generated for each button based on the recorded data.

Researchers generated haptic stimuli with varying parameters of signals for a large set of graphical buttons. In [177], the rise time and the displacement amplitude were two main parameters of the vibrotactile stimuli, controlled by the driving voltage and the current of the piezo actuator. Nishino et al. [178] applied three main parameters for desired tactile effects: vibration strength, activation time length, and vibration type. Park et al. [166] used three parameters for desired tactile effects: vibration strength, activation time length, and vibration type. Pakkanen et al. [175] generated haptic stimuli with various pulse shapes and displacement amplitudes to explore most pleasant haptic stimuli graphical buttons for graphical buttons. Besides, the haptics library of Texas instrument [179] presents a list of haptic signals with different amplitude modulation methods and different CWC forms, which can be used for graphical buttons.

4.2.3 Research opportunities

In summary, for the application context, most graphical buttons with haptic feedback were designed to enhance users' performance in a specific context (e.g., in a smartphone) for a specific task. Also, researchers tried to generate graphical buttons with haptic stimuli which have a similar sensation as pressing a real physical button and tried to explore the most pleasant haptic stimuli for graphical buttons on touchscreens.

However, there are research opportunities in generating a larger set of graphical buttons with different perceived depth and roughness. Different effects with various sensations for graphical buttons are essential because they can be applied in different contexts of different applications. These contexts and applications refer to various scenarios when a button needs to be used with different haptic effects. For example, safety crucial graphical buttons in automotive applications should give the user strong/deep/rough haptic feedback. While for dial-pad for smartphone use cases, buttons should give the user soft/gentle/shallow haptic feedback.

Meanwhile, most researchers tried to mimic the haptic effects of physical buttons for touchscreens, so they set specific values of standard parameters like frequency and duration for haptic stimuli.

However, there is no generation method provided. It lacks the discussion of specific sensations such as perceived depth and roughness. We design the drive signals aiming at reaching different perceived depth and roughness of graphical buttons on touchscreens.

Hence, there are research opportunities in providing ***a generation method and the experiment-driven understanding of various signal parameters and perceived sensations***. In our study, we will discuss what sensations can be reached with different haptic stimuli. As Liu et al. [168] also suggested exploring the parameters corresponding to the perceptual dimensions and design graphical buttons using the relevant parameters.

In this study, we use a smartphone that has mechanical structure embedding a wideband LRA. We aim to generate a large set of drive signals with varying signal parameters and convert them into vibrotactile stimuli for graphical buttons with different perceived depth and roughness.

4.3 Apparatus and technologies

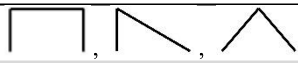
4.3.1 Prototype

The experiment device is a reworked version of the LG V30 smartphone. The phone contains a typical wide-band LRA motor (MPlus 1040) which can convert drive signals into vibrotactile stimuli. It can also present audio stimuli at the same time. The rework of the special LG V30 phone includes the following key elements: the original 1040 LRA was replaced by a wider band 1040 LRA with a lower Q value. The original driver circuit was replaced by a new driver based on a class-D audio amplifier (similar to that in iPhone). The haptic signal was then generated by the audio amplifier and its associated software. When the test Android APP needs to trigger a haptic effect, an audio-like waveform is sent to the audio amplifier to drive the aforementioned LRA in the phone. The following adjustments have been made to enable this study:

- Although the standard Android operating system supported simple haptic interface APIs that could only render limited effects, we have modified the underlying software so that audio-like haptics signals could be used to render much richer set of vibrotactile stimuli.
- A boosted (from 3.6V battery voltage to 10V) class-D audio amplifier was used (similar to the latest iPhone generations from iPhone 7) for the reproduction of the above audio-like haptics drive signal so that the wide-band LRA was capable of reproducing the intended amplitudes of the intended frequencies in the study. The “boosted” audio amplifier could boost the battery output voltage to 10V maximum and then drive the LRA. So, although the battery was 3.84V, 3300mAh, when measuring the voltage amplified and applied on the LRA, up to 10V could be measured (in fact, only for peak signals). This way, the LRA could be driven with much higher peak power to render sharp effects without problems. iPhone Taptic Engine follows the same principle as well.
- The audio interface – ESI U24XL was used in the recording path for the vibration signal, but not the reproduction path. We followed a realistic scenario of practical usage for haptic rendering, so the phone’s internal battery was used. We used the power supplied by the USB ports of the testing PC to record vibration signals.
- According to [170], we used an accelerometer (DRV-ACC16-EVM, with three axes) to measure the frequency response of the actuator (Figure 4.1 shows the Z-axis). The device resonates at 160Hz.

- Drive signals were generated through MATLAB R2018a with a set of parameters listed in Table 4.1. We developed an interface presenting all trials of graphical buttons through Android Studio (API: 25) (Figure 4.2). To control the effects from the visual information, we set all the graphical buttons in the same shape, size, and grey color. For animations, we applied the default setting of buttons in Android Studio when pressing and releasing graphical buttons.

Table 4.1 Parameters of drive signals

Parameters	Values
Envelope shapes*	
Superposition methods*	A, B, C
CWC forms*	Form I, Form II, Form III
Frequency**	60Hz, 90Hz, 150Hz, 300Hz, 400Hz, 450Hz, 2200Hz
Duration (t_0)**	0.01s, 0.03s

Duration (t_0) refers to the duration of an elementary pulse.
Envelope shapes are for the elementary pulse.
Parameters* we considered in the design of the drive signals.
Parameters** we considered in the evaluation.

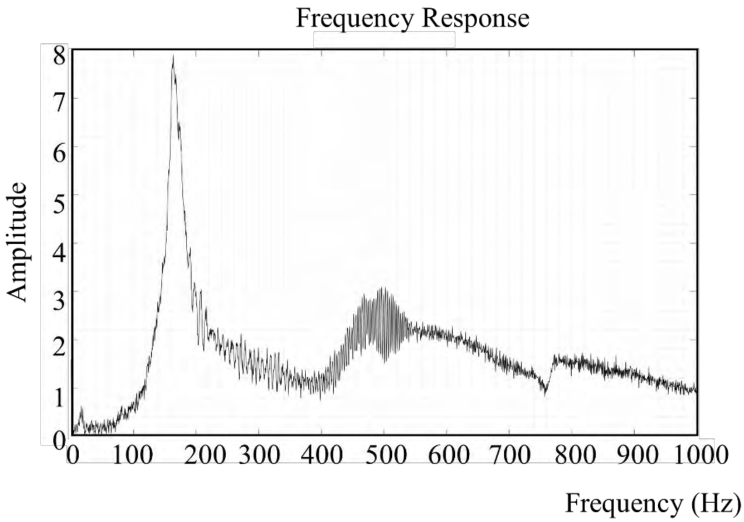


Figure 4.1 The frequency response of the system using a smartphone mockup

Figure 4.2 The interface of the evaluation with 30 graphical buttons

4.3.2 The recording method of the acceleration on touchscreens

An accelerometer (DRV-ACC16-EVM, with three axes) and an audio interface (ESI U24XL) were employed to record the acceleration data of graphical buttons on the touchscreen (Figure 4.3). We did not use the internal accelerometer since its location is not obviously known and different for every phone. Applying the internal accelerometer would make experiments less repeatable. And its maximum sampling frequency was too low (around 200Hz with the fastest mode), while we were sampling at a much higher frequency.

The DRV-ACC16-EVM converted physical acceleration to analog signals. The analog signal was then amplified and converted to a digital signal by ESI U24 XL. The digital signal was transmitted via USB cable to the PC and then accessed with MATLAB via the driver for ESI U24 XL. Displaying and processing of the acquired signal were done using MATLAB. The smartphone was placed on a foam pat, a typical way to measure such signals in the industry. The material property of the foam was optimized so that low-frequency vibration was minimally damped.

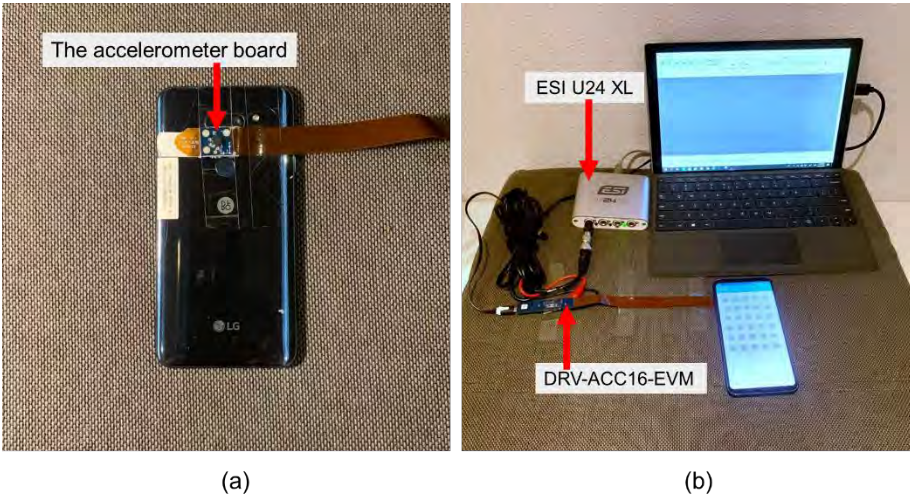


Figure 4.3 (a) The small accelerometer board was attached to the back of the smartphone with transparent adhesive tape. (b) The recording installation.

The small accelerometer board was attached to the back of the smartphone with transparent adhesive tape to make it stable when recording the acceleration (Figure 4.3(a)). The vibration measurement was done on one single point on this phone: location of the home key. This location was the most interesting one because it was where the thumb and palm feel the vibration based on this phone. When measuring the vibration, only the sensor part of the DRV-ACC16-EVM was attached to the phone using Blue Tack, which did not show differences compared to the glue-based attachment.

We connected the ESI U24 XL as an input to the Z-axis test points on the measurement board. The ESI U24 XL was connected to Audacity on a computer to display and record the acceleration (Figure 4.3(b)).

The average acceleration on Z-axis was recorded as audio with a sampling frequency of f=44100Hz. Accelerations of graphical buttons were recorded several times, and we selected the most stable sample for further analysis.

4.4 Design of the drive signals

In this part, we describe a generation method and related functions of drive signals for graphical buttons on touchscreens. We applied the generation method and chose signal parameters for the evaluation.

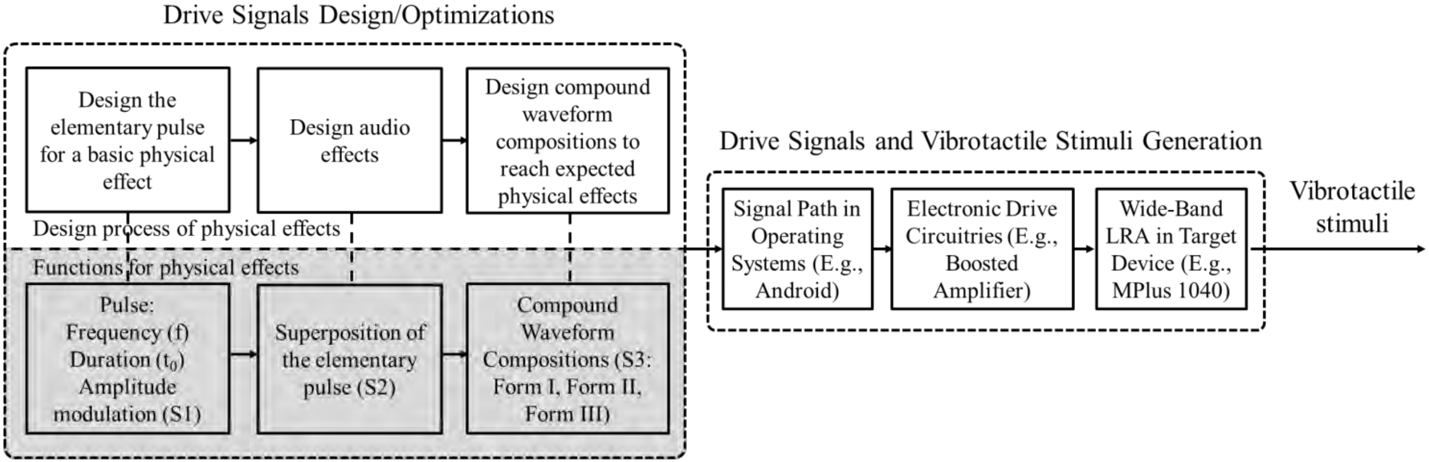


Figure 4.4 Overview of the generation method of the stimuli. There are three steps (S1, S2, and S3) to design drive signals. After determining the elementary pulse, audio effects should be chosen. Then, three CWC forms are presented to get final drive signals. The final vibrotactile stimuli would be converted and presented by the LRA.

4.4.1 Generation methods

This part provides the generation method of drive signals for graphical buttons on touchscreens (Figure 4.4). The dashed box on the left side describes the main procedure to design drive signals. The upper row in the left dashed box shows the design choices of physical effects. The bottom row in the left dashed box shows the function generation to create physical effects. The dashed box on the right side describes the main procedure to convert the drive signals to vibrotactile stimuli.

There are three steps of drive signals design:

1) The first step (S1) is to design the elementary pulse for a basic physical effect. We set the frequency and the duration and modulated the elementary pulse with different envelope shapes. This general amplitude modulation method is also used in [180] and [181] for signal design.
2) The second step (S2) is to design audio effects. In the later evaluation, we primarily focus on testing stimuli on a haptic level. However, we also recognize the importance of considering the design of audio effects as S2 in the generation method. There are several reasons for this decision:
    - Firstly, the LRA used in our study can convert the drive signal into both vibrotactile and audio stimuli simultaneously. Even small changes in the waveform had a significant physical impact on how the sound was perceived. Consequently, it becomes crucial to ensure that the audio stimuli provided by the drive signals mimic those experienced sounds when pressing a physical button. This step ensures that our research accurately represents real-world scenarios.
    - Secondly, our generation method and the function A(t) (4 – 1) are based on multimodal graphical buttons. Although our evaluation only focuses on vibrotactile stimuli as a preliminary assessment in this chapter, our future plans involve incorporating both haptic and audio stimuli. Therefore, we consider multimodal stimuli from the start, recognizing their importance in our design when proposing generation methods.
    - Lastly, we aim to determine the efficiency of the second step in our proposed generation method by investigating whether the superposition methods significantly impact the vibrotactile stimuli within our prototype. This analysis will enable us to evaluate the effectiveness of our generation method and understand the extent to which the superposition methods affect the desired outcomes.

    We consider the superposition of signals in this step, combining vibrotactile and audio effects simultaneously. Humans have a hearing sensitivity range of 20Hz to 20000Hz [182], [183], while fingertips are particularly sensitive to vibrations between about 50Hz and 1000 Hz [184]. Landström et al. [185] show that the levels of frequencies below 250 Hz often do not reach the hearing perception threshold. As a result, higher frequencies tend to be more perceptually significant in terms of sound levels, making individuals more sensitive to them.

3) The third step (S3) is to composite the compound waveforms to create different physical effects.

For drive signals design, we first need an elementary pulse that provides elementary effects. We propose the following general expression for the elementary pulse:

$$A(t) = \left[\sum_{k=1}^{n} I_k(t) + c \cdot R(t)\right] \cdot [u(t) - u(t - t_0)], n \in N_+,$$
$$I_k(t) = O_k(t) \cdot sin2\pi f_k t \qquad (4-1)$$

$A(t)$ is a general function for generating an elementary pulse. Multiple frequencies can be used at the same time to render complex effects. f_k is the possible frequency of drive signals in Hz, t_0 is the duration of the elementary pulse, n is the number of drive signals for superposition without considering the noise signal. $u(t)$ is a step function. $O_k(t)$ is the envelope function that is used to modulate drive signals. $R(t)$ generates random noise, and we use the $rand()$ function in MATLAB for it, while the coefficient c determines the amplitude of the random noise. The noise signal is optional to render more sophisticated sensations associated with real-life buttons, especially mimicking the sound of physical buttons.

4.4.2 Parameters

We chose the sinewave as the waveform since Dabic et al. [186] revealed no role in the waveform for perceived differences of short vibrotactile feedback on touchscreens. Furthermore, Yoon et al. [187] have found that sinewave was rated more comfortable than other waveforms (e.g., square or sawtooth waveforms).

In the subsequent evaluation, we will consider both frequency and duration. Notably, Dabic et al. [186] have highlighted the impact of frequency on perceived differences of short vibrotactile stimuli. Furthermore, duration also plays a crucial role in perceiving vibrotactile stimuli, particularly when the feedback is short. Consequently, in this section, we focus solely on examining envelope shapes, superpositions, and CWC forms. For all stimuli in this section, the baseband frequency was fixed at 150Hz, and the duration of the elementary pulse was fixed at 0.01s ($t_0 = 0.01s$).

4.4.2.1 Envelope shapes

We chose envelope shapes according to the characteristics of the vibration of buttons and the advantages of the LRA applied in this study.

We considered three forms of envelope shapes (ramp, triangle, and square) (Table 4.1). Sadia et al. [171] recorded the actual acceleration, including time before and after the peak point. To mimic this acceleration, we used the triangle shape. The LRA could start vibrating and reach the peak point in a very short time, so we applied a ramp-down envelope shape to optimize its performance. The square shape was included for comparison with the other two envelope shapes.

The functions for envelope shapes are as follows:

$$O_{ramp}(t) = (-1/t_0)t + 1, \quad 0 < t \leq t_0 \qquad (4-2)$$

$$O_{triangle}(t) = \begin{cases} (2/t_0)t, & 0 < t \leq t_0/2 \\ (-2/t_0)t + 2, & t_0/2 < t \leq t_0 \end{cases} \qquad (4-3)$$

$$O_{square}(t) = 1, \quad 0 < t \leq t_0 \qquad (4-4)$$

$O_k(t)$ in (4 – 1) is the envelope function used to modulate the elementary pulse. It is described in (4 – 2) when the envelope shape is ramp down, described in (4 – 3) when it is a triangle, described in (4 – 4) when it is a square (see envelope shapes in Table 4.1).

4.4.2.2 Superposition methods

Superpositions in the generation method are primarily focused on incorporating audio effects for the graphical button (as mentioned in section 4.1). However, since our study does not specifically examine the impact of audio, we utilized superpositions based on the experiences of researchers. Within this study, we employed three distinct methods, named A, B, and C, for signal superposition, allowing us to explore their potential implications.

In the first method (A), we applied a simple and elementary effect like other studies did ([180] and [181]). We did not conduct additivity or homogeneity in the superposition.

In the second method (B), we applied high frequencies in superpositions. In this study, our intention was not to test the effect of high frequency on audio levels. Instead, we simply needed a high frequency signal to show a superposition effect. Based on researchers' experiences, we applied a sinusoidal signal with high frequencies of 400Hz and 2200Hz (the amplitude was set as 0.3 to make a less audio cut for the drive signal). Additionally, we used a sinusoidal signal with a low frequency of 150Hz.

Consequently, users could feel the vibration at 150Hz while perceiving the sound frequencies of 400Hz and 2200Hz.

In the third method (C), a sinusoidal signal and a white noise were applied for the superposition, as we wanted to apply noise to mimic the sound of physical buttons. Detailed values of each superposition method are in Table 4.2. Figure 4.5 shows the three superposition methods.

Table 4.2 Properties of typical signals

Signal number	Envelope shapes	Superposition Methods*	CWC Forms
P1		A	I
P2		A	I
P3		A	I
P4		A	II
P5		B	II
P6		C	II
P7		A	III
P8		B	III
P9		C	III

Specific values of each superposition methods* are as follows:

A: n=1, $t_0 = 0.01s$, for I_1, $f_1 = 150Hz$, $O_1(t) = O_{ramp}(t_0)$, $c = 0$;

B: n=2, $t_0 = 0.01s$, for I_1, $f_1 = 150Hz$, $O_1(t) = O_{ramp}(t_0)$, for I_2, $f_2 = 400Hz$, $O_2(t) = 0.3$, for I_3, $f_3 = 2200Hz$, $O_3(t) = 0.3$, $c = 0$;

C: n=1, $t_0 = 0.01s$, for $I_1, f_1 = 150Hz$, $O_1(t) = O_{ramp}(t_0)$, $c = 0.3$.

Recorded accelerations are in Figure 4.6.

4.4.2.3 CWC forms

We designed CWC forms for physical effects (perceived depth and roughness in this study). Different CWC forms of drive signals in this study are based on the combination of the elementary pulse.

Besides the elementary pulse, we provided two other CWC forms to influence graphical buttons' perceived depth and roughness.

We assume that increasing the duration of the stimulus would increase the perceived depth of graphical buttons, as a longer duration provides a longer response. Meanwhile, a longer response of vibration leads to a different perception when the frequency is fixed [186]. So, we regarded that this could increase perceived roughness at the same time. We added a continuous decreasing signal to the elementary pulse to mimic the elastic effect of physical buttons.

We assume that increasing the number of pulses would enhance the perceived roughness of graphical buttons, as more than one pulse could provide an uneven and grainy effect. We added another pulse signal here. Meanwhile, adding another pulse increases the duration of the signal. We regarded that this could increase the perceived depth at the same time. Together with the elementary pulse, we have three CWC forms in this study.

In Figure 4.5, the drive signal in Form I (F_1) contains an elementary pulse; Form II (F_2) contains an elementary pulse with a fading out signal; Form III (F_3) contains two elementary pulses. Using mathematical language, F_1, F_2 and F_3 for CWC forms are determined by

$$F_1(t) = M(t), \quad 0 < t \leq t_0 \qquad (4-5)$$

$$F_2(t) = \begin{cases} M(t), & 0 < t \leq t_0 \\ M(t)E(t), & t_0 < t \leq t_0 + (\mathrm{b} - \mathrm{a}) \end{cases} \qquad (4-6)$$

$$F_3(t) = \begin{cases} M(t), & 0 < t \leq t_0 \\ 0, & t_0 < t \leq T \\ M(t-T), & t > T \end{cases} \qquad (4-7)$$

where $M(t)$ is the elementary pulse, it could be the general function for generating an elementary pulse $A(t)$ (4 – 1) with different values. T is the period before the second pulse is activated (Form III in Figure 4.5). We do not test the preferable effects of T in this study. We just need stimuli to mimic an uneven and grainy effect. We select $T = 0.04s$, following an iterative process [175] by observing the performance of different choices. Research conducted by Hale and Stanney [188] revealed that a minimum interstimulus interval of 5.5ms is required to perceive distinct stimuli. In our specific scenario with a value of $T = 0.04s$, the resulting interstimulus interval exceeded the threshold of 5.5ms. Thus, the implementation of separate stimuli can be employed effectively to replicate an uneven and grainy effect. In this study, $E(t)$ is a part of an exponential function of the envelope shape to modulate stimuli, which is determined by

$$E(t) = \exp[-k(t + a - t_0)], \; t_0 < t \leq t_0 + (\mathrm{b} - \mathrm{a}) \qquad (4-8)$$

where (a,b) is the range to constrain the signal that we need. The function represents the envelope of the modulated signal. $(\mathrm{b} - \mathrm{a})$ is the extra duration adding to the elementary pulse.

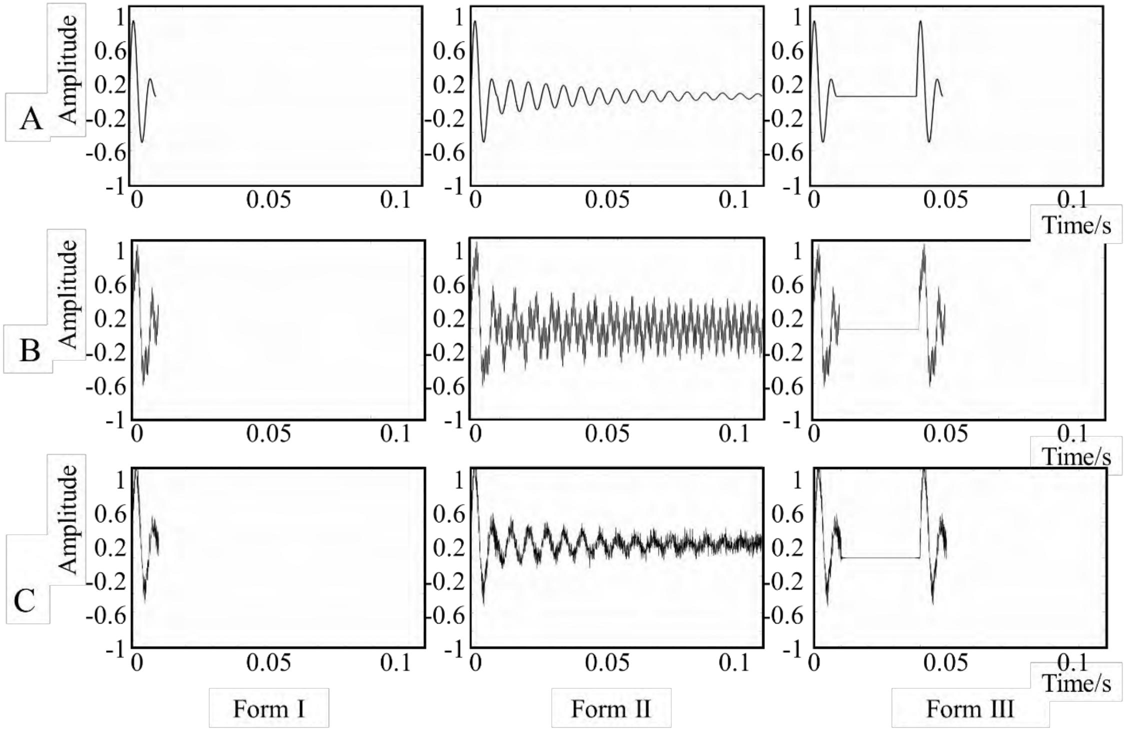


Figure 4.5 Introduction of three superposition methods and three CWC forms of drive signals. As this figure mainly shows the superposition methods and CWC forms, the envelope shapes of the above drive signals are all set as ramps. For CWC forms, Form I contained an elementary pulse (t0 is the duration of the elementary pulse), Form II contained an elementary pulse with a gradually fading out signal, Form III contained two elementary pulses. The superposition methods, namely A, B, and C, are applied from top to bottom.

We did not test the preferable effects of a, b, or k in this study. We just need an envelope shape with a low amplitude with a trend of fading out to mimic the elastic effect of physical buttons. So, we select $a = -2.82,\ b = -2.92,\ k = 20$, following an iterative process [175].

Other detailed values are in Table 4.1, Table 4.2, and Table 4.3.

In the context of presenting graphical buttons on touchscreens, we set the drive signals for pressing and releasing the button the same. The reason is that Pakkanen et al. [175] have conducted a study that has revealed users preferred a design called 'Simple design'. This means that the same stimuli should be used when moving towards or away from the graphical button.

4.4.3 Selecting parameters for the evaluation

The next step is to decrease parameters for the evaluation since all combinations (3*3*3*5*2=270) of the five parameters are too many to test (Table 4.1). Meanwhile, different combinations may reach a similar effect. So, we compare, analyze, and select parameters for the evaluation.

As frequency and duration would be tested in the evaluation (mentioned in section 4.2), we only discuss envelope shapes, superposition methods, and CWC forms in this section. The accelerations of typical vibrotactile stimuli converted from drive signals were recorded and presented in Figure 4.6.

4.4.3.1 Envelope shapes

Figure 4.6 shows that recorded accelerations in Form I and Form III are similar, no matter which envelope shape is applied for the drive signals. As the duration of one pulse was too short, the fine envelope shape could not be observed.

In Form II, the different envelope shapes were applied on the short pulse. The envelopes of the adding fading out signals were the same. So, the envelopes of the recorded accelerations in Form II are also similar.

We only need one envelope shape when the duration is such short. Maybe the envelope shape would lead to different acceleration when the duration was longer, but it was beyond the scope of this study.

The square envelope shape was excluded because of an amplitude cut of the drive signals when applying different superposition methods. Finally, we choose a decaying ramp envelope for the elementary pulse for the evaluation.

4.4.3.2 Superposition methods

Figure 4.6 shows that in Form I and Form III, the recorded accelerations are similar and are not affected by superposition methods significantly when regarding haptic effects as a single interaction modality. In Form II, the small differences of three recorded accelerations due to superposition methods would not significantly affect the perceived differences of vibrotactile stimuli. So, users could feel the vibration at low frequency and hear out the sound at high frequency (superposition methods B) or white noise (superposition methods C).

On the audio level, we excluded superposition methods B and C since the audio effects of B and C can hardly be perceived as possible sound effects from physical buttons when the CWC form is Form II. Thus, we chose superposition method A for the elementary pulse (see Form I (A) in Figure 4.5).

4.4.3.3 CWC forms

Figure 4.6 shows the recorded accelerations of three CWC forms are different. We take all three CWC forms into the evaluation for further analysis.

4.5 Evaluation

The research aim of the evaluation is to explore how frequencies, durations, and the designed CWC forms affect the perceived depth and roughness of graphical buttons on touchscreen. There are two tasks in this part. The first task test frequency and duration of the elementary pulse. We want to explore if the perceived depth and roughness of graphical buttons on touchscreens increase when the frequency approaches the resonant value of the actuator, and if a longer duration of the elementary pulse increases the perceived depth and roughness of graphical buttons on touchscreens. The second task focus on the designed CWC forms. We want to explore if increasing the duration of the stimulus could increase the perceived depth and roughness of graphical buttons on touchscreens. And if increasing the number of pulses could increase the perceived depth and roughness of the graphical button on touchscreens.

4.5.1 Stimuli

We generated drive signals through various combinations of frequencies (60Hz, 90Hz, 150Hz, 300Hz, 450Hz), durations of the elementary pulse (0.01s, 0.03s), and CWC forms (Form I, Form II, Form III).

The actuator resonates at the frequency of 160Hz (Figure 4.1). To protect the actuator, we chose 150Hz instead of the resonant frequency to present a strong vibration. We regarded the resonant frequency as the center. Besides 150Hz, we needed some frequencies away from the resonant frequency. Hatzfeld and Kern [184] have demonstrated that the frequency of good sensitivity on fingertips for vibration starts around 50Hz. According to Figure 4.1, we chose 60Hz, 90Hz, 300Hz, and 450Hz to present weaker vibration than 150Hz.

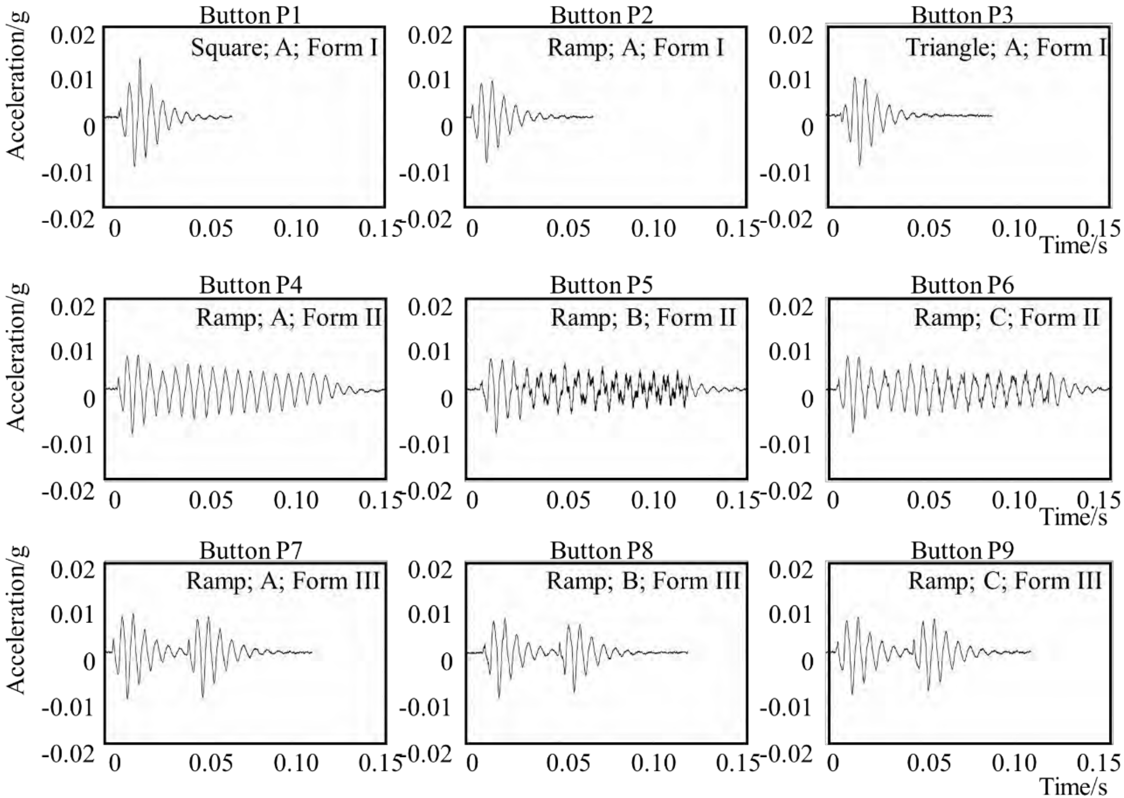


Figure 4.6 Above are recorded accelerations of typical vibrotactile stimuli of graphical buttons converted with 9 typical drive signals (Table 4.2) through an LRA. The frequency of drive signals is 150Hz, the duration of the elementary pulse is 0.01s. Above are the acceleration of the pressing stage of each graphical button.

There were three groups of graphical buttons based on three CWC forms. In Table 4.3 and Figure 4.7, graphical buttons in Form I include button M1 to button M10. Graphical buttons in Form II include button M11 to button M20, while button M21 to button M30 are in Form III. The recorded acceleration of graphical buttons is in Figure 4.7.

4.5.2 Methods

4.5.2.1 Participants

Twenty participants (ten males and ten females) aged from 23 to 35 participated in this study. All participants have no constraints of sensing touch, according to their report. Participants wear noise-canceling headphones playing white noise, which has no pitch or rhythm to block out the sound effects of vibrotactile stimuli (Figure 4.8).

Figure 4.8 Experiment environment.

4.5.2.2 Questionnaires

A questionnaire was created to collect data from participants. Two parts were aimed at two tasks in the questionnaire. In the first part, the questionnaire was set according to Liu et al. [168]. Questions about perceived depth and roughness were constructed with a 10-point Likert scale that ranged from 1 (very shallow) to 10 (very deep) and from 1 (very smooth) to 10 (very rough). In the second part, participants were asked to rank the perceived depth and roughness among specific graphical buttons. The questionnaire was displayed on the computer.

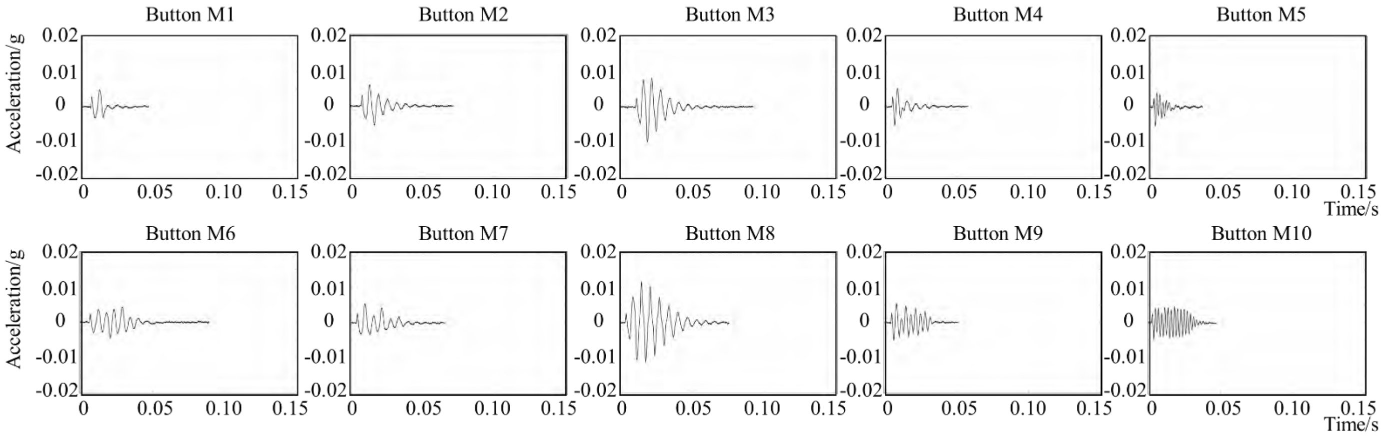
Table 4.3 Properties of 30 drive signals in the evaluation

Group	Drive Signals	Frequency	Duration (t_0)	CWC forms	Drive Signals	Frequency	Duration (t_0)	CWC forms	Drive Signals	Frequency	Duration (t_0)	CWC forms
1	M1	60Hz	0.01s	Form I	M11	60Hz	0.01	Form II	M21	60Hz	0.01s	Form III
2	M2	90Hz	0.01s	Form I	M12	90Hz	0.01	Form II	M22	90Hz	0.01s	Form III
3	M3	150Hz	0.01s	Form I	M13	150Hz	0.01	Form II	M23	150Hz	0.01s	Form III
4	M4	300Hz	0.01s	Form I	M14	300Hz	0.01	Form II	M24	300Hz	0.01s	Form III
5	M5	450Hz	0.01s	Form I	M15	450Hz	0.01	Form II	M25	450Hz	0.01s	Form III
6	M6	60Hz	0.03s	Form I	M16	60Hz	0.03	Form II	M26	60Hz	0.03s	Form III
7	M7	90Hz	0.03s	Form I	M17	90Hz	0.03	Form II	M27	90Hz	0.03s	Form III
8	M8	150Hz	0.03s	Form I	M18	150Hz	0.03	Form II	M28	150Hz	0.03s	Form III
9	M9	300Hz	0.03s	Form I	M19	300Hz	0.03	Form II	M29	300Hz	0.03s	Form III
10	M10	450Hz	0.03s	Form I	M20	450Hz	0.03	Form II	M30	450Hz	0.03s	Form III

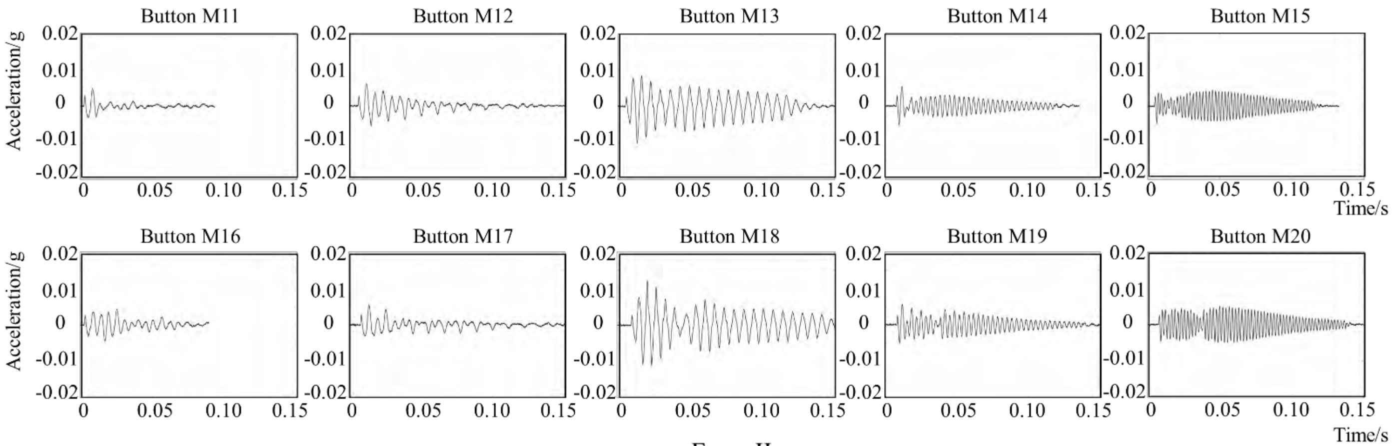
Group 1 to group 10 are for the ranking task in the evaluation.

Duration (t_0) is the duration of the elementary pulse (Figure 4.5); "CWC forms" are compound waveform composition forms.

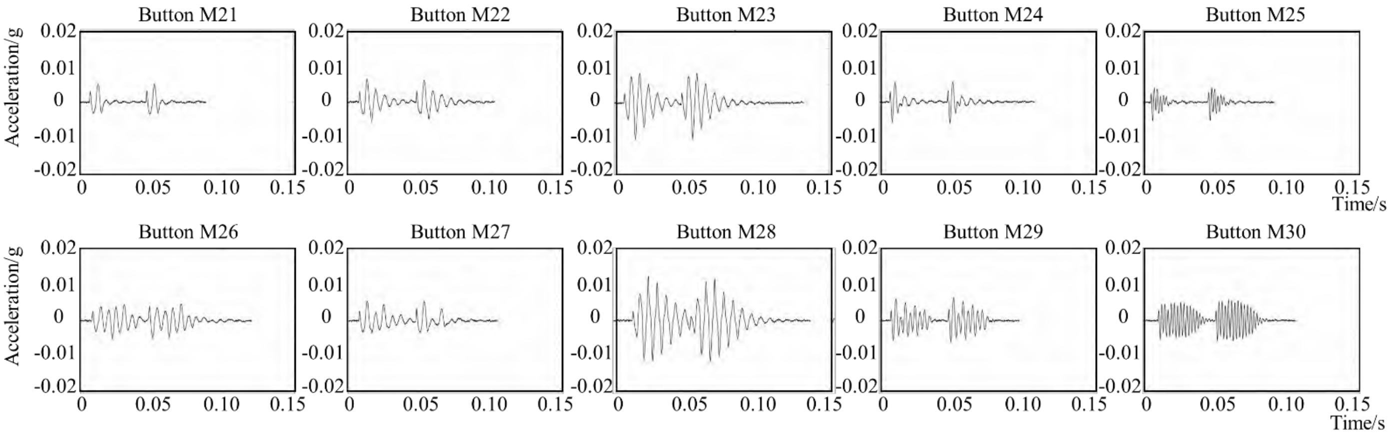
Form I: the drive signals in this group are an elementary pulse, including M1 to M10. Form II: the drive signals in this group are an elementary pulse with a gradually fading out signal, including M11 to M20. Form III: the drive signals in this group are two elementary pulses, including M21 to M30.



Form I



Form II



Form III

Figure 4.7 Recorded acceleration of 30 graphical buttons in the evaluation. Specifically, the recorded acceleration captures the pressing stage of each graphical button.

4.5.2.3 Procedures

There were two tasks in this study. The first task was to perceive and evaluate the perceived depth and roughness of three CWC forms of graphical buttons individually (Table 4.3 and Figure 4.7: Form I, Form II, Form III). Participants tested three CWC forms in a random order. In each CWC form, there were 10 stimuli with various frequencies and durations. The order of 10 stimuli was randomized initially. Participants first tried graphical buttons on touchscreens for a training session to feel possible perceived depth and roughness since perceived depth and roughness were relative instead of being absolute. The order of sensing the perceived depth and roughness was counterbalanced for each participant, which meant one participant tested the perceived depth first while the next participant tested the perceived roughness first.

The second task was a ranking task where participants were asked to rank the perceived depth and roughness of graphical buttons. There were three graphical buttons in each group for ranking, with ten groups of graphical buttons in total in this task (Table 4.3: group 1 to group 10). One group had three CWC forms. The frequency and duration of the elementary pulse in each group were fixed. The task was to press and compare graphical buttons within each group, so it was considered that randomizing the order in each group was not needed [175]. All the randomized orders in this study were delivered to each participant before testing with the questionnaire. Participants followed the order and the number of graphical buttons they got and felt the graphical buttons. The orders were obtained by the random function in Python.

This study complied with minimal risk according to the checklist for automatic approval from Ethical Review Board (July 2020) of Eindhoven University of Technology.

4.5.3 Results

In the first task, we used SPSS 23.0 to conduct a two-way repeated-measures ANOVA. Then, we applied Bonferroni analysis for the post hoc test to explore the trend of the perceived depth and roughness with varying frequencies. Finally, we conducted a Spearman correlation analysis to check the correlation between perceived depth and roughness. Two fixed durations of the elementary pulse (0.01s and 0.03s) were tested separately.

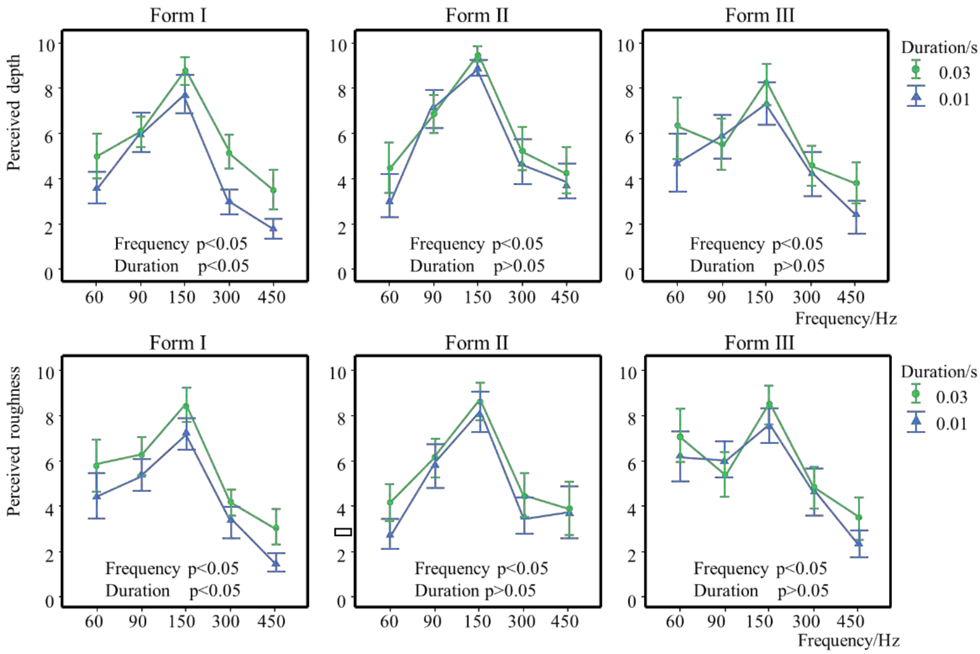


Figure 4.9 Perceived depth and roughness (averaged scores of all participants)

Pairwise comparisons were conducted between constructive frequencies. We only considered two neighboring frequencies as a pair, resulting in four frequency pairs (pair 1: 60Hz-90Hz, pair 2: 90Hz-150Hz, pair 3: 150Hz-300Hz, pair 4: 300Hz-450Hz). The results are shown in Figure 4.9. Interaction effects were only observed between frequency and duration of the elementary pulse in Form I, $F(2.957,112.354)=3.744$, $p<0.05$. The duration of the elementary pulse had significant effects on perceived depth and roughness only in Form I, $F(1,38)=11.170$, $p<0.05$ for perceived depth, $F(1,38)=9.313$, $p<0.05$ for perceived roughness. The frequency had significant effects on perceived depth and roughness in all pairs of three forms ($p<0.05$).

For the post hoc test, results showed that there were no significant differences for perceived depth and roughness between 60Hz and 90Hz at 0.03s ($p>0.05$) in Form I, between 300Hz and 450Hz at both 0.01s and 0.03s ($p>0.05$) in Form II, between 60Hz and 90Hz at both 0.01s and 0.03s ($p>0.05$), between 300Hz and 450Hz at 0.03s ($p>0.05$) in Form III. No significant differences were found between 60Hz and 90Hz at 0.01s for perceived roughness in three forms. Significant differences for perceived depth and roughness could be observed in the rest pairs ($p<0.05$).

In the second task, Friedman's rank tests and Wilcoxon signed-ranks tests were performed on the data in the ranking task. A Friedman test indicated a significant main effect of three CWC forms in all groups ($p<0.05$). The detailed results for the perceived depth and roughness were in Table 4.4.

We conducted a Spearman correlation analysis to check the correlation between perceived depth and roughness. The detailed results are in Table 4.5. The correlation between perceived depth and roughness was not always significant, but it was significant at most frequencies and durations of the elementary pulse.

4.6 Discussion

4.6.1 Frequency

1) Near the resonant frequency

The two-way repeated-measures ANOVA indicates that frequency plays a dominant role in perceiving the perceived depth and roughness of graphical buttons on the touchscreen. Perceived depth is the deepest, and perceived roughness is the roughest when the frequency is at 150Hz in this study. This observation could be attributed to the recorded acceleration amplitude, which was significantly higher at 150Hz than those at other selected frequencies (Figure 4.7).

Additionally, the curves of equal perceived intensity at the fingertip [184] show that the perceived intensity at 150Hz is not weaker than the rest frequencies applied in this study when the acceleration amplitude is fixed. Consequently, the higher amplitude of the recorded acceleration at 150Hz leads to a stronger perceived intensity compared to the other frequencies. This heightened intensity likely contributes to the greater perception of depth and roughness experienced at 150Hz.

The above discussion may explain why the perceived depth and roughness are the greatest when the frequency is near the resonant frequency.

2) Away from the resonant frequency

Figure 4.7 shows the recorded acceleration amplitudes are similar when the frequencies are at 60Hz, 90Hz, 300Hz, and 450Hz. This observation suggests that frequency should be the main factor affecting users' perceiving in graphical buttons when it's away from the resonant frequency.

Table 4.4 Perceived depth and roughness of graphical buttons in task 2

Group	Frequency	Duration (t_0)	Ranking results of perceived depth	Ranking results of perceived roughness
1	60Hz	0.01s	Form II = Form III > Form I	Form II > Form III > Form I
2	90Hz	0.01s	Form II > Form III > Form I	Form II = Form III > Form I
3	150Hz	0.01s	Form II > Form III > Form I	Form II = Form III > Form I
4	300Hz	0.01s	Form II = Form III > Form I	Form II > Form III > Form I
5	450Hz	0.01s	Form II > Form III > Form I	Form II = Form III > Form I
6	60Hz	0.03s	Form III > Form II > Form I	Form III > Form II = Form I
7	90Hz	0.03s	Form II > Form III > Form I	Form II = Form III > Form I
8	150Hz	0.03s	Form II = Form III > Form I	Form II = Form III > Form I
9	300Hz	0.03s	Form II = Form III > Form I	Form II = Form III > Form I
10	450Hz	0.03s	Form II = Form III > Form I	Form III > Form II > Form I

Duration (t_0) is the duration of the elementary pulse.

We used "=" to represent the relations between two graphical buttons when there were no significant differences between them; We used ">" to represent the former graphical button ranked higher than the latter one.

Table 4.5 The spearman correlation between perceived depth and roughness of graphical buttons in task 2

Group	Duration	Frequency pairs	Correlation	Group	Duration	Frequency pairs	Correlation	Group	Duration	Frequency pairs	Correlation
Form I	0.01s	60D-60R	+0.28***	Form II	0.01s	60D-60R	+0.36***	Form III	0.01s	60D-60R	+0.45*
	0.01s	90D-90RW	+0.51*		0.01s	90D-90R	+0.64*		0.01s	90D-90R	+0.57*
	0.01s	150D-150R	+0.64*		0.01s	150D-150R	+0.36***		0.01s	150D-150R	+0.83*
	0.01s	300D-300R	+0.44**		0.01s	300D-300R	+0.48*		0.01s	300D-300R	+0.69*
	0.01s	450D-450R	+0.54*		0.01s	450D-450R	+0.76*		0.01s	450D-450R	+0.54*
	0.03s	60D-60R	+0.64*		0.03s	60D-60R	+0.50*		0.03s	60D-60R	+0.44**
	0.03s	90D-90R	+0.54*		0.03s	90D-90R	+0.63*		0.03s	90D-90R	+0.49*
	0.03s	150D-150R	+0.62*		0.03s	150D-150R	+0.14***		0.03s	150D-150R	+0.68*
	0.03s	300D-300R	+0.34***		0.03s	300D-300R	+0.59*		0.03s	300D-300R	+0.36***
	0.03s	450D-450R	+0.44**		0.03s	450D-450R	+0.56*		0.03s	450D-450R	+0.68*

D = Perceived depth; R = Perceived roughness.

"60D-60R" means explore the correlation between perceived depth and roughness when the frequency is 60Hz.

N=20; *$p<0.01$, two-tailed test; **$p<0.05$, one-tailed test. ***No significant correlation between perceived depth and roughness.

In the study, we regarded the resonant frequency as the center. In each CWC form, the perceived depth and roughness at 90Hz were not found to be shallower or smoother than those at 60Hz. Similarly, at 300Hz, the perceived depth and roughness were not shallower or smoother than those at 450Hz. This shows that perceived depth and roughness decrease when the frequency moves away from the resonant frequency.

4.6.2 Duration

A longer duration increases the perceived depth and roughness of pulse signals at a fixed frequency. Those longer signals make users feel a longer response of haptic feedback response during button presses, creating a deeper and rougher sensation. Thus, ranking tasks indicate that Form II and Form III offer a deeper and rougher sensation of graphical buttons on touchscreens than Form I because they have a longer duration.

For Form II and Form III, the duration of the elementary pulse does not affect the perceived depth and roughness. Instead, it is the entire duration of converted vibrotactile stimuli in these forms that matters, and it tends to be longer than in Form I (Figure 4.7). Comparing Form II and Form III, we find that at a fixed frequency of 60Hz, Form III has a longer entire duration of vibrotactile stimuli. However, at other frequencies, Form II's entire duration is longer than in Form III (Figure 4.7).

The changes in duration and frequency caused a changing perceived depth and roughness of graphical buttons on the touchscreens in this study. In the future design, we could set an elementary drive signal first. And try to create perceived depth and roughness based on the results in this study. We could increase the perceived depth and roughness of graphical buttons on touchscreens by increasing duration or adding pulses to the vibrotactile stimuli or setting the frequency near the resonant value. We could decrease the perceived depth and roughness by making the frequency away from the resonant frequency of the vibration actuators or making the output duration of vibrotactile stimuli shorter.

4.6.3 Perceived dimension

The study showed that the frequency response at 150Hz (near the resonant frequency) was significantly higher compared to other frequencies tested. This indicates a link between the perceived depth and roughness of graphical buttons on touchscreens and the intensity of the vibration. Users felt a stronger intensity, resulting in a perception of greater depth and roughness. This suggests that there may be only one perceived dimension for graphical buttons on touchscreens.

Further analysis in Figure 4.9 supported these findings, showing a similar trend in perceived depth and roughness while changing the frequency and duration of vibration. Table 4.5 also revealed a positive correlation between perceived depth and roughness across various frequencies and durations. These findings support the idea that graphical buttons on touchscreens are perceived primarily along a single dimension.

4.6.4 Calibration

The generation method presented in this chapter was only experimented with our prototype. It's important to note that different prototypes may have different parameters while achieving similar perceptions. Our focus was on the physical effects of vibrotactile stimuli and user perceptions, rather than the waveform itself. The duration and number of pulses in vibrotactile stimuli are not restricted to our prototype alone. Other porotypes can also create longer or shorter durations with varying pulse counts, allowing for practical ways to increase or decrease perceived depth and roughness.

Suppose possible calibration is needed in other prototypes. The calibration could be conducted based on the generation method and the physical effects discussed in this study. For example, in this study, we regarded the resonant frequency as the center, resulting in a graphical button that felt deep and rough due to the strong perceived intensity. In other prototypes, the resonant frequency may be 130Hz or 180Hz. Then, researchers could choose 130Hz or 180Hz as the center for calibration. Meanwhile, it is important to consider the frequency dependency [184] at fingertips when conducting the possible calibration.

4.7 Limitations and future work

1) Parameters

We selected frequencies based on the characteristics of our prototype, utilizing the LRA from this chapter. However, two key issues may affect the results. Firstly, the recorded acceleration amplitudes of vibrotactile stimuli were not uniformly controlled around the resonant frequency. Secondly, the intensity of the vibrotactile stimuli was not standardized. This lack of control over both frequency and intensity may have impacted the overall efficiency of the general frequency results.

Despite these challenges, the resonant frequency of an actuator played a significant role in determining the amplitude (Figure 4.1) and intensity of the recorded acceleration of vibrotactile stimuli [189]. Considering this, we discussed the frequency results from two perspectives: around the resonant frequency and away from it. Analyzing the results from these two aspects still provided valuable insights.

Future work should control the acceleration amplitudes and the intensity of vibrotactile stimuli at all chosen frequencies. This will enable the exploration of a general frequency guideline for the perceived depth and roughness more accurately.

By doing so, the research results will be more efficient and applicable to different systems and vibration actuators.

2) Generation methods

We propose superpositions in the generation method for audio effects because we aim to generate multimodal stimuli in future. However, we only test vibrotactile stimuli in this chapter. It is important to note that the inclusion of superpositions may lead to confusion when only-vibrotactile stimuli are needed.

In the future, we may provide two separate generation methods: one for vibrotactile-only stimuli and the other for multimodal stimuli only. Then, designers or researchers could select one generation method that meets their needs, ensuring efficient and clear stimuli generation.

3) Measurement bias

We measure the effect of frequency and duration in task 1 with the Likert scale and CWC forms in task 2 with a ranking test. However, there could be scale bias [190] in these two tasks because the dependent variables were the same in two tasks (i.e., perceived depth and roughness). Future user studies should consider testing all parameters together with an adequately random sequence of stimuli when dependent variables are the same. This may reduce scale bias, save testing time, and increase testing efficiency.

In task 1, we randomized the vibrotactile stimuli on the touchscreen to minimize expectation bias. However, on the one hand, the sequence of vibrotactile stimuli within each form remained consistent for each participant. This could introduce a sequence bias during evaluation. On the other hand, there was a training session before the official study. Although the training session was very short, the consistent sequence of vibrotactile stimuli might cause expectation bias again. To address these issues, future evaluations require adequate random sequence to reduce both expectation and sequence bias effectively.

Regarding the results of task 1 (i.e., frequency plays a significant role), although there were biases in the evaluation, the findings were still meaningful. The reason is that we discussed the impact of frequency based on the resonant frequency, whether near or away from it. The resonant frequency of an actuator is very special, and it usually has the largest magnitude gain [181]. In our prototype, the frequency response (Figure 4.1) and the recorded acceleration (Figure 4.7) can all show that the vibrotactile stimuli at the resonant frequency offer the greatest perception of graphical buttons.

4) Multimodal stimuli

We only considered the vibrotactile effects of graphical buttons on touchscreens as a single interaction modality. In addition, only a few values were used when applying different amplitude modulations and superpositions. Hence, it seems that the amplitude modulation and superposition methods of drive signals have little effect on perceived differences. However, when considering the audio and vibrotactile effects of drive signals together as cross-modality interfacing, we found that the effects of graphical buttons become more sophisticated while modifying the parameters of amplitude modulation and superposition.

We could study multimodal stimuli for virtual widgets on the touchscreen in the future. Multimodal stimuli could present richer effects compared to vibrotactile stimuli only.

4.8 Conclusion

This study presents a generation method to generate a big set of graphical buttons on touchscreens to mimic the sensations of different physical effects. We applied a smartphone containing an embedded wideband LRA motor that can convert wideband drive signals into vibrotactile stimuli on the touchscreen. We designed drive signals with a set of varying parameters, and we conducted two phases of studies to:

- Design drive signals for graphical buttons on touchscreens.
- Explore the perceived depth and roughness of graphical buttons on touchscreens.

In addition to the generation method of the drive signals, we have the following findings that can benefit the future design of graphical buttons:

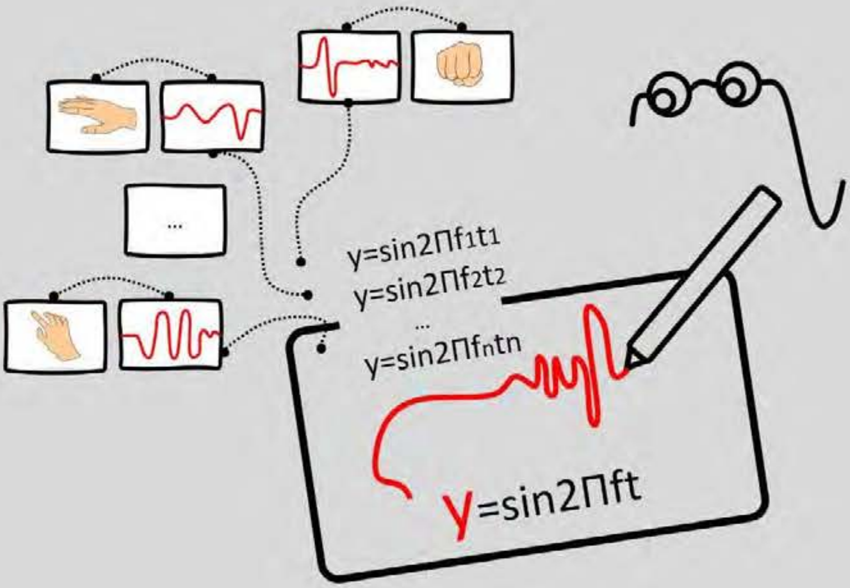
1) The perceived depth and roughness of graphical buttons increase when the frequency approaches the resonant frequency. Perceived depth and roughness will decrease when the frequency moves away from the resonant frequency.
2) A longer duration of stimuli helps to increase the perceived depth and roughness of a graphical button on touchscreens.
3) Increasing the number of pulses helps to increase the perceived depth and roughness of a graphical button on touchscreens.
4) Perceived depth and roughness have a very similar trend with varying frequencies at a fixed duration. The correlation between perceived depth and roughness is not always significant, but it is significant at most frequencies and durations.

The above findings can guide graphical button design using the generation method proposed in this chapter. Although we only applied several parameters in this study, parameters are not just limited to those applied in this study. Researchers or designers could apply the generation method, or the functions proposed in this study and choose parameters meeting their physical effects.

In the following chapter, we will provide a generation method to design mediated social touch signals based on the generation method proposed in this chapter. We will apply signal parameters affecting users in perceiving vibrotactile stimuli from this study (i.e., frequency, duration, and CWC forms) to design mediated social touch signals. We will create vibrotactile stimuli designed in this study with touch properties explored in Chapter 3 to represent mediated social touch gestures.

Chapter 5

Receivers Recognizing Mediated Social Touch Signals



This chapter is based on:
Q. Wei, M. Li, and J. Hu, "Designing Mediated Social Touch Signals," Submitted to *International Journal of Human-Computer Studies*, 2023.

Abstract

We conducted an exploration of mediated social touch (MST) with hand gestures (Chapter 3), collected related touch properties (Chapter 3), and tested user perception with vibrotactile stimuli (Chapter 4). This chapter mainly provides a generation method for designing MST signals. We try to create the vibrotactile stimuli in Chapter 4 with the touch properties presented in Chapter 3 to represent MST gestures.

Background: The advanced haptic technology in smartphones makes mediated social touch (MST) possible for rich remote communication between people.

Methods: This Chapter presents a generation method for MST signals on smartphones. We provide a function to transfer MST gesture pressure to MST signal frequency. We set the duration and create different compound waveform compositions for MST signals. We conducted two user studies.

Results: First, we explored how likely the designed MST signals could be understood as intended MST gestures. We selected 23 MST signals that were suitable for intended MST gestures. Then, we conducted experiments with a recognition task to explore to which extent the designed MST signals could be recognized as intended MST gestures. We found that around 70% of designed MST signals could be recognized above a precision of 25%, which was two times better than the random recognition rate. These concrete measures can be referenced when designing MST signals. We also provided some design implications and guidelines for MST signals for future applications.

5.1 Introduction

5.1.1 Background, related work, and design opportunities

In current remote communication, audio and visual connection such as voice and video calls provide clear information. However, non-verbal cues are missing in many remote applications.

Mediated social touch (MST) helps to provide non-verbal cues in remote communication. MST means 'the ability of one actor to touch another actor over a distance by means of tactile or kinesthetic feedback technology' [15]. It is a new form of physical interaction and can bring richer experiences to remote communication. Many researchers tried to transmit MST signals using different tools such as mobile devices [28], [45] and wearables [49], [37].

Haptic technologies have been applied in mobile devices, providing possibilities for transmitting MST signals. For example, iPhones starting from iPhone 7 have embedded the Taptic Engine – a kind of linear resonance actuator (LRA), which could provide various haptic stimuli [169]. Besides, other haptic actuators, such as voice-coil vibrators [97], Minebea Linear Vibration Motors [57], [58], and eccentric motors [31], have also been applied to mobile devices to produce haptic stimuli.

Research prototypes have been developed to transmit typical MST signals. POKE [48], CheekTouch [18], [19], Kissenger [47], ForcePhone [21], KUSUGURI [23], MobiLimb [20], In-Flat [82], and Wrigglo [85] are typical prototypes designed for smartphones to transmit MST signals.

There are various ways to transmit MST signals. Some systems are designed to capture and process data and transmit real-time generated signals. Rantala et al. [28] designed a haptic device that could transfer the touch input through the varying amplitude of the mixed sine wave with specific vibration actuators. Huisman et al. [191] created a touch device with a central control platform that could run software to collect sensor data, drive the actuators, and communicate real-time information. Park et al. [18] designed CheekTouch. One user's finger motion on the haptic surface could be rendered on the other user's phone in real time using the Arduino board to activate the vibrotactile actuators. Hemmert et al. [141] designed a mobile phone-like haptic device equipped with sensors and actuators. Force sensors make the sender's phone force-sensitive, while a motor on the receiver's phone with the same force exerted on the sender's phone. Hoggan et al. [21] and Chang et al. [144] designed prototypes to transfer the pressure of social touch to vibration intensity between users in real time. Chang et al. [144] used force-sensing resistors and a voltage-controlled oscillator to map the touch and vibrations. Furukawa et al. [23] connected two haptic devices via a Bluetooth connection, implemented in a GameKit framework in iOS5 SDK, which could transmit the touch data to each other. Park et al. [48] used an air pump for POKE, enabling the transmission of MST signals through the inflation and deflation of the device's surface, responding to touch pressure and finger movements. Besides, some studies focus on using smartphones to control the touch display on haptic devices. For example, users could use a smartphone to make the haptic device – Sphero mini [86] and Cubble [87] vibrate or change color at a distance.

Other systems work with pre-defined social touch signals. For example, some research work generates MST signals by setting parameters according to collected data. For example, Park et al. [19] asked participants to freely express 'Pat,' 'Slap,' 'Tickle,' and 'Kiss' on the screen of CheekTouch, while Wei et al. [92] performed gestures of 'Knock,' 'Hit,' 'Stroke,' and 'Hug' on a flat plate. They applied collected patterns and physical signals to design vibrotactile stimuli for MST gestures. Moreover, other researchers design haptic signals with various temporal parameters, such as frequency [98], amplitude [60], duration [76], envelope attributes [56], to express emotional intentions.

From the above-mentioned related work, we can observe: (1) Most studies mainly developed prototypes for MST signal transmission. They did not propose a generation method for MST signals; (2) Some studies provided MST signals based on researchers' experiences instead of a comprehensive study on the touch properties of MST gestures (e.g., pressure and duration); (3) For real-time generated signals, although users can feel other people's MST gestures by sensing the real-time signals, they may not understand their meaning since sometimes the MST gestures people make are arbitrary; (4) Some studies mapped haptic stimuli to pressure but did not present the exact relations between them. It is not clear whether the relations could be captured using mathematical functions; (5) Most studies applied multiple actuators to provide MST signals. However, only one actuator is usually embedded in most mobile devices, such as smartphones. (6) The number of the studied MST signals was quite limited.

In this study, we try to focus on the following design opportunities of the design of MST signals:

- Provide a generation method.
- Design based on the touch properties of MST gestures.
- Design a rich set of MST signals.
- Use just one actuator for the MST signals.
- Consider users engaging with smartphones and interacting with touchscreens.

5.1.2 Overview of the MST signal design

Figure 5.1 shows the overview of the MST signal design. Chapter 3 explored how to express MST gestures. We design MST signals based on the data collected from our Chapter 3.

This study proposes a generation method for MST signals on smartphones. We conduct this study based on the following steps:

1) We first propose a function to transfer MST gesture pressure to MST signal frequency.
2) We calculate the frequency for MST signals based on MST gesture pressure collected earlier (see Chapter 3).
3) We set the duration for MST signals based on the recorded duration of MST gestures (see Chapter 3).
4) We create different compound waveform composition (CWC) forms.
5) We conduct the first user study to explore how likely the designed MST signals be understood as intended MST gestures. We try to select suitable MST signals for MST gestures.
6) We conduct the second user study to explore to which extent the designed MST signals be recognized as intended MST gestures.

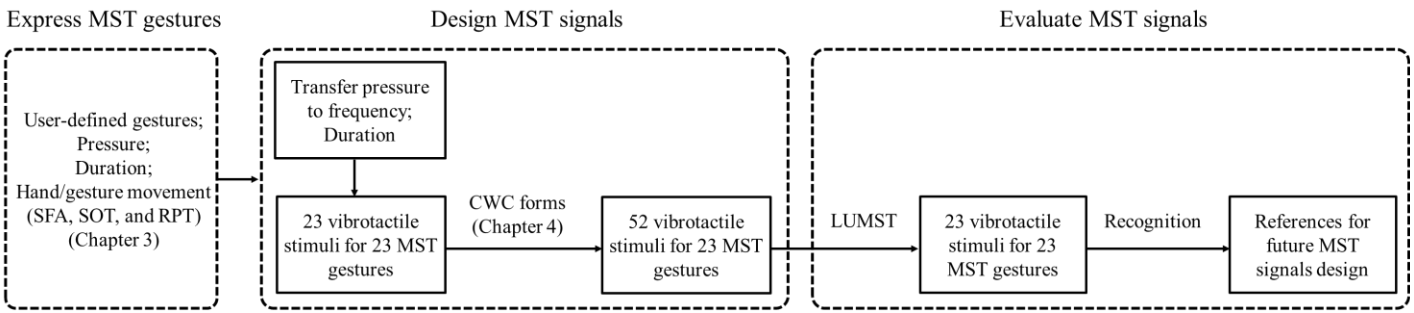


Figure 5.1 Overview of the MST signal design

We collected 23 user-defined MST gestures from Chapter 3. Thus, in this Chapter, we design MST signals for the 23 MST gestures ('Grab,' 'Hit,' 'Hug,' 'Kiss,' 'Lift,' 'Nuzzle,' 'Pat,' 'Pinch,' 'Poke,' 'Press,' 'Pull,' 'Push,' 'Rock,' 'Rub,' 'Scratch,' 'Shake,' 'Slap,' 'Squeeze,' 'Stroke,' 'Tap,' 'Tickle,' 'Toss,' and 'Tremble').

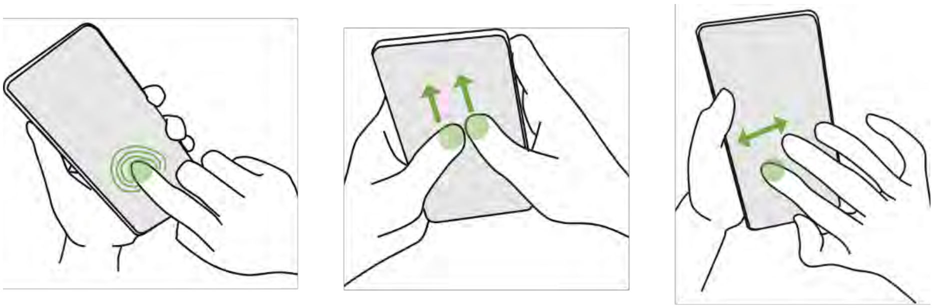
5.1.3 Related data collected earlier

We will design MST signals based on the earlier results as presented in Chapter 3 and Chapter 4. The main factors applied in this study are pressure, duration, user-defined gestures, and hand/finger movement collected in the Chapter 3 study. The applications of these factors are as follows.

Pressure and duration. We collected the pressure and duration of each social touch gesture. Collected pressure and duration will be applied for the design of the parameters – frequency and duration.

User-defined gestures. We obtained a set of user-defined MST gestures considering touch properties and context [80]. This set will be applied for choosing rational frequency and duration for the MST signals.

Hand/finger movement. We proposed classifications based on hand/finger movement [160]. It also describes the spatial relations between the hands/fingers and the touchscreen' [80]. We will apply three hand/finger movements: straight gestures from the air (SFA), straight gestures on the touchscreen (SOT), and repetitive gestures (RPT) on the touchscreen (Figure 5.2). We choose frequency and duration for MST signals and design CWC forms based on the touch properties of these three hand/finger movements.



(a) (b) (c)

Figure 5.2 Examples of three hand/finger movements. (a) 'Poke' from the SFA group; (b) 'Lift' from the SOT group; (c) 'Shake' from the RPT group. These figures are also shown in Chapter 3.

5.2 Frequency

We choose frequency rather than amplitude to control the intensity of vibrotactile stimuli for the following reasons:

1) Whether the amplitude change can cause a greater change in perceived intensity is related to the frequency range. For example, Hatzfeld [184] found that the same amplitude increase for low-frequency components could evoke a stronger perceived intensity than the mid or high-frequency components. This means controlling the frequency is more convenient to obtain a greater change in the perceived intensity of vibrotactile stimuli.
2) We are considering the multi-modal stimuli for future design. The LRA applied in this study can present vibrotactile and audio stimuli at the same time. The changing frequency generates a changing sound. Although we only test vibrotactile stimuli in this study, we still need to retain the possibility of using the drive signals designed to present multi-modal stimuli in future research.

5.2.1 Technology applied in this chapter

We use a wide-band LRA (MPlus 1040) to generate MST signals. The LRA has been embedded in an LG V30 smartphone. The LRA motor converts drive signals into vibrotactile stimuli. This is similar to the technology applied in Chapter 4.

Figure 5.3 shows the frequency response of the system using a mobile phone mockup applied in this study. The frequency corresponding to the highest acceleration is 160Hz (the resonant frequency, Point B in Figure 5.3). The acceleration decreases to the lowest turning point (Point A and C in Figure 5.3) when the frequency changes from 160Hz to 40Hz and from 160Hz to 400Hz.

We apply the low-frequency range (40Hz to 160Hz) to present a sensitive perceived difference in vibrotactile stimuli. The reason is that Hatzfeld [184] has shown that ‘a slight amplitude increase for low-frequency components will evoke the same perceived intensity than a much larger amplitude change of mid- and high-frequency components’.

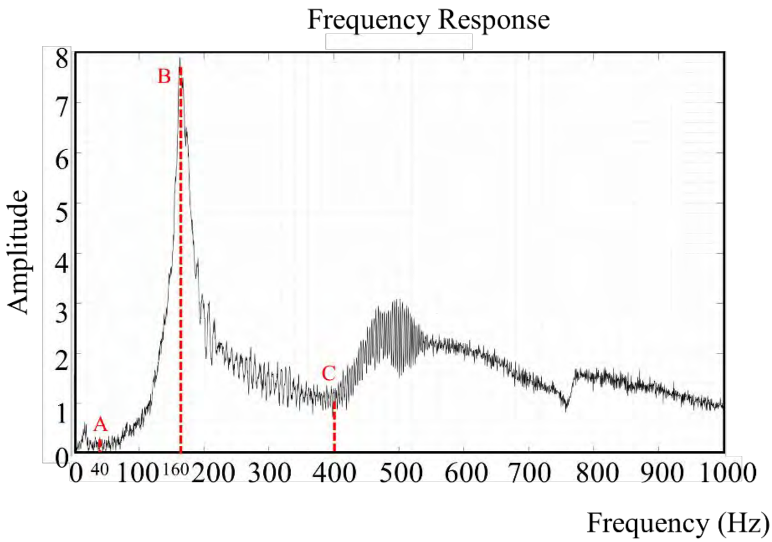


Figure 5.3 The frequency response of the system using a mobile phone mockup – this figure was originally from [192]

5.2.2 Mapping pressure to frequency

We map the pressure to the frequency. One possible bridge between the frequency and the pressure could be the perceived intensity of vibrotactile stimuli.

From pressure to the intensity of vibrotactile stimuli, Chang et al. [144], Rantala et al. [28], and Hoggan et al. [21] have demonstrated there could be a connection between the pressure and the intensity of vibrotactile stimuli. For example, ComTouch [144] converts hand pressure into vibrational intensity between users in real time.

From frequency to the intensity of vibrotactile stimuli, the perceived intensity of vibrotactile stimuli is significantly affected by the frequency and the acceleration amplitude [193]. Meanwhile, the frequency response (Figure 5.3) [192] also shows that varying frequencies help to reach different accelerations of vibrotactile stimuli, resulting in different perceived intensities of vibrotactile stimuli.

Figure 5.4 shows the detailed connections. The sender sends an MST gesture while the receiver perceives the MST signal. We connect the pressure intensity to the signal intensity. The signal intensity could be affected by the frequency [193]. We use frequency to control the MST signal intensity.

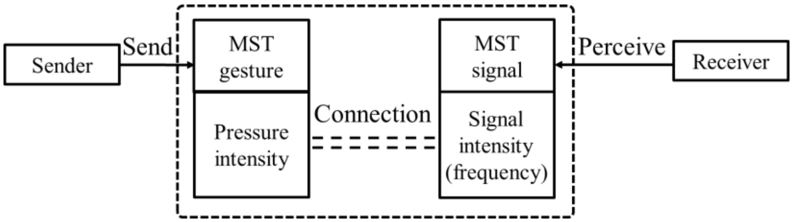


Figure 5.4 The connection between a sender's MST gesture and a receiver's perceiving of MST signals

A parabolic function is applied to describe the mapping between the frequency and the pressure. The process of deriving the parabolic function is as follows:

1) *We apply a standard function rather than a fitting function*. We collected pressure of MST gestures [80]. We chose a typical relation between the pressure and the duration before the pressure reached the first highest point (e.g., from point O to point A in Figure 5.5) and conducted the curve estimation by the SPSS. Figure 5.5 presents an example of 'Grab' [80]. The results showed that the pressure could be regarded as increasing with time in the form of a linear (r^2=0.362, p=0.03), or a quadratic (r^2=0.686, p=0.003), or a cubic function (r^2=0.882, p<0.001). Based on the results, a standard function is significantly effective. For technical convenience, we choose a standard function in this study.

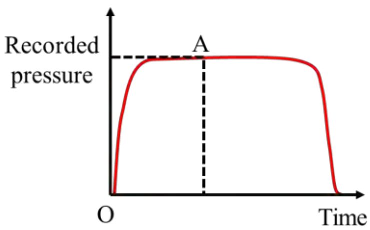


Figure 5.5 An example of recorded pressure ('Grab' from P1)

2) *We apply a convex function to describe the relations between the frequency and the pressure*. The recorded pressure reaches the highest point in a short time [80], which means the perceived intensity and accelerations of the vibrotactile stimuli should also reach the highest point in a very short time. So, the frequency response should also reach the highest point in a very short time.

   Figure 5.6 shows three possible trends between the pressure and duration (Figure 5.6: left) and between the frequency and the frequency response (Figure 5.6: right) – convex (A), linear (B), and concave (C). It is obvious that the convex trend can reach a stronger pressure at the same time and a higher frequency response at the same frequency compared to the linear and concave trends (Figure 5.6). So, we chose the convex function to describe the relations between the frequency and the frequency response. The frequency response means the accelerations of vibrotactile stimuli, which correlates to the perceived intensity of vibrotactile stimuli and the pressure intensity. Thus, we set a convex function to describe the relations between the frequency and the pressure.

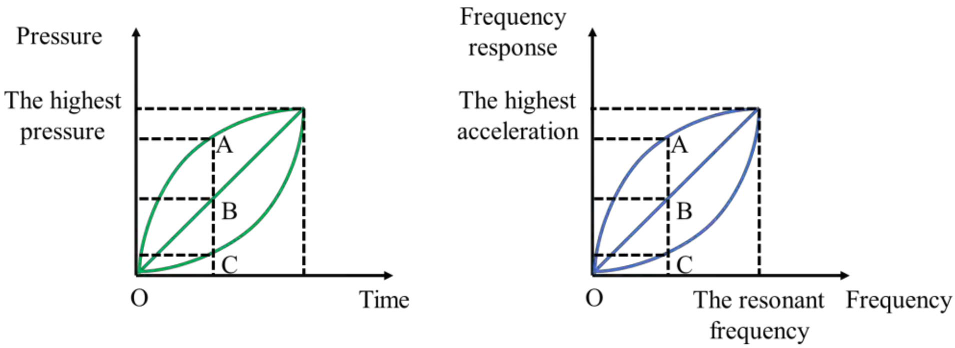


Figure 5.6 The comparison among three trends of frequency – concave (A), linear (B), and convex (C)

3) *The derivative of the highest point of the function should be 0* (i.e., when $F = F_{max}$, $f(F)' = 0$, $f(F) = f_h$). After analyzing the collected pressure, we found that the typical growth rate of the pressure of most MST gestures decreased before reaching the first turning point (the first crest, Point A in Figure 5.5), and the pressure reached the first turning point in a very short time. When the duration rises from 0 to the first turning point of pressure (point A in Figure 5.5), the growth rate of corresponding pressure decreases to 0 at that point.
4) *The quadratic (a parabolic) function is chosen due to the technical convenience.* On the one hand, many trends are significantly effective for curve estimation, but there may be no significant perceived differences among them. For technical convenience, we choose a quadratic function rather than a cubic function since the quadratic function needs fewer known points to be specific than the cubic one. On the other hand, we only got two known points representing the highest and the lowest turning point of the perceived intensity. We choose a parabolic function since the two known points are effective for the vertex formula of a parabola.

The parabola may be one of the effective functions to some extent. Other quadratic, cubic, or quartic functions may also work. However, testing more than one function in this study may produce complexity. We decided to start with a simple function. We explore to which extent users could recognize the designed MST signals based on this parabolic function.

We only consider the highest pressure of one MST gesture in the general function. For example, the recorded pressure of 'Grab' from P1 rose from 0 to 920 (we used Arduino to record pressure, the range is from 0 to 1023) and decreased to 0 during 0.95s, we chose 920 as the pressure for the later calculation of frequency.

As the pressure changes when the user presses the touchscreen, the highest pressure appears when the user exerts the highest force. The highest perceived intensity of vibrotactile stimuli should appear simultaneously with the highest pressure that the user exerts.

The function mapping the frequency and the pressure is as follows:

$$f(F) = \frac{f_l - f_h}{(F_{max} - F_{min})^2}(F - F_{max})^2 + f_h, \quad F_{min} \leq F \leq F_{max} \qquad (5-1)$$

$f(F)$ is the frequency corresponding to the highest pressure of an MST gesture that the user exerts on the touchscreen.

f_l represents the frequency, and the corresponding acceleration peak of f_l is at the lowest turning point in the chosen range of frequency (Point A in Figure 5.3). f_h represents the frequency, and the corresponding acceleration peak of f_h is the highest (Point B in Figure 5.3). The frequency range represents the range of perceived intensity of vibration. As mentioned in 2.2, the frequency range $(f_l,\ f_h)$ applied in this study was (40Hz, 160Hz) (Figure 5.7).

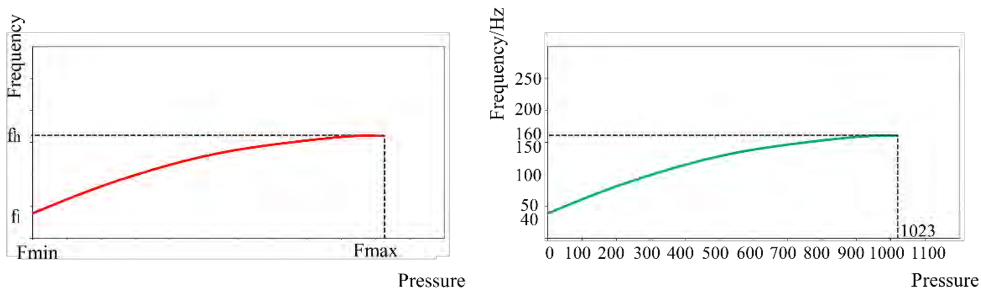


Figure 5.7 The relation between pressure and frequency. Left: Function (5 – 1). Right: Function (5 – 3).

F_{max} and F_{min} represent the upper and the lower limit of the preset pressure range, respectively. The preset pressure range is based on the pressure sensor. As we used Arduino to record pressure in Chapter 3, the range of the pressure sensor here was (0, 1023), so the preset pressure range (F_{min}, F_{max}) was set as (0, 1023) in this study (Figure 5.7).

5.2.3 Frequency of MST signals

The function of the drive signal for MST gestures A(F,t) is as follow:

$$A(F,t) = O(t)\sin\{2\pi f(F)t\} \qquad (5-2)$$

where t is the duration of the drive signal. $O(t)$ is the amplitude modulation function. In the SFA group, we chose a ramp down envelope shape, the same as in [192], $O(t) = -\frac{1}{t_0}t + 1$. t_0 is the duration of the drive signal (one pulse in the SFA group). In the other two groups (SOT and RPT), the drive signals in these groups have a long duration and envelope shapes may affect the perceived intensity of the vibrotactile stimuli, so we set $O(t) = 1$.

As mentioned earlier, the preset pressure range (F_{min}, F_{max}) is (0, 1023). The frequency range (f_l, f_h) is (40Hz, 160Hz). The parabolic function calculated from Function (5 – 1) is as follows:

$$f(F) = -\frac{120}{1023^2} \times (F - 1023)^2 + 160 \qquad (5-3)$$

We applied Function (5 – 3) to calculate frequencies. The calculated frequencies are in Table 5.1.

5.3 Duration

The way to choose the duration of MST signals is to make it similar to the duration the user's fingers/hands contact the touchscreen, which is the duration of recorded social touch gestures in Chapter 3.

Detailed durations of MST signals are in Table 5.2. We round off the recorded duration to two digits after the decimal. The reasons are, on one hand, choosing duration is a preliminary design step for the MST signal. We will improve CWC forms later in iterations. The duration will improve during the iterations. On the other hand, the perceived difference may not be significant when the duration is too precise. For example, in 'Lift,' the average recorded duration is 0.99s. Users may not distinguish the duration of vibrotactile stimuli between 0.99s and 1.00s. So, 1.00s could also be effective for representing 'Lift.'

5.4 Compound waveform compositions

We obtained 23 MST signals from the last section. We regard them as elementary drive signals. We continue designing CWC forms based on these elementary drive signals. We design CWC forms for the following reasons:

1) Providing CWC forms could be an iteration process. We cannot guarantee the designed vibrotactile stimuli are totally reasonable. We need CWC forms and try to select a more suitable vibrotactile stimulus for MST gestures among different CWC forms.
2) CWC forms may help differentiate MST signals with similar frequencies and durations. We recorded the pressure and duration of MST gestures in Chapter 3. There may be a situation like this: two MST gestures have similar pressure and duration. The corresponding vibrotactile stimuli may also be similar. For example, the vibrotactile stimuli for 'Pat' and 'Tap' are all short pulses with gentle perceived intensity. CWC forms could provide slightly different patterns. We could set one short pulse for 'Pat' and two short pules for 'Tap', which may be easier to differentiate.

We have explored the perceived depth and roughness of vertical key clicks on the touchscreen in Chapter 4. In this Chapter, we extend the research from human-computer interaction to computer-mediated human-to-human interaction.

Metaphorically, perceived depth could represent the deformation of skin on vertical travel in social touch. Perceived roughness could represent the uneven distribution of force on the skin [192]. So, the more/less deformation of skin and the stronger/weaker uneven distribution force could make users feel a stronger/gentler force exerts by others through vibrotactile stimuli on touchscreens.

Physically, we have demonstrated that adding/decreasing the number of pulses/duration help to increase/decrease the perceived depth and roughness of vertical key clicks on the touchscreen [192]. So, the main way to design CWC forms in this study is to consider adding/decreasing the number of pulses /duration to the drive signal or bidirectionally transferring signals between continuous and subdivided ones. We do not consider the SOT group here because MST signals in this group are long, constant, and continuous, which is not easy to design CWC forms based on the abovementioned adding/decreasing the number of pulses /duration or bidirectionally transferring signals between continuous and subdivided ones.

5.4.1 CWC forms for the SFA group

For 'Hit', 'Pat', 'Slap', 'Tickle', and 'Tap' in the SFA group, we change the number of pulses or the duration for different CWC forms. Physically, when adding duration to the elementary drive signal, we try to mimic the elastic effect when touching others because the skin is not a rigid surface. Thus, a fading signal is added to mimic an elastic effect [192].

Table 5.1 Frequency of the MST signals

MST signals in the SFA group	The average recorded pressure (*)	Frequency (Hz) (**)	MST signals in the SOT group	The average recorded pressure (*)	Frequency (Hz) (***)	MST signals is the RPT group	The average recorded pressure (*)	Frequency (Hz) (****)
Hit	703	148	Lift	806	155	Nuzzle	192-407	81-116-81
Kiss	769	153	Pull	720	149	Rock	362-418	110-118-110
Pat	404	116	Push	775	153	Rub	353-605	109-140-109
Poke	647	144	Scratch	478	126	Shake	365-627	110-142-110
Press	880	158	Stroke	285	40-98-40	Tremble	272-508	96-130-96
Slap	745	151	Toss	633	40-143			
Tap	446	122	Hug	827	156			
Tickle	405	116	Pinch	813	155			
			Squeeze	818	155			
			Grab	747	40-151			

* The average recorded pressure with Arduino is presented in Chapter 3.

** In the SFA group, we chose the highest pressure during an MST gesture to calculate the corresponding frequency to present the strongest perceived intensity because the duration of MST gestures in this group is short, which is not easy for users to recognize the change in intensity.

*** In the SOT group, for 'Pull', 'Push', 'Hug', 'Pinch', 'Lift', 'Squeeze', and 'Scratch', we displayed these MST signals with a feeling of force exerting on the other people. Yohanan and MacLean [130] describe these MST gestures with words like 'exert force', 'firmly press', 'tightly', and 'sharply'. The perceived intensity of vibrotactile stimuli is expected to show a strong and constant force exerting on others. So, we applied one frequency to display a constant perceived intensity.

For 'Stroke', Yohanan and MacLean [130] explain it as moving hands with gentle pressure. Thus, we apply a monotonic changing frequency to gradually change the perceived intensity to show the gentle changing pressure.

For 'Toss', the finger swipes up and flies out of the touchscreen in the user-defined gesture [80]. Thus, we apply a monotonic changing frequency to present a gradually changing perceived intensity to show a metaphor of the finger's flying out of the touchscreen.

For 'Grab', Yohanan and MacLean [130] explain that it is a gesture with a sudden and rough movement. Thus, we applied a monotonic changing frequency to present a suddenly changing feeling of force.

The lower limit of frequency for 'Toss', 'Grab', and 'Stroke' was set to 40Hz, corresponding to the lowest perceived intensity in the preset frequency range.

**** In the RPT group, the recorded pressure fluctuated in a wavy pattern. A repeated changing frequency was needed to reach a repeated change in the acceleration of vibrotactile stimuli.

Table 5.2 Duration of the MST signals

MST signals in the SFA group	Average recorded duration (*)	MST signals duration (**)	MST signals in the SOT group	Average recorded duration (*)	MST signals duration	MST signals in the RPT group	Average recorded duration (*)	MST signals duration (***)
Hit	0.10	0.05*2	Lift	1.00	1.00	Nuzzle	0.60	0.20*3
Kiss	0.30	0.15*2	Pull	0.70	0.70	Rock	0.80	0.20*4
Pat	0.10	0.05*2	Push	0.60	0.60	Rub	1.00	0.25*4
Poke	0.30	0.15*2	Scratch	0.50	0.50	Shake	0.84	0.12*7
Press	0.40	0.20*2	Stroke	0.60	0.60	Tremble	0.84	0.12*7
Slap	0.10	0.05*2	Toss	0.30	0.30			
Tickle	0.10	0.05*2	Hug	1.00	1.00			
Tap	0.08	0.04*2	Pinch	0.70	0.70			
			Squeeze	0.80	0.80			
			Grab	0.50	0.50			

* The average recorded duration is presented in Chapter 3.

** In the SFA group, the MST signal duration includes both the press and release stage of a graphic button on the touchscreen triggering vibrotactile stimuli. For example, in ‘Hit,’ the average recorded duration was 0.10s, while the vibrotactile stimuli of the press stage (0.05s) and release stage (0.05s) were 0.10s in all.

*** In the RPT group, the MST signal duration is written as “the duration of each repeat time * the repeat times”. For example, in ‘Nuzzle’, there are three repeat times. The whole duration is written as 0.2*3.

Besides the elementary drive signal (Form I in Figure 5.8), we provide three more CWC forms in this group (Figure 5.8). Form I is a single pulse and is regarded as the elementary signal. Form II refers to adding the number of pulses to Form I. Form III refers to adding the duration to Form I. Form IV combines Form II and Form III. Form I, Form II, and Form III have demonstrated effectiveness in human-computer interaction [192]. We also applied them in this study to further explore the effectiveness of computer-mediated human-to-human interaction.

We employed a separate model for the SFA group with a duration longer than 0.1s. Gestures such as ‘Kiss’, ‘Poke’, and ‘Press’ can easily last beyond 0.1s (even more than 0.25s) (Table 5.2). It will be too long for them if they are modeled as ‘Hit’, ‘Pat’, ‘Slap’, ‘Tickle’, and ‘Tap’, which last around 0.1s (Table 5.2). As an alternative, we shrunk the duration of the elementary signal (Form III in Figure 5.9) by half and then applied the previous model.

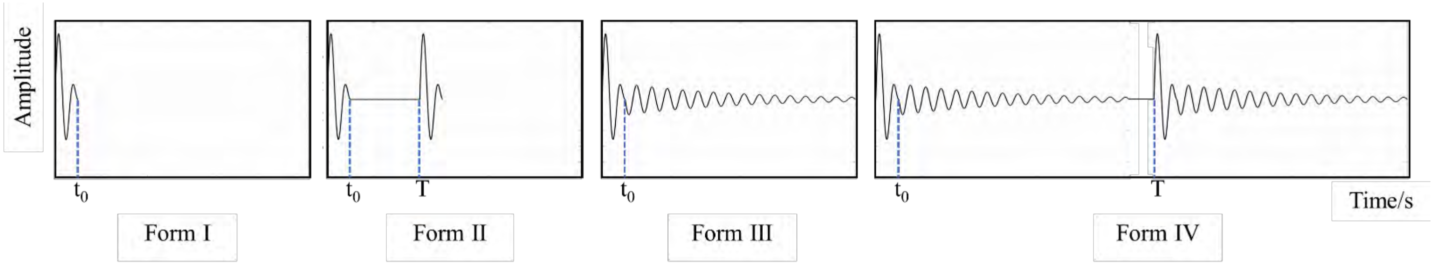


Figure 5.8 Drive signals of four CWC forms for 'Hit', 'Pat', 'Slap', 'Tickle', and 'Tap'. t_0 is the input duration of the elementary pulse (Form I). T is the period before the second pulse is activated.

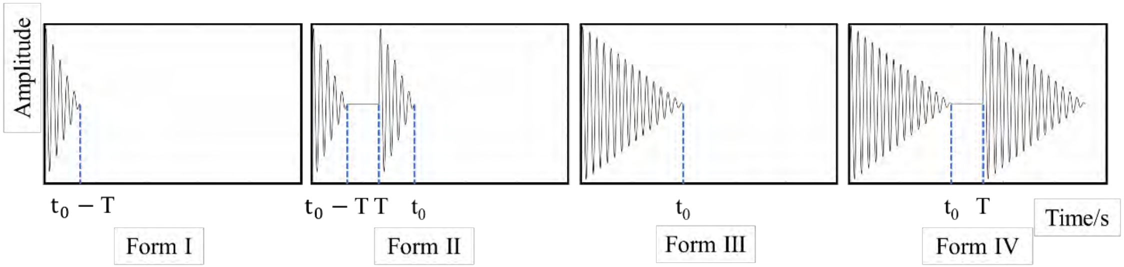


Figure 5.9 Drive signals of four CWC forms for 'Kiss', 'Poke', and 'Press'. t_0 is the input duration of the elementary pulse (Form III); T is the period before the second pulse is activated.

5.4.2 CWC forms for the RPT group

For ‘Nuzzle’, ‘Rock’, ‘Rub’, ‘Shake’, and ‘Tremble’, the elementary signals are continuous with a repeated changing frequency. We apply subdivided signals for them. We want to explore if the subdivided signals could be recognized well as an MST gesture in this group.

The recorded pressure in this group changes as a waving pattern [80]. We set a short pulse with different frequencies at the turning point of recorded pressure (Point A, B, C, D, E, F, and G in Figure 5.10) as an indicator marker for the turning point of a repeated movement. We take the extremum of the pressure waveform as the onsets of the repeated pulses.

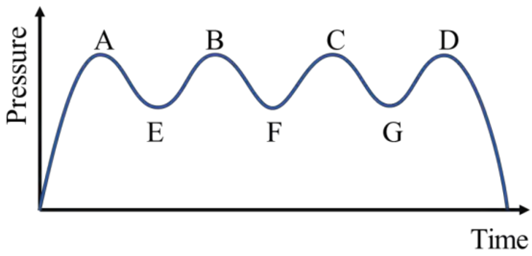


Figure 5.10 An indicator of pressure changing like a wave in the RPT group

An indicator of drive signals of two CWC forms in the RPT group is in Figure 5.11. Form I (Figure 5.11 (a)) is the elementary signal, which is continuous with a repeated changing frequency. Form II (Figure 5.11 (b)) is the transferred subdivided signals. In Form II, the frequencies for odd-numbered pulses are the same, while the frequencies for even-numbered pulses are the same.

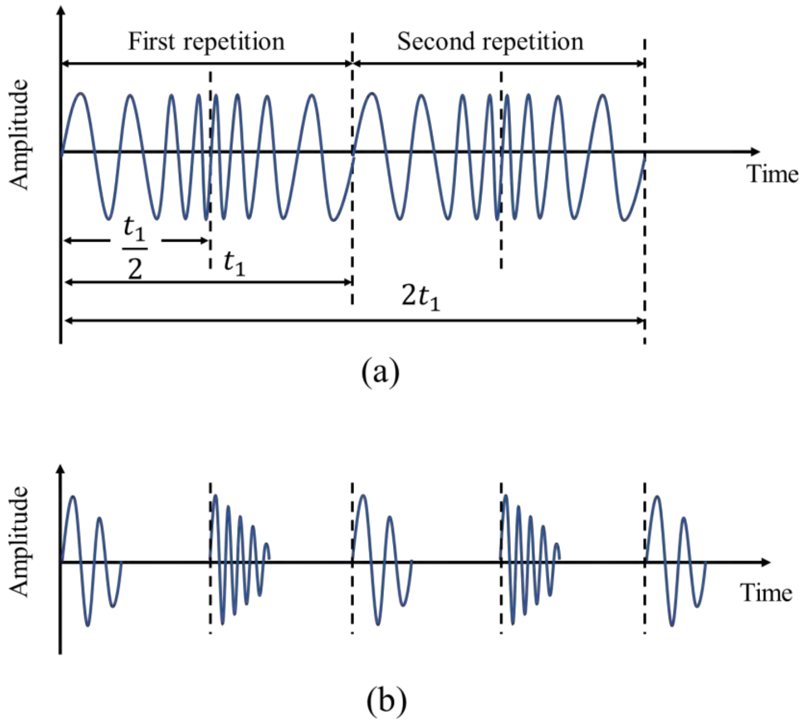
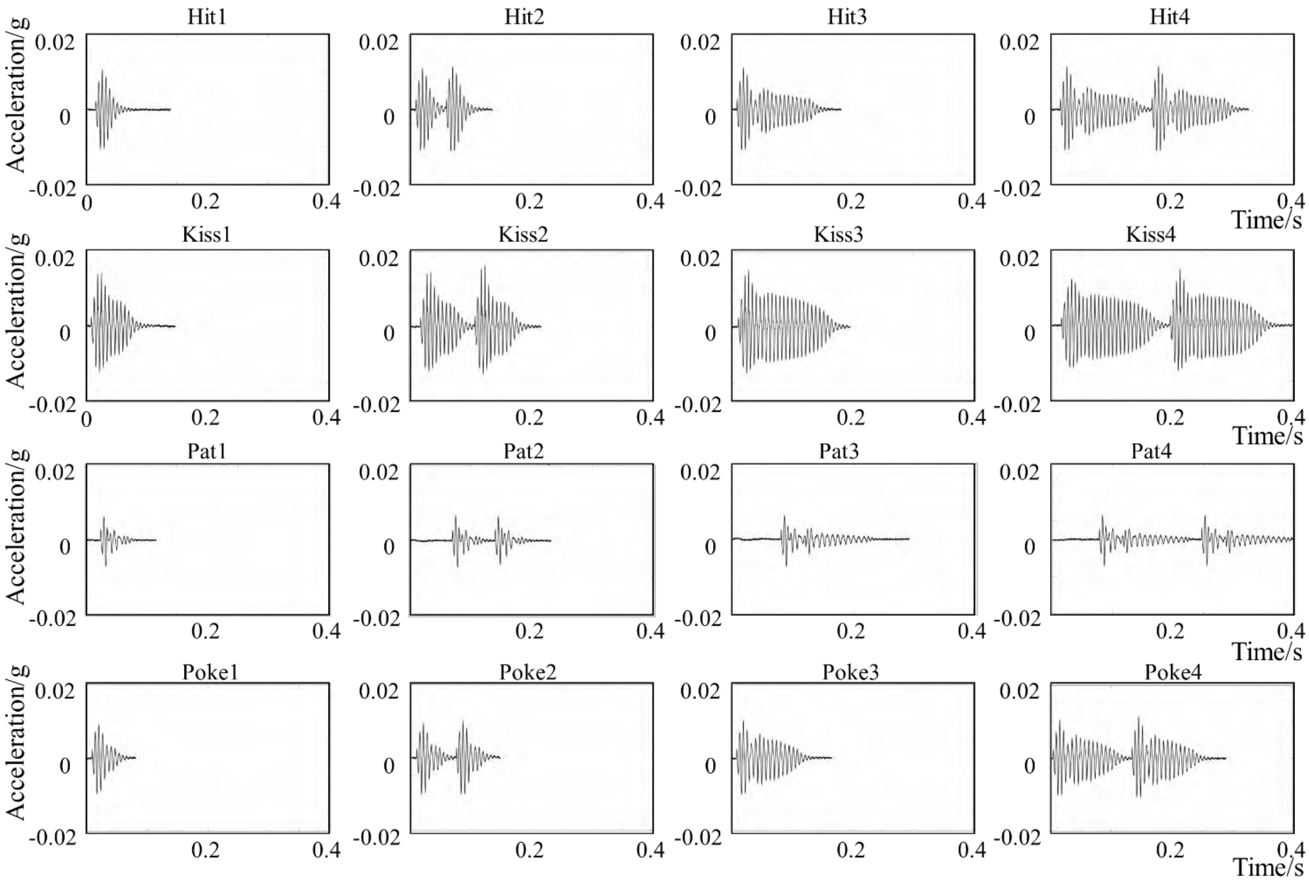


Figure 5.11 An indicator of drive signals of two CWC forms in the RPT group. (a) CWC form I, continuous one with changing a repeated changing frequency; (b) CWC form II, subdivided signal. t_1 is the duration of repetition (e.g., from point E to point F in Figure 5.10).

5.5 Recording accelerations of vibrotactile stimuli on smartphones

We recorded accelerations of MST signals using the same method as in Chapter 4. An accelerometer (TI DRV-ACC16-EVM, with three axes) and an audio input device (U24XL) were used to measure the acceleration of vibrotactile stimuli on the smartphone. Key recording elements are: "1) TI DRV-ACC16-EVM tool converted the physical acceleration to analog signals. Then, the ESI U24 XL amplified and converted the analog signal to a digital signal. 2) The smartphone was placed on foam. This is typical in the industry to damp low-frequency vibration minimally when measuring. 3) The small accelerometer board was attached to the back of the smartphone" [192]. Detailed recording methods were presented in Chapter 4.

Figure 5.12, Figure 5.13, and Figure 5.14 show the recorded accelerations of the MST signals in the SFA, the RPT, and the SOT groups, respectively.


Hit1
Hit2
Hit3
Hit4
Kiss1
Kiss2
Kiss3
Kiss4
Pat1
Pat2
Pat3
Pat4
Poke1
Poke2
Poke3
Poke4
Acceleration/g
0.02
0
-0.02
0
0.2
0.4
Time/s

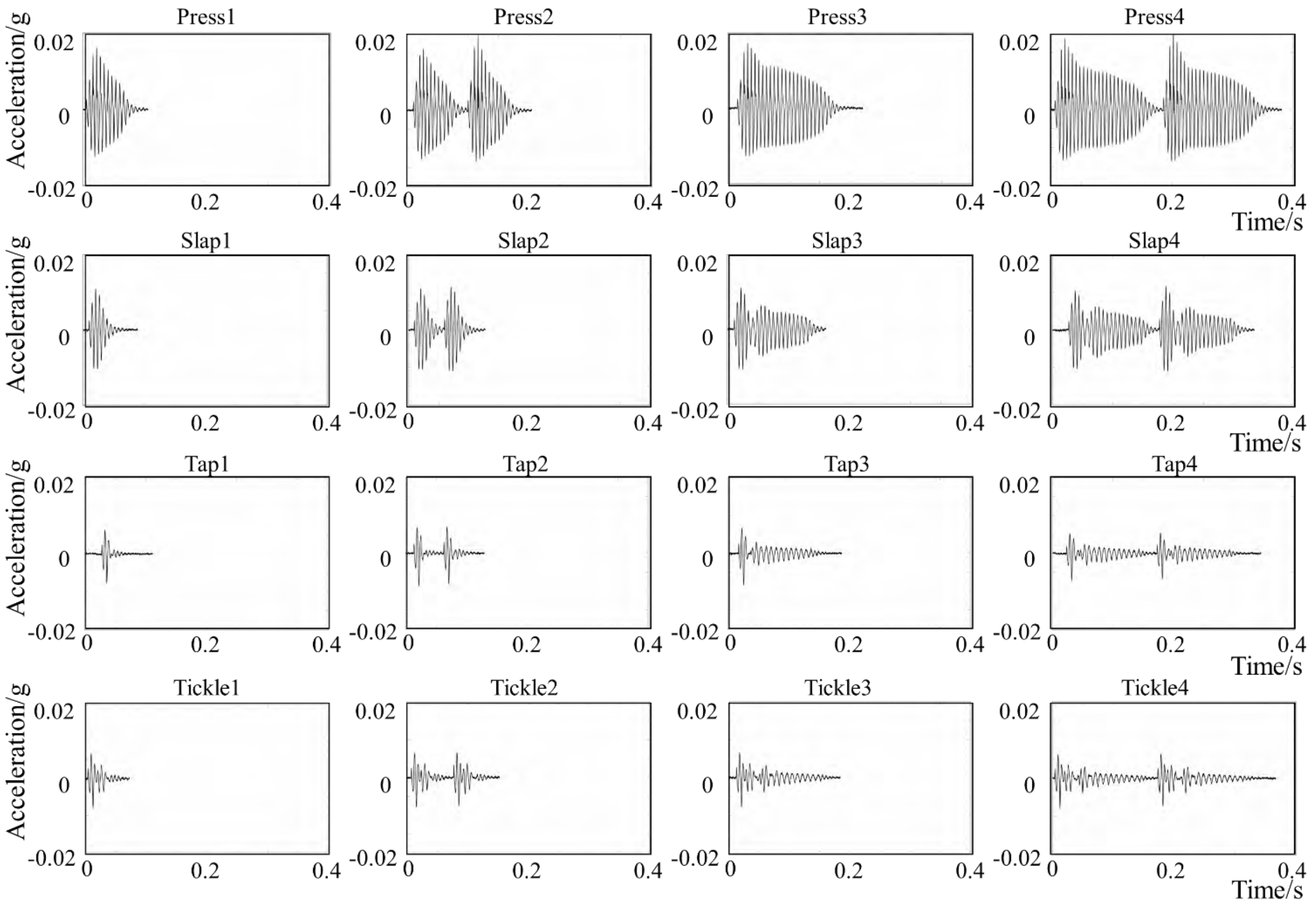


Figure 5.12 Recorded accelerations of MST signals in the SFA group

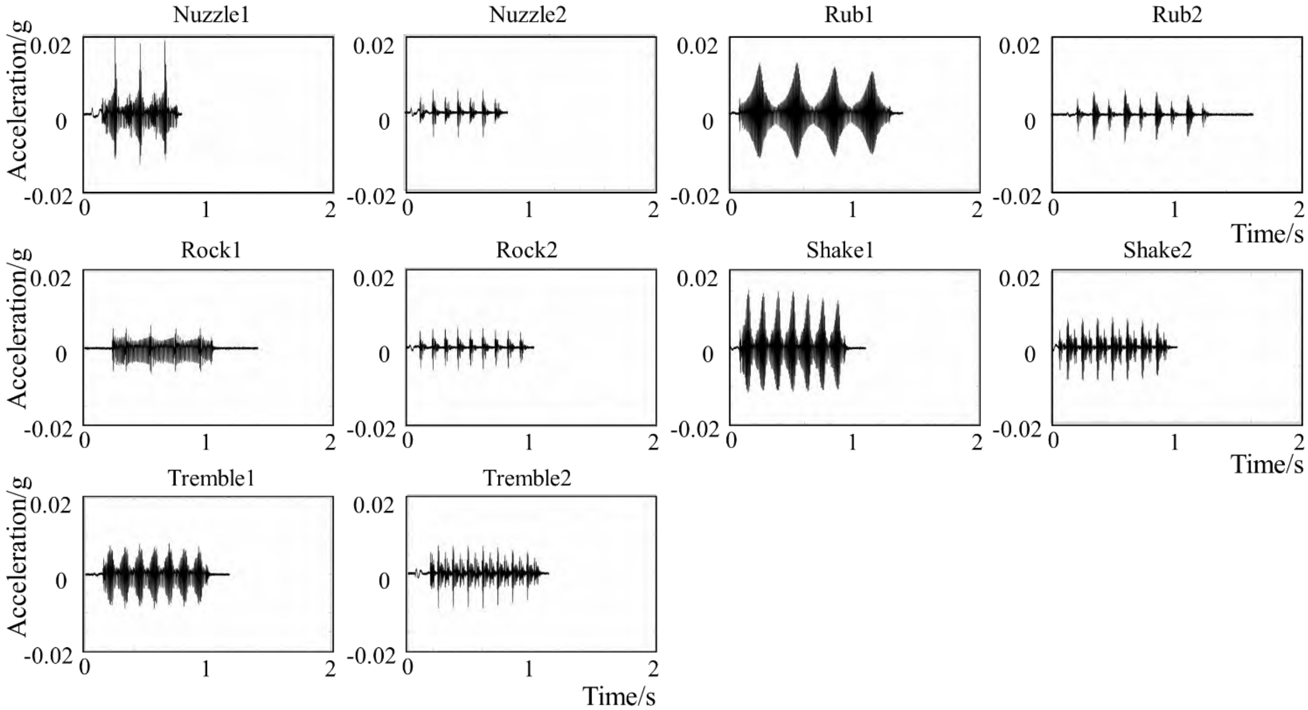


Figure 5.13 Recorded accelerations of MST signals in the RPT group

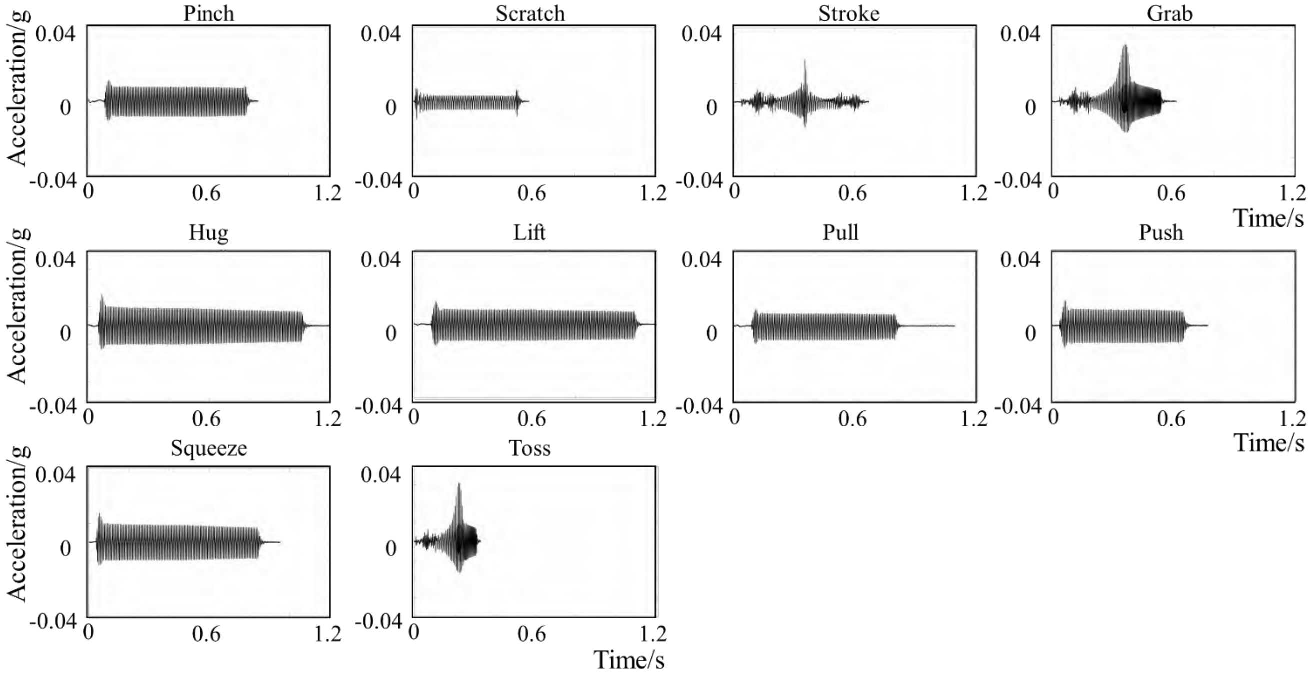


Figure 5.14 Recorded accelerations of MST signals in the SOT group

5.6 Experiment 1

In this study, we first conducted a subjective rating using the Likert scale to evaluate how likelihood the designed MST signals could be understood as intended MST gestures, similar to what Brunet et al. [194] and Sand et al. [195] did. We designed 52 MST signals for 23 MST gestures. We want to exclude MST signals that are obviously not suitable for a specific MST gesture. It is difficult to recognize 52 stimuli since Yoo et al. [196] have demonstrated that users can recognize at most 8-9 stimuli provided by one actuator at a time. We try to narrow down the number of MST signals by choosing the most well-understood signal. This study was approved by the Ethical Review Board from Eindhoven University of Technology with the approval number ERB2020ID137.

5.6.1 Experiment setup

We applied a special version of the LG V30 smartphone, embedded with a typical wide-band LRA motor (MPlus 1040). We generated drive signals using MATLAB R2018a. We developed an interface to generate MST signals with Android Studio (API: 25) (Figure 5.15). We applied graphical buttons as the carrier to trigger the corresponding MST signals. All the graphical buttons were set in the same shape, size, and color to control the visual variable. We applied the default setting of buttons in Android Studio for animations when pressing and releasing graphical buttons.

Figure 5.15 User interface of the experiment software

5.6.2 Participants

We invited twenty participants (twelve females and eight males, aged from 23 to 36) to participate in this study. Participants were recruited from the local university. All participants had no constraints of sensing touch, according to their report.

Participants wore noise-canceling headphones playing white noise with no pitch or rhythm to block out vibrotactile stimuli' sound effects (Figure 5.16). Participants were asked to hold the test phone with two hands (Figure 5.16). Participants used their right thumb to press the button on the touchscreen to trigger the MST signals.

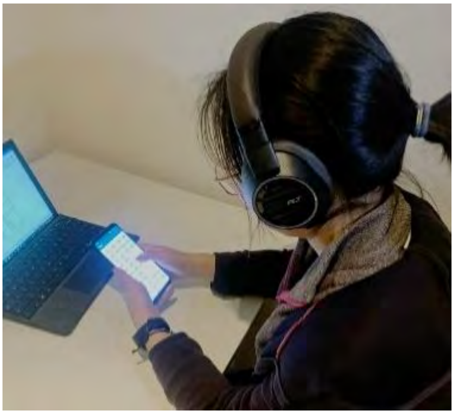


Figure 5.16 Test setting

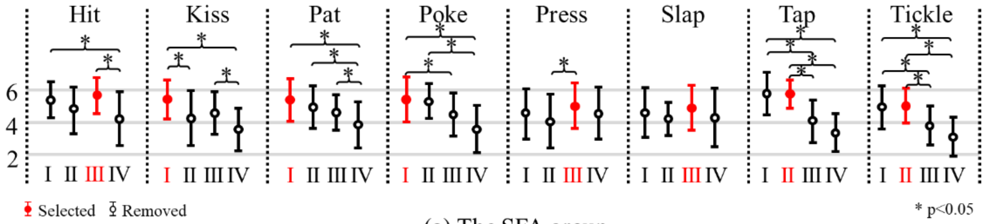
5.6.3 Procedure

Before the experiment, the experimenter introduced the test and handed out the consent forms and questionnaires.

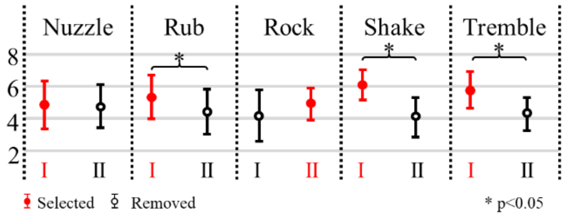
During the experiment, participants were first introduced to how the MST signals represented the MST gestures because it was difficult to tell the vibrotactile stimuli as a single modality. For example, the MST signal for 'Hug' was constant and strong. We would tell participants we designed the MST signal for a feeling of a tight embrace with a strong force.

Participants needed to press the graphical buttons once to trigger the MST signals and act as receivers. After each stimulus, they were asked to consider the likelihood to be understood as a mediated social touch (LUMST) and filled out the 7-point Likert Scale from 1 (very unlikely) to 7 (very likely).

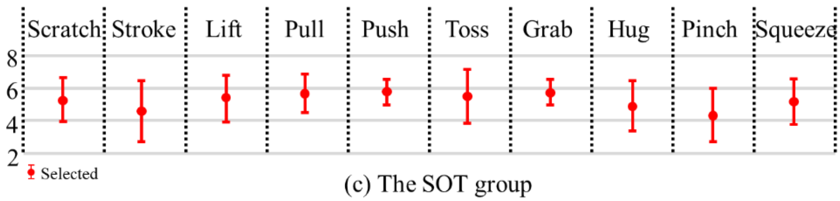
The orders of MST signals were randomized for each participant. All the randomized orders in this study were delivered to each participant before answering the questionnaire. Participants followed the order of MST signals they got and perceived them one by one. All the randomized orders in this study were obtained using the random function in Python.



(a) The SFA group



(b) The RPT group



(c) The SOT group

Figure 5.17 Descriptive data and comparison results of LUMST.
* A significant difference exists between the two CWC forms (p<0.05). Signals marked in red were chosen for the next experiment.

5.6.4 Results

We used SPSS 23.0 to conduct the quantitative analysis. We have designed a total of 52 vibrotactile stimuli for 23 MST gestures. We need to select 23 vibrotactile stimuli for them. To determine the most suitable vibrotactile stimuli, we employed ANOVA test (normal distribution), Wilcoxon signed-rank test (nonnormal distribution, two samples) [197], and Friedman test (nonnormal distribution, more than two samples) [198], utilizing the LUMST ratings to identify those with the highest scores. We removed CWC forms with significantly lower LUMST than the elementary ones. If we still have more than one CWC form for one MST gesture. We conduct other comparisons, mainly choosing the CWC form with a higher mean or minor variance as the final MST signal.

Based on the above analysis, we selected 23 MST signals. In Figure 5.17, we marked 23 MST signals that would be used for the next experiment in red.

5.7 Experiment 2

We selected 23 MST signals from Experiment 1. Now we continue testing the recognition performance for them. We want to explore to which extent the designed MST signals could be recognized as intended MST gestures.

5.7.1 Experiment setup

We used the same test phone as mentioned in section 6.1. We divided 23 MST signals into three groups randomly. Two groups have eight MST signals, and one group has seven MST signals. The reason was that Yoo et al. [196] demonstrated that users could recognize at most 8-9 stimuli using one single actuator at a time.

5.7.2 Participants

We invited twenty participants (ten females and ten males, aged from 24 to 38) to participate in this study. Participants were recruited from the local university. All participants had no constraints of sensing touch, according to their report. Participants wore noise-canceling headphones playing white noise with no pitch or rhythm to block out vibrotactile stimuli' sound effects.

5.7.3 Procedure

Before the experiment, we introduced the study, provided the consent form, and briefly introduced the MST signals.

During the experiment, participants need to finish a recognition exercise. Participants were asked to perceive the vibrotactile stimuli on the test phone one by one and match the MST gesture name displayed on the computer touchscreen. Participants tell the name of vibrotactile stimuli displayed on the test phone verbally. The experimenter recorded their answers on the paper questionnaire.

Twenty-three MST signals were presented to each participant three times. As we displayed 23 MST signals in three groups, each participant needed to finish nine groups. The order of vibrotactile stimuli was randomized for each participant. We manually set the different order of vibrotactile stimuli on the test phone for each participant.

5.7.4 Results

1) Recognition performance for each MST signal

Figure 5.18 shows the confusion matrix of recognition for each MST signal. In the experiment, participants were asked to recognize at most 8 MST signals in one group, so the random recognition rate should be 12.5%. In our experiment the overall precision was 35.94%, ranged from 13.3% (Pinch) to 71.7% (Shake).

We sequenced the recognition precision of each MST signal (Figure 5.19 (a)). We found that MST signals in the RPT groups could be recognized better. We statistically proved it by conducting the ANOVA test on the accurate recognition times of MST signals based on different hand/finger movements (Figure 5.19(b)).

Figure 5.19 (a) and (c) showed that selected 23 MST signals that ranked in the top half in both LUMST and recognition included 'Shake,' 'Pat,' 'Tap,' 'Poke,' 'Tremble,' 'Push,' 'Toss,' 'Grab,' and 'Pull.' (marked with ^ in Figure 5.19). It indicates that these designed MST signals could be understood and recognized to some extent. In contrast, 'Hug,' 'Stroke,' 'Press,' and 'Pinch' (marked with ^^ in Figure 5.19) ranked in the bottom third. It means signal iteration is needed for them. We will discuss them in the discussion part.

2) Recognition results between different hand/finger movements

We also provide the confusion matrix based on the hand/finger movement (Figure 5.20). The precision for each group was 77.1% (SFA), 76.7% (SOT), and 80.0% (RPT), resulting in an average precision of 77.5%. This result showed that the recognition performance based on the hand/finger movement was always above 75%.

	SFA	SOT	RPT	Sum	Precision
SFA	**370**	**83**	**27**	**480**	**77.1%**
SOT	**81**	**460**	**59**	**600**	**76.7%**
RPT	**33**	**27**	**240**	**300**	**80.0%**
Sum	**484**	**570**	**326**	**1380**	

Figure 5.20 Confusion matrix of the recognition results based on hand/finger movement

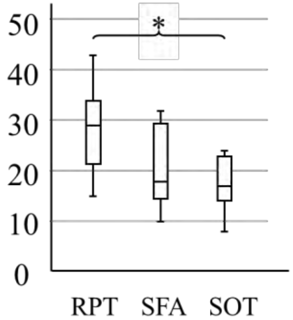
		SFA								SOT										RPT						
		Hit	Kiss	Pat	Poke	Press	Slap	Tap	Tickle	Grab	Hug	Lift	Pinch	Pull	Push	Scratch	Squeeze	Stroke	Toss	Nuzzle	Rock	Rub	Shake	Tremble	Sum	Precision
SFA	Hit	16	3		7	6	2	5	5		2	1	4		1		1	2	1			2	2		60	26.7%
	Kiss	6	13	6	6	1	7	7	2	1		3	3		1		1		1	1			1		60	21.7%
	Pat	3	4	32	5	1		10	1	1			1				1	1							60	53.3%
	Poke	2	2	8	28	3		8	2		2		2						2				1		60	46.7%
	Press	6	2	2	2	10	4	1	1	6	1	1	4	2	1	2	4	1	3	1	2		3	1	60	16.7%
	Slap	6	2	5	2	2	19	5		2	1		4	1	1	3			5	1		1			60	31.7%
	Tap	1	3	9	2		2	31	2	1	1		1			1				4	1			1	60	51.7%
	Tickle	5	6	3	5	4	1	9	17		1		1			1	1	1		3	1	1			60	28.3%
SOT	Grab	1	2	1		2				23	1	2	2	4	2	5	3	1	5	2		1	1	2	60	38.3%
	Hug	1				4	2			1	14	4	2	5	4	7	7	1		1	1	2	2	2	60	23.3%
	Lift		3			1				4	3	17	1	10	5	4	4		1	1		2	1	3	60	23.3%
	Pinch	1			3	7					5	8	8	11	4	3	6	1	1			1		1	60	13.3%
	Pull				1	1	1			3	1	6	4	23	8	4	2	1	1		1		1	2	60	38.3%
	Push	1				2		1	2	1	4	2	1	7	24	3	6	2	1			1		2	60	40.0%
	Scratch		4		1	6			1	3	2	1	3	7	4	11	5	4	2		1	3		2	60	18.3%
	Squeeze					4	2			2	2	3		4	8	4	17	3	1	3	2	1	1	3	60	28.3%
	Stroke		5		1	1		2	4	3	2	3	4	2	1	5	2	14	1	5	3	1		1	60	23.3%
	Toss		1	1	1	3	4		3	3		3	5	1	2	4	1	1	24	1	1			1	60	40.0%
RPT	Nuzzle			1	1	1	1		1	1	1		1			2		4	2	29	5	6	3	1	60	48.3%
	Rock	2		1	1		2		9							1	1	1	1	5	24	3	2	7	60	40.0%
	Rub								2		1	1				1				3	6	34	8	4	60	56.7%
	Shake	1							2				1		1						2	3	43	7	60	71.7%
	Tremble	1					1		6		1	1	1			1	2	1		2	4	5	9	25	60	41.7%
	Sum	53	50	69	66	59	48	79	60	55	45	56	53	77	67	62	64	39	52	62	54	67	78	65	1380	

Figure 5.18 Confusion matrix of the recognition results for each MST signal

Movement forms	MST signal	Precision
RPT	Shake ^	71.7%
RPT	Rub	56.7%
SFA	Pat ^	53.3%
SFA	Tap ^	51.7%
RPT	Nuzzle	48.3%
SFA	Poke ^	46.7%
RPT	Tremble ^	41.7%
SOT	Push ^	40.0%
SOT	Toss ^	40.0%
RPT	Rock	40.0%
SOT	Grab ^	38.3%
SOT	Pull ^	38.3%
SFA	Slap	31.7%
SFA	Tickle	28.3%
SOT	Squeeze	28.3%
SFA	Hit	26.7%
SOT	Hug ^^	23.3%
SOT	Lift	23.3%
SOT	Stroke ^^	23.3%
SFA	Kiss	21.7%
SOT	Scratch	18.3%
SFA	Press ^^	16.7%
SOT	Pinch ^^	13.3%

Top half ↑ (rows Shake to Pull); Bottom third ↓ (rows Hit to Pinch)

(a)



(b)

Movement forms	MST signal	LUMST
RPT	Shake ^	6.10
SOT	Push ^	5.80
SOT	Grab ^	5.80
SFA	Tap ^	5.75
RPT	Tremble ^	5.75
SOT	Pull ^	5.65
SFA	Hit	5.60
SOT	Toss ^	5.50
SFA	Pat ^	5.40
SFA	Poke ^	5.40
SFA	Kiss	5.40
SOT	Lift	5.35
RPT	Rub	5.35
SOT	Scratch	5.30
SOT	Squeeze	5.20
SFA	Press ^^	5.10
SFA	Tickle	5.00
SOT	Hug ^^	4.95
SFA	Slap	4.90
RPT	Rock	4.90
RPT	Nuzzle	4.85
SOT	Stroke ^^	4.50
SOT	Pinch ^^	4.30

Top half ↑ (rows Shake to Lift); Bottom third ↓ (rows Press to Pinch)

(c)

Figure 5.19 (a) A sequence of the recognition precision; (b) Accurate recognition times based on hand/finger movement; (c) A sequence of the LUMST results. We marked different hand/finger movements (see section 1.3) with green (RPT group), grey (SFA group), and blue (SOT group) squares. MST signals ranked in the top half in both LUMST and recognition were marked as ^, while those ranked in the bottom third were marked as ^^.

5.8 Discussion and Limitations

5.8.1 The performance of transferring MST gesture pressure to MST signal frequency

In this study, the MST gesture pressure and the MST signal intensity were connected by frequency. We provided a function to transfer MST gesture pressure to MST signal frequency. We have mentioned the advantages of doing so in section 2. However, some MST signals did not reach the threshold expected to be clearly understood or recognized. We found three possible reasons based on the aspects of transferring pressure to frequency, as follows:

- This could be related to the duration of a tap-like MST gesture, which can affect pressure [199]. The short duration of one tap-like gesture may have a gentler pressure than a longer one. This may cause a low LUMST or recognition. For example, 'Hit' and 'Slap' should be forcible and sharp [130], but the recorded pressure is slightly lower than 'Kiss' since 'Kiss' has a longer duration. Nevertheless, the longer duration and a transferred frequency slightly closer to the resonant frequency make 'Kiss' even a bit stronger than 'Hit' and 'Slap' with vibrotactile stimuli.
- Some MST gestures may have multiple expressions, but we only provide one MST signal for participants to perceive. To illustrate this, Figure 5.18 shows that 'Press' has a low recognition precision (16.7%). Some participants recognized 'Press' as an MST gesture with a short duration, such as 'Hit', while some recognized it as an MST gesture with a long duration, just like 'Squeeze'. This indicates that the expressions of 'Press' have different types with short or long press.
- This might be caused by the mechanism of the system and the actuator. For example, 'Stroke' should be a gentle MST gesture. We recorded a gentle stroke pressure as presented in Chapter 3. The transferred frequency changes from 40Hz to 98Hz, which should provide gentle vibrotactile stimuli. However, Figure 5.14 shows that the recorded highest acceleration amplitude was even higher than some strong MST signals such as 'Lift' or 'Squeeze'. Participants in Experiment 1 also rated a relatively low score in LUMST and mentioned that the vibrotactile stimuli for 'Stroke' were too strong. The highest acceleration amplitude would be huge if the frequency changes within a certain range.

Based on the above, we could further iterate the designed MST signals as follows:

- We could adjust the parameters of the drive signals, such as the duration or frequency, to make vibrotactile stimuli better match the MST gesture. For example: (1) Decreasing the frequency of 'Kiss' will make it relatively weaker and, in consequence, easier to understand; (2) For ‘Pinch,’ there should be a sharp grip between fingers and thumb [130]. This can be done by changing the frequency from low to high and decreasing the duration; (3) Making the vibrotactile stimuli of ‘Stroke’ gentler by decreasing the frequency will improve it since the stimuli were too strong and with a sudden change.

- We could provide different MST signals based on different contexts for MST gestures with other intended expressions. For example, we could provide short duration vibrotactile stimuli when users ‘Press’ shortly. Long-duration vibrotactile stimuli could be provided when users ‘Press’ long and steady.

5.8.2 LUMST and recognition performance

Figure 5.19 (a) illustrates that five of the seven MST signals with the lowest recognition precision are from the SOT group. The reason could be that many MST gestures in the SOT group belong to metaphorical gestures, which are inherently difficult to perform [80]. Thus, it is understandable that MST signals designed based on them are not easy to recognize. For example, for ‘Lift’ (Figure 5.2 (b)), participants move their thumbs from the bottom to the top with a strong force to show ‘Lift’ someone up [80]. We only displayed the strong force of ‘Lift’ by the MST signal. We could not display the gesture movement – from bottom to top, by the MST signal, which may cause a low recognition precision.

We could improve it by displaying the gesture movement and changing the MST signal intensity instead of only displaying a constant and strong force. For example, ‘Toss’ was designed to show a metaphor of the finger’s flying out of the touchscreen. ‘Grab’ was designed to show a sudden change of movement and force. Thus, they have a noticeable signal intensity change (Figure 5.14). They belong to the SOT group, but the recognition precision is still in the top half.

Some MST signals selected from Experiment 1 were scored in the top two-thirds, meaning they could be understood to some extent. However, the recognition performance was low, ranked in the bottom third. For example, ‘Kiss,’ ‘Lift,’ and ‘Scratch’ got a LUMST of 5.40, 5.35, and 5.30 out of 7, while a recognition precision was 21.7%, 23.3%, and 18.3%, respectively. The possible reasons are as follows:

- Additional information besides vibrotactile stimuli could affect the LUMST and the recognition performance. In Experiment 1, we explained the vibrotactile stimuli to the participants, and they used this information to rate them so that we may get a good result in LUMST. However, in Experiment 2, participants had no clear information about the vibrotactile stimuli during the recognition task. Unlike Brunet et al. [194] who provided 21 vibration patterns for 21 metaphors, they had a very high precision rate for each metaphor. The difference can be that they displayed metaphors with figures and asked participants to match the vibration patterns with figures. However, we used a word to display the name of MST gesture and asked participants to match the vibrotactile stimuli with the name. Kotz and Cals [200] indicate that figures can be more efficient and provide more information than words if designed well.

- MST signal morphology could affect the recognition performance. Many MST signals in one hand/finger movement are clustered because those MST gestures are closer in pressure, duration, and hand/finger movement. We also used similar design ideas when designing vibrotactile stimuli for them. For example, in the SOT group, vibrotactile stimuli are all long-duration signals, such as 'Hug' and 'Lift', where the vibrotactile stimuli are all strong, constant, and long. It was not surprising that participants had difficulties recognizing them quickly because they did not have significantly different rhythms or tempo patterns. Researchers have found that rhythms or tempo patterns are important parameters when differentiating vibrotactile stimuli [201], [202], [203].

From such results, it is possible to derivate some guidelines when designing MST signals for applications:

- Controlling the number of displayed MST signals. Using and trying to remember fewer haptic stimuli would not cause a high workload and might provide a better recognition performance [204]. Sand et al. [195] provided only six haptic stimuli without metaphors. They asked participants to remember the form of haptic stimuli and they got a higher overall accuracy result (66%) in the recognition task than us. Meanwhile, there is also no need to provide every MST signal because it has been found that users have frequently used MST gestures in social communication [80]. We could consider providing only necessary MST signals for users in future mobile communication.
- Using MST signals with different CWC forms. For example, 'Pat' and 'Tickle' have the same frequency and duration. It could be set with one short pulse for 'Pat' and two short pulses for 'Tickle'. As a result, it would be easy for users to remember and recognize them in a single application.
- Adding information such as visual stickers besides vibrotactile stimuli when using similar MST signals. As an illustration, vibrotactile stimuli in the SOT group are all constant and with long duration. Thus, we could add visual information, such as gesture stickers, to differentiate those MST signals.

5.8.3 Evaluation alternatives

The generation method proposed in this study may not be effective for all MST signals. The low LUMST and recognition precision of some MST signals may also mean that the generation method is less effective for them.

We sort out research topics that may arise in each step during the generation method (Figure 5.21). This study first tries to transfer pressure to frequency and creates different CWC forms for each MST signal. We found that the possible evaluation alternatives could be:

1) Different bridges between MST gesture pressure intensity and MST signal intensity, e.g., frequency versus amplitude control.
2) Different functions for transferring the MST gesture pressure to the MST signal frequency.
3) Other hand/finger movements
4) Different CWC forms.

In Figure 5.21, the box with a solid line are choices we made in each step, while those with the dashed line are other possible choices we decided not to consider. It is impossible to compare all unsure factors or parameters in one study. So, this study mainly focused on the following aspects:

- We connect the MST signal intensity to the MST gesture pressure intensity.
- We use frequency to control the MST signal intensity.
- We use a parabolic function to transfer MST gesture pressure to MST signal frequency.
- We use the specific CWC forms designed in this study.

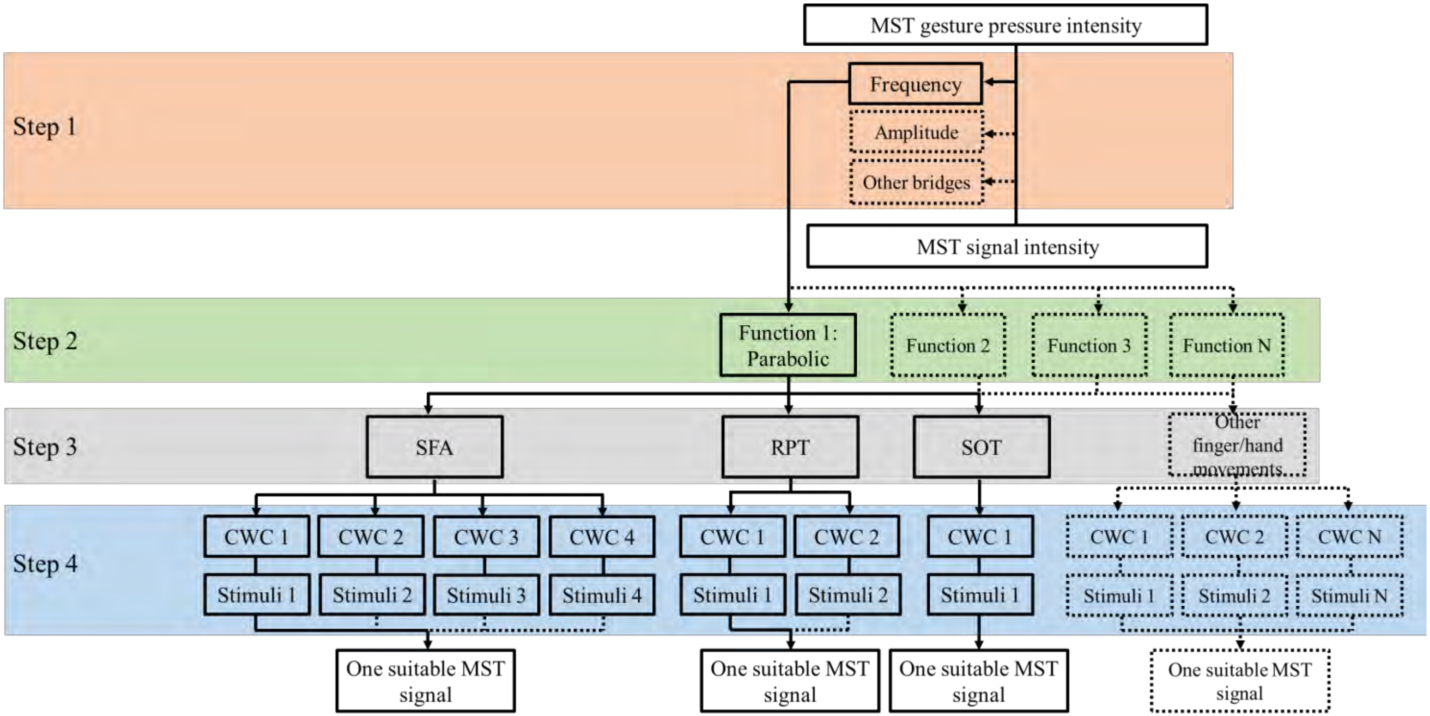


Figure 5.21 Alternatives in the design steps

5.8.4 Calibration

For other hardware structures or actuators, calibration may be needed. The frequency and duration in Table 5.1 and Table 5.2 works based on our system (LRA, MPlus 1040). The same frequency and duration may lead to different acceleration or output duration for other hardware structures or actuators.

The frequency could be calibrated based on the vibration intensity. For example, in ‘Lift,’ the frequency is set to 155Hz based on our system (f0=160Hz), which leads to strong perceived intensity since ‘Lift’ needs a strong force. However, for other hardware structures or actuators, the resonant frequency may not be 160Hz. Researchers just need to calculate the frequencies based on Function (5 – 1) and try to reach similar accelerations of vibrotactile stimuli and provide users with similar perceiving effects.

Duration could be calibrated based on the output. For example, in ‘Hit’, the input duration is set to 0.01s based on our hardware structure. The output duration transferred by the LRA applied in our hardware structure is 0.2s. 0.2s is the duration that users will perceive. If other hardware structures or actuators are applied, researchers just need to make the vibrotactile stimuli that users perceive to be 0.2s for the calibration. The duration of the input drive signals may not be 0.01s with other systems.

5.8.5 Limitations

We proposed a preliminary design of MST signals in this study. However, we did not consider specific applications in different contexts when evaluating MST signals. The recognition performance may be different when we apply MST signals in social communication since Jones and Tan [205] mentioned that humans were inclined to perceive and judge stimuli in a context.

In our experiment, participants pressed the graphical buttons to trigger the MST signals. But the different speeds of user pressing buttons may cause different perceiving in MST signals, especially for those with long duration. For example, in the SFA group, the MST signals were triggered in both the press and release stages of the graphical buttons. For long-duration signals such as the Form IV of ‘Press’, if participants pressed the button at a relatively lower speed, they would perceive the MST signal in Figure 5.22 (a). In comparison, they would perceive the one in Figure 5.22 (b) if they pressed the button at a relatively higher speed. Participants may not feel the double ‘clicks’ feelings. Thus, we should consider the speeds of user pressing buttons when designing MST signals in future research.

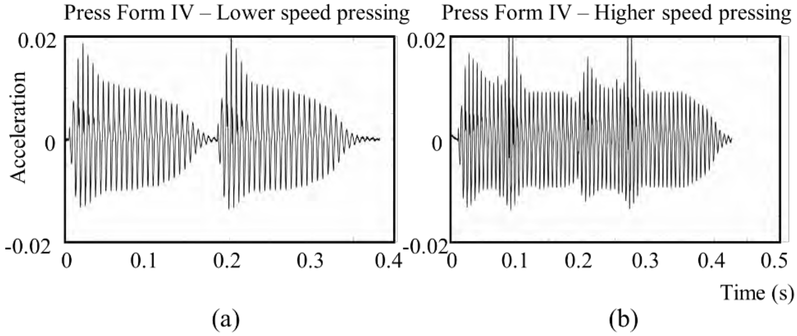


Figure 5.22 Examples of recorded accelerations of Form IV in the SFA group – Press (a) accelerations of lower speed; (b) accelerations of higher speed

The introduction of MST signals before the experiment may cause a recall effect which may affect the recognition of the designed signals. Before experiment 2, we briefly introduced the 23 MST signals to the participants. We did this because Brunet et al. [194], Chan et al. [206], Jones et al. [207], and Jacob et al. [208] have demonstrated that a short learning process could make the recognition performance of haptic stimuli better. On the other hand, it seems that the introduction process may cause a recall effect. However, according to Enriquez et al., [209], [210] there would be an iterated reinforced learning phase, which may last 45 mins when testing the recall performance of haptic stimuli. Participants should also be informed of their errors in the learning phase. In contrast, we did not have this learning phase. There was no need for participants to remember the MST signals in our experiment. Thus, the results should mainly be attributed to recognition instead of the recall effects.

5.9 Conclusion and future work

This study provides a generation method for MST signals on smartphones. Firstly, we provide a function to transfer the MST gesture pressure to MST signal frequency. Then, we set the MST signal duration similar to the MST gesture duration collected from Chapter 3. Moreover, we create different CWC forms and try to iterate and differentiate the MST signals.

We conducted user studies to explore how likely the designed MST signals could be understood as intended and to which extent the designed MST signals could be recognized as intended. We check the LUMST and the recognition performance of MST signals. We selected 23 MST signals from the designed 52 MST signals based on the LUMST results. We found that around 70% of designed MST signals could be recognized above a precision of 25%, which was two times better than the random recognition rate. These concrete measures can be referenced when designing MST signals in future applications.

We also suggest design implications and guidelines for MST signals on smartphones for future applications:

- Design MST signals based on contexts.
- Control the number of displayed MST signals and provide only necessary ones based on contexts in future mobile communication.
- Design long-duration MST signals with intensity changes and try to display hand/finger movement of the MST gestures.
- Use MST signals with different CWC forms when the frequency and duration are similar.
- Add information such as visual stickers besides vibrotactile stimuli when using similar MST signals.

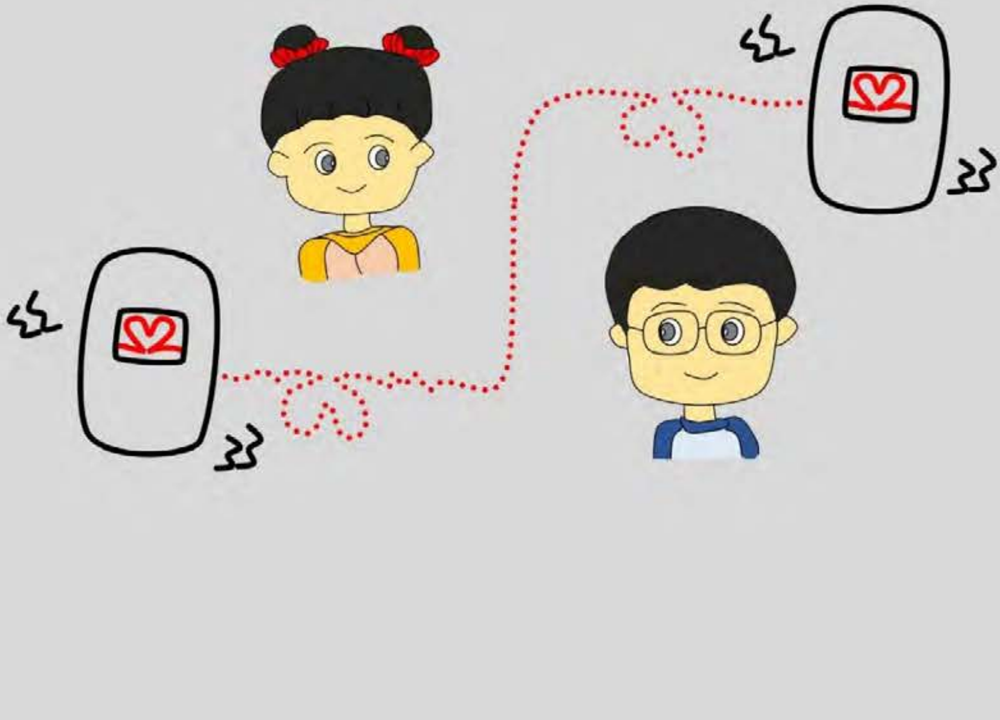
The main contributions of this study are:

1) A generation method of MST signals for smartphones involving frequency, duration, and CWC forms.
2) A function to transfer MST gesture pressure to MST signal frequency.
3) A rich set of MST signals.
4) Design implications and guidelines for MST signals on smartphones for future applications.

In the next chapter, we will apply MST signals designed in this chapter to mobile communication and explore the effects of using MST signals in a specific context. Multi-modal stimuli will also be considered when designing MST signals for a better understanding.

Chapter 6

Communication between Senders and Receivers



This chapter is based on:
Q. Wei, J. Hu, and M. Li, "Enhancing social messaging with mediated social touch," *International Journal of Human-Computer Interaction*, pp. 1–20, 2022.

Abstract
We presented the design of mediated social touch signals in the last chapter. In this chapter, we will present an experiment where we apply the designed mediated social touch signals for mobile communication.

Background: Mediated social touch (MST) is a popular way to communicate emotion and connect people in mobile communication.

Goal: This work applies MST gestures with vibrotactile stimuli in two online communication modes – asynchronous and synchronous communication (texting and video calling) to enhance social presence for mobile communication.

Methods: We first designed the application that included the visual design of MST gestures, the vibrotactile stimuli design for MST gestures, and the interface design for texting and video calling. Then, we conducted a user study to explore if the MST gestures with vibrotactile stimuli could increase social presence in texting and video calling compared to MST gestures without vibrotactile stimuli. We also explored if the communication modes affected social presence when applying MST signals.

Results: The quantitative data analysis shows that adding vibrotactile stimuli to MST gestures helps to increase social presence in the aspects of co-presence, perceived behaviour interdependence, perceived affective understanding, and perceived emotional interdependence. Adding vibrotactile stimuli to MST gestures causes no significant differences in attentional allocation and perceived message understanding. There is no significant difference between texting and video calling when applying MST gestures in mobile communication. The qualitative data analysis shows that participants think MST gestures with vibrotactile stimuli are interesting, and they are willing to use it in mobile communication, but the application design should be iterated based on their feedback.

6.1 Introduction

Mediated social touch (MST) describes one person touching another person over a distance with tactile or kinesthetic feedback [15]. Researchers have demonstrated that the mobile device is the most wanted non-wearable device to communicate MST signals [16]. The recent haptic technology with embedded vibration actuators, makes it possible to communicate MST signals through mobile devices [28], [142]. For example, the Taptic Engine, which could simulate various vibrotactile effects for different applications [143], has been embedded in iPhones since iPhone 7. Researchers have developed prototypes and applications for mobile devices to communicate MST signals such as patting, slapping, kissing, tickling, poking, and stroking [19], [20], [23], [26], [48], [141].

MST signals are important in mobile communication since they can elicit feelings of social presence [4]. Social presence describes the degree to which a user is perceived as real [32], [33], [34] and with access to intelligence, intentions, and sensory impressions [35]. Haptic feedback is a popular and useful way to increase social presence and convey more affective information in mediated social interaction [4], [32], [36] during phone calls, video conferencing, and text messaging [4]. For example, researchers have applied haptic feedback for mediated social interaction in a collaborative environment [37], [38], [39], [40], [41] to increase social presence.

However, few MST studies focused on mobile devices with haptic feedback in social presence. To cover this gap, in this chapter, we present the MST gesture design with vibrotactile stimuli for mobile communication. The objective is to increase social presence in mobile communication by applying MST gestures with vibrotactile stimuli. We will apply the haptic technology [192], using a mobile device embedded with a linear resonance actuator (LRA) to explore the field of MST signals, online communication, and social presence.

The detailed design factors in this study are the visuals of MST gestures, the vibrotactile stimuli of MST gestures, and the interfaces of mobile communication applications. In the user study, we will explore if the MST gestures with vibrotactile stimuli have a higher social presence than the MST gestures without vibrotactile stimuli. We will also explore if there is any difference between synchronous (video calling) and asynchronous communication (texting) in social presence when applying MST signals.

6.2 Related work

6.2.1 MST gestures with haptic stimuli on mobile devices

Many researchers have developed prototypes for communicating MST gestures with haptic stimuli on mobile devices. Zhang and Cheok [26] designed a haptic device – Kissenger – that displays kissing when using mobile devices for online communication to make users feel a deeper emotional connection. The haptic device could capture the real-time sensor data and transmit it to the mobile application and other users over the communication network. Users can use the haptic device for touch communication during video or audio calls. Besides the communication between a dyad, Kissenger can also be used in social applications such as Skype, Facebook and Whatsapp for communications between multiple people. Park et al., [19] designed CheekTouch to transmit MST signals such as patting, slapping, tickling and kissing during a phone call. The haptic prototype was attached to the mobile phone. Users can use different finger gestures on the phone screen to trigger different vibrotactile stimuli on the other party's cheek. Park et al., [48] designed POKE to transmit MST signals during a phone call. This prototype was an inflatable surface that could be attached to the back of the mobile device for inputting MST gestures, and to the front of the mobile device for receiving MST signals. Hoggan et al., [21] designed Pressage and ForcePhone. Users can squeeze the side of the phone with different pressures to trigger different vibrations on the recipient's phone during a phone call. Teyssier et al., [20] developed MobiLimb, for mobile devices. It could create MST signals such as stroking and patting with haptic stimuli. Furukawa et al., [23] designed KUSUGURI, with this tactile interface, the dyads could send and receive tickling. Bales et al., [107] designed CoupleVIBE, which could send touch cues between partners' mobile phones by vibrations to share location information.

Based on the above, we found some space for further investigation:

- *Communication modes*. Many researchers focused on traditional phone calls, with the phone on the ear. This study will consider other communication modes like video calling and texting. Zhang and Cheok [26] considered video calling, but there was an additional prototype for the mobile device. This study will use a mobile device embedded with an LRA to display vibrotactile stimuli directly without extra devices.
- *Touch modality*. In the above studies, visual and haptic information are mostly separated. Wilson and Brewster [99] has demonstrated that combining multiple modalities could increase the available range of emotional states. This study will apply multimodal MST signals, with visual and haptic information together. We will explore if multi-modal modalities have better feedback than a single modality.

6.2.2 Social presence with haptic stimuli

Social presence with haptic stimuli has been explored in collaborative environments [37], [38], [39], [40], [41], remote communication [211], affect communication [212], interaction with a virtual agent [212], [213], and behaviour influence [33]. Researchers used haptic devices such as wearables [37], robotic hands [41], [211], smartwatches [33], mobile devices [33], and haptic prototypes designed for hands [39], [40], [213] and feet [213].

Oh et al., [32] reviewed studies on haptic social presence and found that haptic stimuli influenced perceptions of social presence significantly with a positive relationship existing between the two [32].

Based on the above, we observe the following:

- *Haptic devices*. In social presence, most haptic devices are wearables, robots, and other prototypes developed to present haptic stimuli. Few studies applied mobile devices in the social presence field. Hadi and Valenzuela [33] used a mobile device and conducted studies to show that text messages with haptic alerts help improve consumer performance on related tasks. The increased sense of social presence helped drive this effect. However, the context of their work differs from ours. They applied haptic alert messages to influence behaviour, while we planned to apply vibrotactile stimuli for MST gestures in mobile communication to increase social presence.

- *Contexts*. Most studies focused on collaborative tasks (e.g., collaboratively designing and drawing a new logo or poster [37], and passing an object between two people [38]). This study will consider a daily casual chatting context without specific collaborative goals.

6.2.3 Asynchronous and synchronous MST signals transmission and emotional expressions in mobile applications

Synchronous communication includes face-to-face and telephone conversations, such as phone calls and video calling [214]. Asynchronous communication is usually conducted through email, online discussion boards, or direct messages such as texting in WhatsApp, WeChat, or iMessage [215].

Many researchers have developed prototypes and applications for synchronous MST signals in mobile communication. For phone calls, researchers have designed prototypes such as Kissenger [26], CheekTouch [19], POKE [48], ForcePhone and Pressage [21], CoupleVIBE [107], and Bendi [22]. For video calling, prototypes can communicate MST such as remote handshaking [211] and kissing [26]. Other examples of MST signals for synchronous communication are tickling with KUSUGURI [23], grasping by a mobile sized prototype [141] and handshaking by SansTouch [49].

Researchers have also developed prototypes and applications for asynchronous communication, adding vibrotactile stimuli to specific text or using multimodal emoji during texting. For example, Pradana et al., [88] designed a ring-shaped wearable system – Ring U, which could promote emotional communication between people during texting messages using vibrotactile expressions. MobiLimb [20] could allow users to send a tactile emoji during texting. The other user can feel the tactile emoji on their hands while holding the phone or on the wrist with MobiLimb [20]. Israr et al., [62] designed Feel Messenger, a social and instant messaging application that provided emoji and expressions with vibrotactile stimuli. Wilson and Brewster [99] designed Multi-Moji for mobile communication applications, which combined vibrotactile, thermal, and visual stimuli together to expand the affective range of feedback. Wei et al., [92] proposed different methods to design vibrotactile stimuli for emoji and stickers in online chatting applications.

Based on the above, we find that:

- *For synchronous communication*, most MST signals on mobile devices have a single modality during a phone call, mainly the haptic modality. We will consider multimodal MST signals in visual and haptic modalities. Besides phone calls, we will also consider texting and video calling. Zhang and Cheok [26] considered kissing on mobile devices during video calls, but the MST types were limited. Users needed to use their lips and cheeks to touch the prototype to feel kissing [26], which might not be convenient for some people. This study will consider designing for a phone on the hands.
- *For asynchronous communication*, most studies mainly applied multimodal emoji to expand the affective range of feedback. Most emoji express different looks and emotions. There is a lack of considering specific multimodal MST signals on mobile devices. This study will consider multimodal MST signals in online communication.

6.3 Application Design

6.3.1 Design of mediated social touch

6.3.1.1 Selection of MST gestures

We explored the touch properties and designed vibrotactile stimuli for 23 MST gestures [80], [216], as also presented in earlier chapters. We only choose six MST gestures ('Hit', 'Pat', 'Stroke', 'Nuzzle', 'Push', and 'Hug') in this study, for the following reasons:

- This goal of this research is to explore if adding vibrotactile stimuli could increase the social presence and if there is a significant difference between synchronous (video calling) and asynchronous communication (texting) in social presence when applying MST signals. The key point is not the categories of MST gestures; therefore, it is not necessary to apply all MST signals.
- Due to technical limitation at this stage, it is not convenient to apply all MST signals on the interface because the interface is too small to display all MST signals without overlapping.

As touch communicates emotion [8], [9], our aim was to select MST gestures with different emotional expressions [9] and frequently used in mobile communication [80]. We selected 'Hit', 'Hug', 'Nuzzle', 'Pat', 'Push', and 'Stroke' in this study for the following reasons:

- *From the perspective of emotional expression*. We found that 'Hit', 'Hug', 'Nuzzle', 'Pat', 'Push', and 'Stroke' could cover rich emotional expressions such as 'Anger', 'Happiness', 'Sadness', 'Disgust', 'Love', 'Gratitude', and

‘Sympathy’ between male-male, male-female, female-female, female-male [9]. We do not consider ‘Fear’ in this study, as our dialogue in the user study will not cause fear.

- *From the perspective of usage frequency.* Chapter 3 shows that users use ‘Hug’, ‘Pat’, and ‘Stroke’ frequently and sometimes use ‘Hit’, ‘Nuzzle’, and ‘Push’ [80]. It is effective to apply these MST gestures in this study.

Table 6.1 shows the possible expressions these selected MST gestures could express [9] and the usage frequency in mobile communication [80].

Table 6.1 Selection of MST gestures

Selected MST gestures	Emotional expressions [1]	Usage frequency [2]
‘Hit’	Anger	Sometimes used (3.5 < mean ≤ 5)
‘Pat’	Happiness, Love, Gratitude, Sympathy	Frequently used (mean≥5)
‘Stroke’	Sad, Love, Sympathy	Frequently used (mean≥5)
‘Nuzzle’	Sad	Sometimes used (3.5 < mean ≤ 5)
‘Push’	Anger, Push,	Sometimes used (3.5 < mean ≤ 5)
‘Hug’	Happiness, Sad, Love, Gratitude, Sympathy	Frequently used (mean≥5)

[1] Emotional expressions were extracted from [9].

[2] Participants filled a 7-point Likert Scale for usage frequency [80] (also presented in Chapter 3). The detailed value of usage frequency of MST signals could be found in Chapter 3.

6.3.1.2 Visual design

We need visual hints for MST gesture input. We used the concrete figures of hands as stickers for MST gesture input for the following reasons:

- *Visual compensation*. It has been shown that using visual and vibrotactile stimuli together can increase the expressiveness of information [94]. To make the receiver understand the MST signals sent by the sender in online communication, we apply the concrete figure of hands to display the accurate MST gestures. To make the sender aware of what MST signals they are sending, we make the sender’s and receiver’s phones display the same concrete figures of hands.
- *Demands in the user study*. The MST gestures correspond to the recorded gestures from participants from Chapter 3. We created the visuals of MST gestures to closely resemble the recorded gestures. We did not use adorable hand figures commonly found in many mobile applications because they may affect the research results.

The principles to design visual stimuli of MST gestures are as follows:

- *User-defined gestures*. We designed visual stickers based on user-defined gestures for MST. The reason is that user-defined gestures are extracted from users' natural gestures, which can reflect the users' typical behaviour [145]. We applied the elicitation study [145], obtained user-defined gestures for MST, and calculated each user-defined gesture's agreement rate [80], as also presented in Chapter 3.

- *Emoji*. For some MST gestures that are not easy to understand only based on the figure of user-defined gestures [80], we designed them based on emoji. The reason is that emoji have been widely used and as validated effective in terms of being understood by users.

Table 6.2 shows the visual design concepts. We designed the visual sticker based on user-defined gestures for 'Hit', 'Pat', 'Stroke', 'Nuzzle', and 'Push'. The visual stickers of these MST gestures are similar to user-defined gestures.

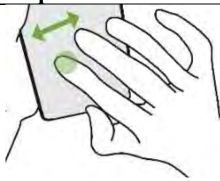
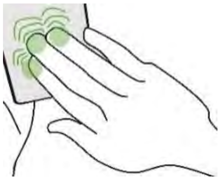
As presented in Chapter 3, 'Hug' and 'Squeeze' have the same user-defined gesture with different contexts. Regarding visual modality as the single channel, it is not easy to differentiate the user-defined gestures of these two MST gestures. It was also found that the user-defined gesture for 'Hug' was in the metaphor group. So, we refer to emoji to choose a unique one for 'Hug'. Figure 6.1 shows the visual stickers we designed for the input MST gestures in this study.

6.3.1.3 Vibrotactile stimuli

In Chapter 5, we presented a generation method to design vibrotactile stimuli for MST gestures based on social touch properties such as pressure and duration. We applied the recommended vibrotactile stimuli for these MST gestures (except for 'Stroke'). The results showed that the vibrotactile stimuli for 'Stroke' were too strong. In this study, we changed the frequency of 'Stroke' to give it a gentle intensity.

Table 6.3 shows the parameters and recorded accelerations of vibrotactile stimuli for the MST gestures.

Table 6.2 Visual design inspiration

MST gestures	Inspiration	MST gestures	Inspiration
Hit [1]		Nuzzle [1]	
Pat [1]		Push [1]	
Stroke [1]		Hug [2]	

[1] The inspiration of these MST gestures come from user-defined gestures [80].

[2] The inspiration of 'Hug' come from emoji [217].

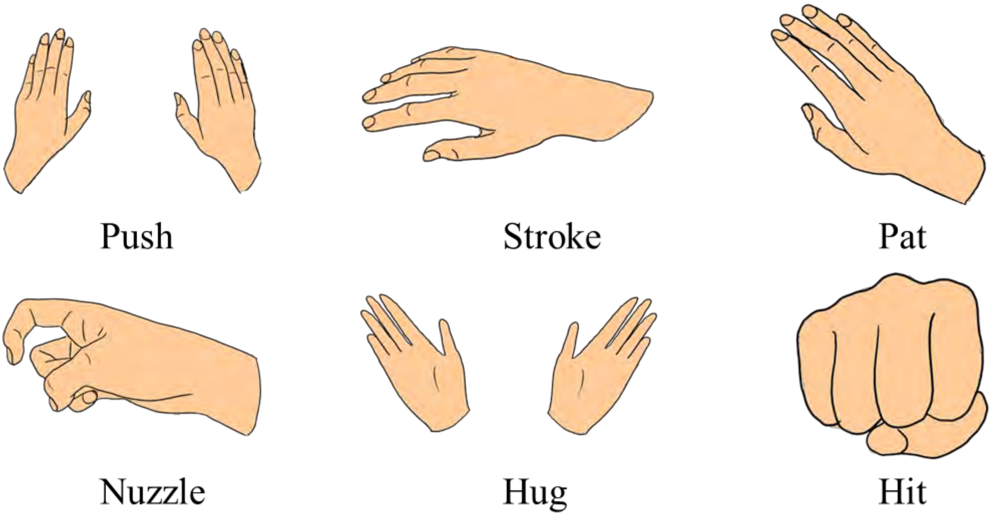
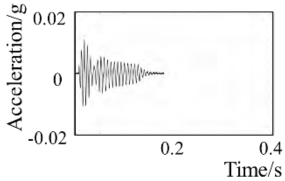
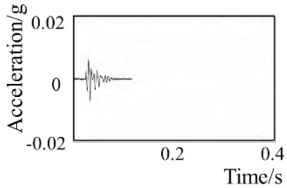
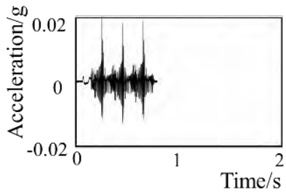
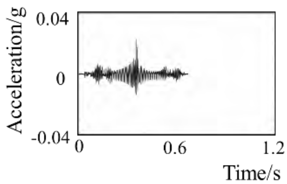
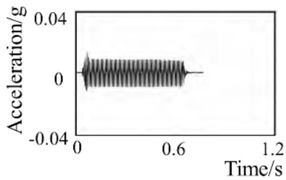
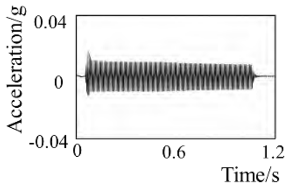


Figure 6.1 Visual design of stickers when input MST gestures.

Table 6.3 Details of vibrotactile stimuli for the MST gestures selected from based on Chapter 5

Selected MST gestures	Frequency	Duration	Recorded accelerations
'Hit'	148 Hz	0.15 s	
'Pat'	116 Hz	0.10 s	
'Nuzzle'	86 Hz – 116 Hz – 86 Hz	0.60 s	
'Stroke'	40 Hz – 70 Hz	0.60 s	
'Push'	153 Hz	0.60 s	
'Hug'	156 Hz	1.00 s	

6.3.2 Interface design

We developed texting and video calling interfaces with haptic input and display using Android Studio (API: 25).

6.3.2.1 Interface for texting and sticker animation

Figure 6.2 shows the interface for texting. The visual stickers of MST gestures are invisible at first. The visual sticker of MST gestures shows up when the user touches a specific area. When the user's finger leaves the area, the visual sticker of MST gestures becomes invisible again. The positions of the visual stickers are fixed. We set the positions of visual stickers considering two aspects: 1) proper positions in real life and 2) evenly distributed over the interface. For example, 'Stroke' on the head, 'Nuzzle' on the nose, 'Hit' in the face, 'Pat' on the shoulder, and 'Push' the shoulder are all possible gestures in real life. 'Hug' around the shoulder could also be possible in real life. Figure 6.2(c) and Figure 6.2(e) show the positions and the display of different MST gestures:

- *Stroke*. We set the position of 'Stroke' on the upper head. The visual sticker is displayed when the user touches the upper head of the picture. The visual sticker of 'Stroke' moves laterally along with the user finger's lateral movement on the touchscreen.
- *Nuzzle*. We set the 'Nuzzle' position on the center of the nose. The visual sticker is displayed when the user touches the nose. The 'Nuzzle' sticker moves back and forth along with the lateral movement of the user's finger on the touchscreen.
- *Hit*. We set the position of 'Hit' on the left side of the head (Figure 6.2(c)). The visual sticker is displayed when the user touches the left side of the head of the picture. There is no lateral movement.
- *Pat*. We set the position of 'Pat' on the right side of the shoulder (Figure 6.2(c)). The visual sticker is displayed when the user touches the right shoulder. There is no lateral movement.
- *Push*. We set the position of 'Push' in the middle of two shoulders and at a lower position than 'Pat'. The visual sticker is displayed when the user touches a specific area. There is no lateral movement.
- *Hug*. We set the position of 'Hug' around the middle of two shoulders and at a lower position than 'Push'. The visual sticker is displayed when the user touches a specific area. There is no lateral movement.

The position of each MST gesture on users' pictures is the same (Figure 6.2(c) and Figure 6.2(e)).

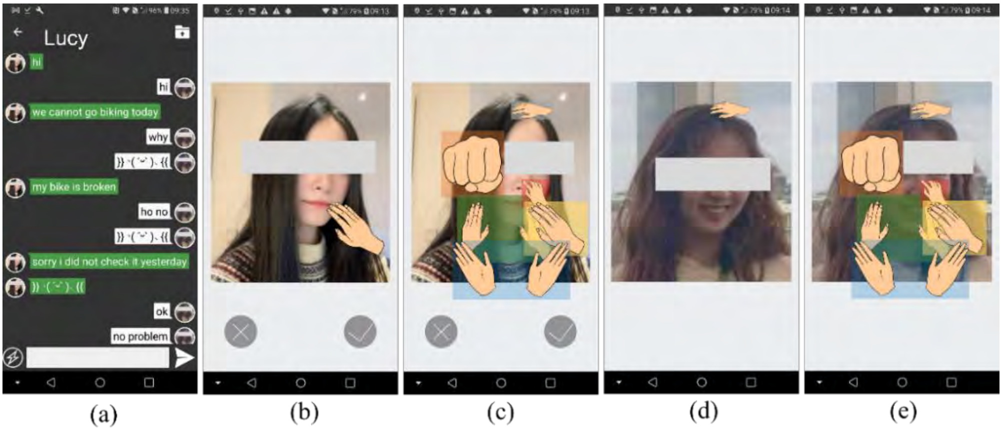


Figure 6.2 Interface for texting. (a) interface for texting for sending [1], (b) interface for the participants to send MST gestures (the photo is the experimenter), (c) positions of each MST gesture, (d) interface for the participants to receive MST gestures (the photo is the participant), (e) positions of each MST gesture for receiving.

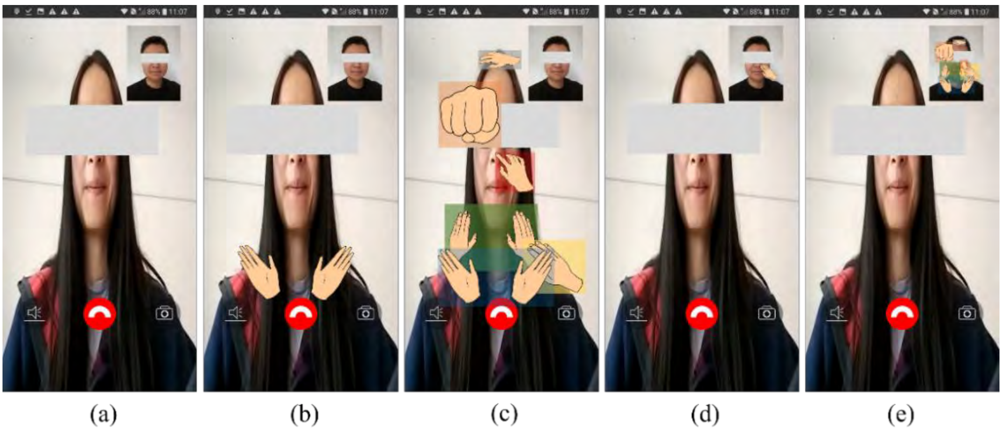


Figure 6.3 Interface for video calls. (a) basic interface for video calls [2], (b) interface for the participants to send MST gestures (the full-screen picture is the experimenter), (c) positions of each MST gesture on the experimenter's picture (d) interface for the participant to receive MST gestures (the picture box in the upper right corner shows the participant), (e) positions of each MST gesture on the participant's picture.

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[1] based on an open-source application. https://github.com/Baloneo/LANC
[2] based on an open-source application. https://github.com/xmtggh/VideoCalling

(Note: Due to the technical limitation, the picture of the experimenter is stretched according to the ratio of the screen. Although it might have influenced user experience, no participants complained.)

6.3.2.2 Interface for video calls

Figure 6.3 shows the interface for video calls. The relative positions of stickers in the video calling interface are similar to those in the texting interface. 'Stroke' the upper head, 'Hit' the left side of the head, 'Nuzzle' the center of the nose, 'Pat' the right shoulder, 'Push' the shoulder, and 'Hug' the lower part of the shoulder (Figure 6.3(c) and Figure 6.3(e)).

For the participant's picture box in the upper right corner of the interface, the relative positions of MST gestures are similar to those on the experimenter's image (the full-screen image). The size of the stickers is smaller than that of the experimenter's image (Figure 6.3(c) and Figure 6.3(e)).

6.3.3 Interface structure

We developed a mobile application for texting and video calling. We created the necessary interfaces and functionalities for the user study. We do not consider other interfaces or functionalities irrelevant to this study, such as login and logout.

6.3.3.1 Texting

Figure 6.4 shows the structure of texting. There are five layers (Table 6.4):

1) *Layer 1*. This layer shows the texting interface. The basic layout is similar to that in other existing applications, such as WhatsApp, WeChat, and Teams. The primary functions on this page are texting, sending the message, and jumping to Layer 2 – the MST input interface. We provided a haptic button () on the left lower corner of this page. On its right are the text input box and the send button.
2) *Layer 2 and Layer 3.* These two layers show MST gestures input interface. Pressing the haptic button in Layer 1 leads to Layer 2. The central part with the picture of the other person is the area for MST gestures input. We provided buttons for confirming () and cancelling () the MST input. When cancelling the MST gestures input, the interface jumps back to Layer 1. When starting to input the MST gestures, Layer 3 shows the sticker of MST gestures. When confirming the MST gestures input, the interface jumps to Layer 4 and automatically sends the textual MST icon

(}} ヽ(´ ᵕ `)ﾉ {{). We create this MST icon based on Kaomoji. The four curly brackets indicate the vibration sensation, while the center part implies a face.

3) *Layer 4*. Pressing the textual MST icon from the participant's side (the white dialog box in Layer 4, Figure 6.4) leads to Layer 3, which shows what the participant has sent. Pressing the textual MST icon from the other side (the green dialog box in Layer 4, Figure 6.4) leads to Layer 5.
4) *Layer 5*. This layer displays the MST signals. It shows what MST signals the other person sent.

Table 6.4 Description of the interface structure of texting.

Layer	Interface	Description
1	Texting interface	Layout of texting interface
2	MST gesture input interface	Layout of MST gestures input interface
3	MST gesture input interface	When inputting MST gestures, the participant's test phone showed the other person's picture (the experimenter) and the stickers of input MST gestures.
4	MST icons	Pressing the MST icon leads participants to the MST signals display (Layer 5) or MST gestures input (Layer 3) interface.
5	MST signals display interface	When receiving MST signals, the participant's test phone showed the participant's image and MST signals the other person (the experimenter) sent to them.

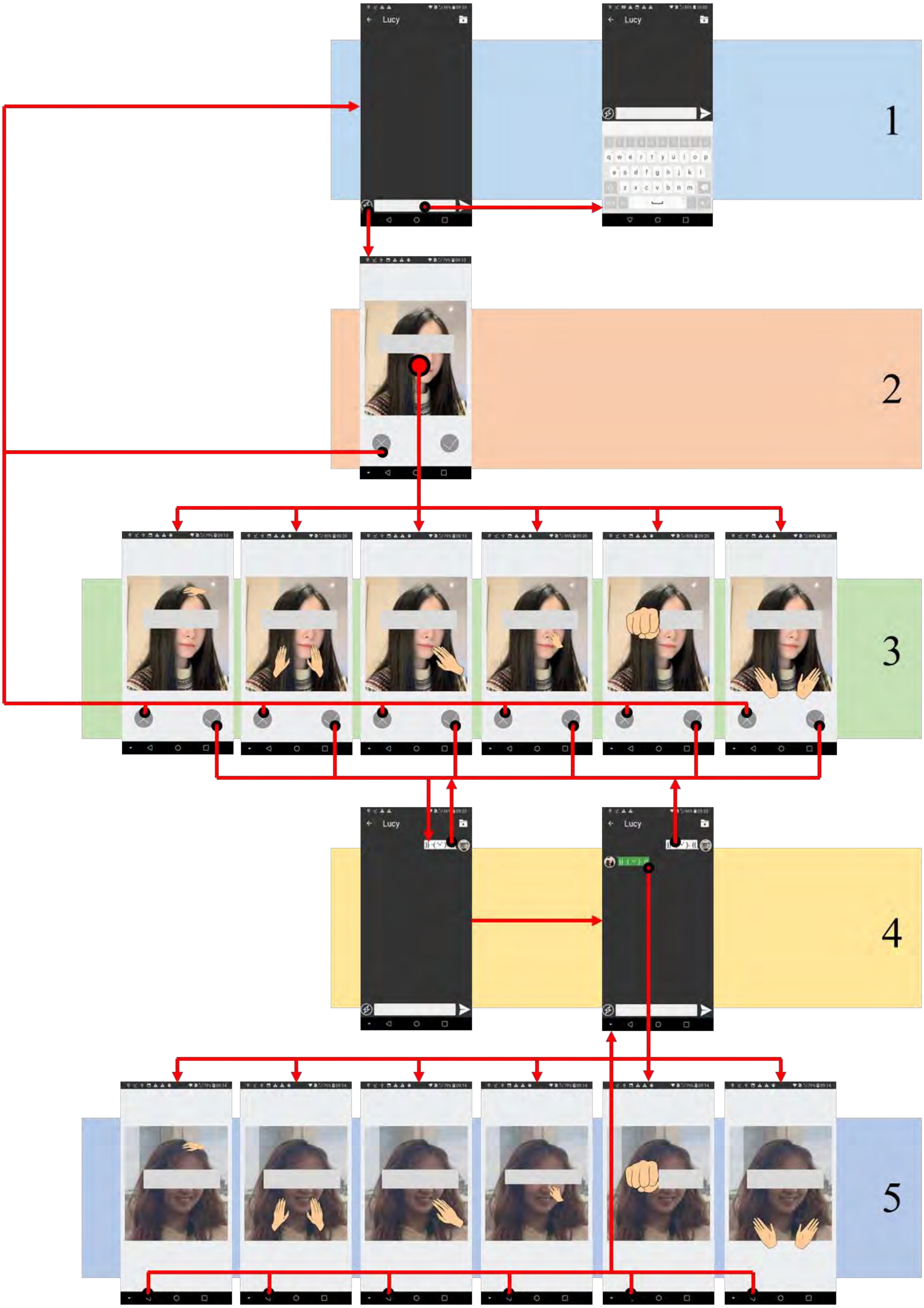


Figure 6.4 Structure of texting

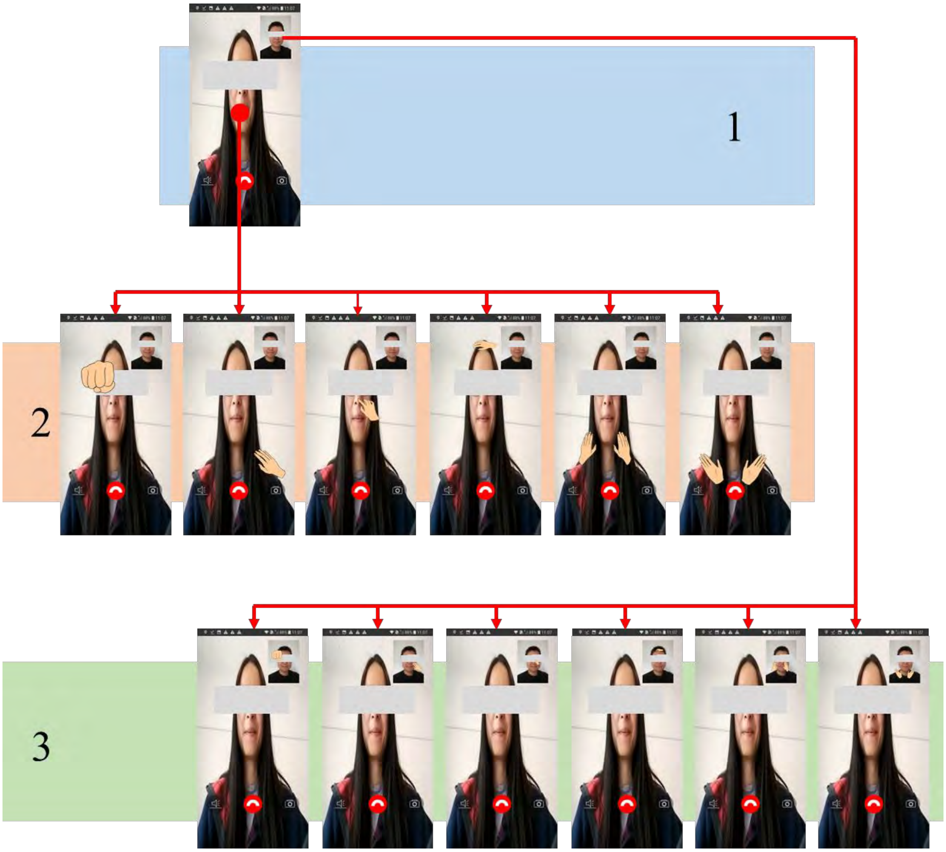


Figure 6.5 Structure of video calling

6.3.3.2 Video calls

Figure 6.5 shows the structure of the interface for video calls. There are three layers (Table 6.5):

1) *Layer 1*. This layer shows the layout of the video calling interface. The basic layout of this interface is similar to that in other existing applications, such as WeChat and Teams. The primary function on this page is transmitting the synchronous video images of the dyads.
2) *Layer 2*. This layer describes the MST gestures input interface. The display area of the other people is also the MST gestures input area. The participants could input MST gestures directly on the interface when video calling with other people, which seems like the participant is touching other people through the touchscreen face to face.
3) *Layer 3*. This layer describes the MST signals display interface. The window in the upper right corner displays the synchronous video image of the participants and the MST signals that other people sent, which seems like the other person is touching the participants through the touchscreen face to face.

Table 6.5 Description of the interface structure of video calling.

Layer	Interface	Description
1	Video calling interface	Layout of video calling interface.
2	MST gestures input interface	When inputting MST gestures, the participant's test phone showed the other person's synchronous video image (the experimenter) and the stickers of input MST gestures.
3	MST signals receive interface	When receiving MST signals, the MST signals would display in the upper right corner, which showed the synchronous video image of the participant and the stickers of MST gestures the other person (the experimenter) sent to them.

6.4 User study

6.4.1 Research questions

We designed and applied MST signals for online communication. The research aim was to explore if the MST gestures with vibrotactile stimuli have a higher social presence than MST gestures without vibrotactile stimuli, and if there is a difference between synchronous (video calling) and asynchronous communication (texting) in social presence when applying MST signals.

6.4.2 Experiment design

We tested two communication modes – texting and video calling, in two conditions – MST gestures without vibrotactile stimuli and MST gestures with vibrotactile stimuli. We applied a 2×2 mixed factorial experimental design. The condition was the within-subjects factor, and the communication mode was the between-subjects factor.

The independent variables were the condition and the communication mode. The dependent variable was social presence. Visual feedback was included in both conditions.

6.4.3 Participants

We recruited 40 participants (aged 22 to 37, mean = 27.13, SD=3.65, 24 females and 16 males) from the local university to participate in the user study. Participants were asked to wear noise-cancelling headphones (AirPods Pro) to avoid the sounds from the vibrotactile stimuli (Figure 6.6). All participants had experience using smartphones and online communication applications for texting and video calling.

Participants were asked to hold the test phone with two hands when texting (Figure 6.6(a)). When inputting MST gestures, participants were asked to hold the test phone with their left hand and input MST gestures with the right index finger (Figure 6.6(b)). Although both the thumb and index fingers were mainly used for interaction with a smartphone's touchscreen [218], we advised using the index finger when inputting MST gestures. The reason is that Table 6.2 shows that the index finger is more frequently used than the thumb finger in the user-defined gesture for the chosen MST gestures in this study.

(a) (b)

Figure 6.6 Test environment. (a) texting, (b) video calling (The second phone on the desk is used for voice transmission)

6.4.4 Experiment setup

6.4.4.1 Apparatus

We used a customized version of the LG V30 smartphone as our test phone, the same as that in our previous experiments [192], [80], [216]. It contained a Linear Resonance Actuator (LRA) (MPlus 1040). The LRA could convert the drive signals to vibrotactile stimuli.

We used two smartphones (both are LG V30). One was with the software that could trigger MST gestures with vibrotactile stimuli (with visual and haptic feedback). The other was with the software that could trigger MST gestures without vibrotactile stimuli (with only visual feedback). During the user study, if participants needed to test MST gestures with vibrotactile stimuli, they would use the one that can provide vibrotactile stimuli. Or they would use the one providing no vibrotactile stimuli to test the other condition.

6.4.4.2 Experiment environment

Participants sat in front of a desk, wearing noise-cancelling headphones (Airpods Pro), which also had a function of telephony (Figure 6.6). The experimenter stayed in another room to interact with the participants with texting or video calling (Figure 6.7). The experiment was a role-play scenario setting. Participants were asked to imagine they were talking with a friend online. The role-play setting could help participants to stay focused on the topic and conversation [219], [220]. The details of the environments are as follows:

- *Texting*. Participants and the experimenter used the test phones to chat over the local area network.
- *Video calling.* Due to the technical limitation, the video call application we developed could not transmit voice well. We provided an iPhone to participants. The headphones were connected to the iPhone. The experimenter used another phone to call the iPhone with the participants. Participants used the test phone for synchronous video images transmission and used the iPhone with headphones for synchronous voices transmission (Figure 6.7).

6.4.4.3 Scenario

We tried to create a situation in which the participants might feel disappointed and then relieved, so that they might use the MST signals to express their emotions. We provided one scenario with two activities: A1 – go biking and A2 – visiting a garden. In the scenario, the experimenter and the participant had arranged an activity for the weekend. However, due to some reasons, the arranged activity could not be conducted. The experimenter contacted the participant by texting or video calling to discuss these issues and tried to suggest a new activity.

Some participants might prefer A1, while other participants might prefer A2. In order not to let the activity preference affect the experimental results, the order of activities provided to each participant is counterbalanced.

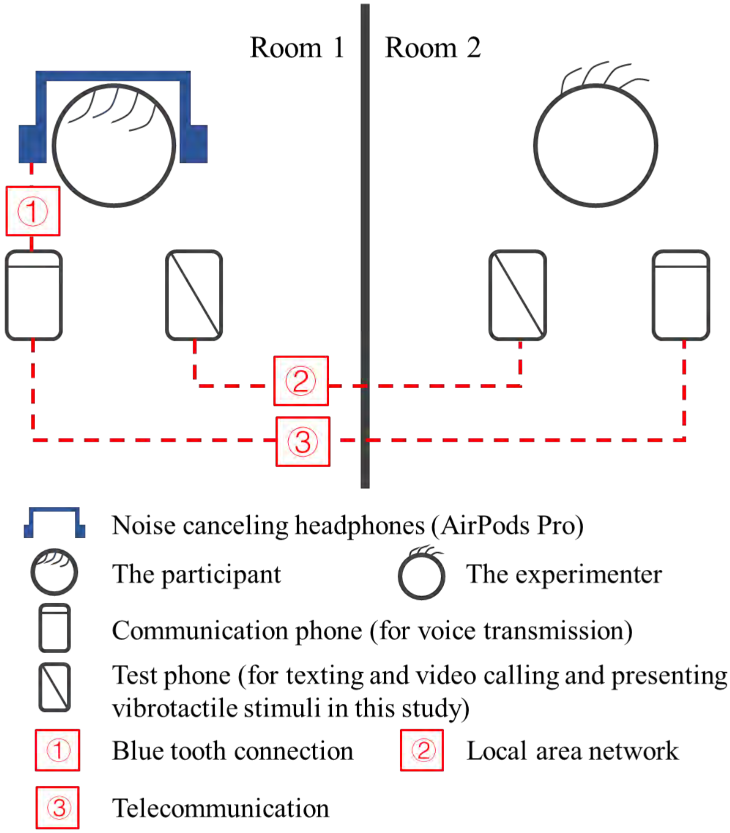


Figure 6.7 Setup of test environment

When A1 – go biking was the arranged activity while A2 – visiting a garden was the suggested new activity, the details of A1 and A2 presented to participants were as follows:

- A1: '*You (the participant) bought a new bicycle last week, and you want to find a partner to go biking very much. You invited your friend Lucy (the experimenter) to go biking in the weekend. Lucy has not used her bike for a long time. However, she forgot to check if her bike was ready to use. On Saturday morning, you were waiting for Lucy to set off. She suddenly found* *that her bike was broken. She needed to tell you that you could not go biking today (by texting or video calling).*'

- A2: '*Your friend Lucy (the experimenter) suddenly found that a seasonal garden just opened on this Saturday. This garden was only open for the public twice a year, two weeks in spring, two weeks in autumn. You missed the open time last autumn. You wanted to visit this garden very much. Now is a great chance to go there.*'

When A2 – visiting a garden was the arranged activity while A1 – go biking was the suggested new activity, the details of A2 and A1 presenting to participants were as follows:

- A2: '*Your friend Lucy (the experimenter) invited you (the participant) to go to a seasonal garden in the weekend. This garden was only open for the public twice a year, two weeks in spring, and two weeks in autumn. You missed the open time last autumn. Now is a great chance to go there. You and Lucy planned to meet at the bus station on Saturday morning. Before leaving the house, Lucy checked the details of the garden. Suddenly she found that she got the opening hour wrong. The garden would open next week in this spring, not this week. So, you could not go to the garden today.*'
- A1: '*Lucy (the experimenter) found the weather was great today. She wanted to invite you (the participant) to go biking to a forest.*'

We gave an example of dialogue in texting (selected from one participant in the user study) to show how the experimenter communicate with the participant, as follows:

> Experimenter (initiates the conversation): *'Sorry, we cannot go to the park today. I remembered a wrong opening hour. It will open next weekend, not this weekend.'*
> Participant: *'That is so bad', '}} ٩(ˊᵕˋ)و {{'.*
> Experimenter (proposes another activity): *'The weather is great, maybe we could go biking to the forest?'*
> Participant: *'Great! Even better!', '}} ٩(ˊᵕˋ)و {{'*
> Experimenter (suggests a meeting time and location): *'Then we could meet at your house in 20 minutes. See you.'*
> Participant: *'See you.', '}} ٩(ˊᵕˋ)و {{'*

The dialogue was a guided discussion. The experimenter needed to guide the discussion direction. We did not limit the exact words and sentences that the participant said. Participants could use MST gestures whenever they wanted to use them. The experimenter and participants worked together to complete the communication.

6.4.4.4 Measures

We collected quantitative data and qualitative data in the user study. This study was approved by the Ethical Review Board from Eindhoven University of Technology with the approval number ERB2021ID15.

We applied a measurement of Networked Minds Measure of Social Presence Inventory (NMSPI) [221] for quantitative data. This questionnaire has been validated to have the ability to distinguish levels of social presence for mediated interactions [221], which is effective for MST signals measurement in this study. There are six dimensions (Table 6.6). Each dimension has six items in a 7-point Likert scale ranging from one (strongly disagree) to seven (strongly agree). The detailed Likert scale items are in [221]. An example of the questionnaire is in Table 6.6. Based on our applications, we introduced to participants what the dimensions and questions meant in Table 6.6. The whole questionnaire was used to rate the MST signals function in this study.

For qualitative data, we interviewed participants. For privacy concerns, we only record the voice of participants and only the transcripts were kept and used for analysis. There are two fixed questions and an open discussion for each participant:

- Can you feel that you are touching the other person, or the other person is touching you (MST gestures with vibrotactile stimuli)?
- If this function is available in a real online communication application, will you use it (MST gestures with vibrotactile stimuli)?
- Talking about anything that came to your mind based on the experiences of the test.

6.4.5 Procedure

We first briefly introduced the test to the participants and provided consent forms and questionnaires.

We introduced the test interface to the participants. As the visual stickers of MST gestures were not visible at first, a training session was needed for participants to get familiar with the test interface and the position of MST gestures.

There were two communication modes – texting and video calling. Twenty participants (P1-P20 in Table 6.7) tested texting, while the other twenty participants (P21-P40 in Table 6.7) tested video calling (between-subjects). There were two conditions – MST gestures with vibrotactile stimuli and MST gestures without vibrotactile stimuli (within-subjects).

The order of the activities provided to each participant was counterbalanced. Table 6.7 shows the activities and the order for participants.

Table 6.6 Example questionnaire of NMSPM [221]

Dimensions [1]	**Typical questions** [1]	**Explanations if the participants asked** [2]
Co-presence	I caught my partner's attention.	Is there any feedback showing that my partner responds to my sending MST signals?
Attentional Allocation	My partner remained focused on me throughout our interaction.	Did my partner notice that I sent MST signals?
Perceived Message Understanding	It was easy to understand my partner.	Can I understand the meaning when my partner sends MST signals to me?
Perceived Affective Understanding	My emotions were not clear to my partner.	Does my partner show that they don't quite understand the emotions I want to express through MST signals?
Perceived Emotional Interdependence	I was sometimes influenced by my partner's moods.	Do the MST signals communicating emotions sent from my partner influence me?
Perceived Behavior Interdependence	My partner's behavior was closely tied to my behavior.	Can I feel the connection between my partner and me through sending MST signals? Is there any feedback showing that my partner behaves to respond to my MST signals?

- [1] Dimensions and typical questions were from [221].
- [2] All the questions should be answered by rating the experience related to MST (not the overall experience with texting or video calls).

Table 6.7 Test communication modes, conditions, and activities for participants.

	MST gestures with vibrotactile stimuli		**MST gestures without vibrotactile stimuli**	
	Participants	Activity order	Participants	Activity order
Texting	P1 – P10	A1 → A2	P1 – P10	A2 → A1
	P11 – P20	A2 → A1	P11 – P20	A1 → A2
Video calling	P21 – P30	A1 → A2	P21 – P30	A2 → A1
	P31 – P40	A2 → A1	P31 – P40	A1 → A2

After the introduction and the training session, the detailed procedure for each participant was as follows:

1) Participants first tried one communication mode with one condition, having online communication with the experimenter. For example, a participant first tried using MST gestures without vibrotactile stimuli when texting.
2) Participants filled the 7-point Likert scale on the questionnaire for subjective ratings. (e.g., subjective ratings for MST gestures without vibrotactile stimuli when texting).
3) Participants tried the same communication mode with the other condition, having online communication with the experimenter. For example, the participant tried using MST gestures with vibrotactile stimuli when texting.
4) Participants filled the 7-point Likert scale on another questionnaire for subjective ratings (e.g., subjective ratings for MST gestures with vibrotactile stimuli when texting).
5) The experimenter interviewed the participants.

6.5 Results

6.5.1 Quantitative results

6.5.1.1 Between-subjects analysis

We used SPSS 23.0 to analyse data. We conducted a normality test first. All data sets in each dimension conformed to normalized distribution ($p>0.01$ in behaviour interdependence, $p>0.05$ in the rest five dimensions). There were no interactive effects between the communication mode and the condition in all dimensions ($p>0.05$).

We conducted one-way MANOVA to test if the communication mode matters in each dimension of social presence. Figure 6.8 showed no significant differences between different communication modes in each dimension of social presence ($p>0.05$). This indicated there was no significant difference between texting and video calling when applying the MST signals in online communication. We also found no significant gender effects during the evaluation ($p>0.05$).

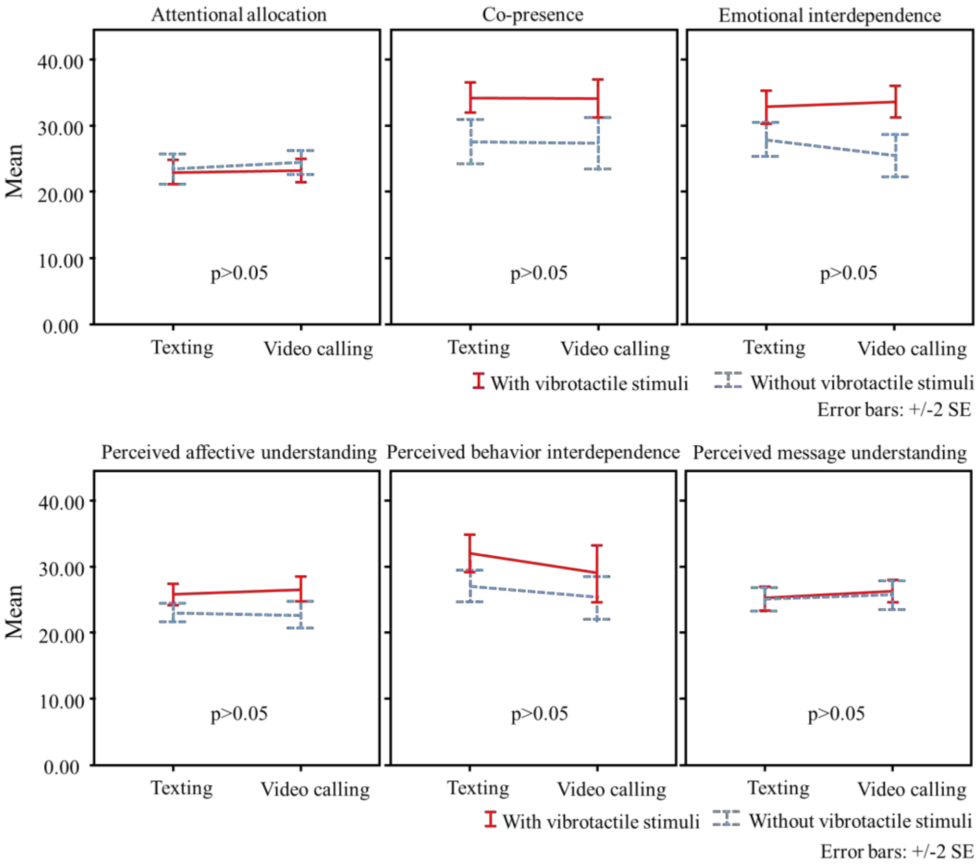


Figure 6.8 Dimensions of social presence. Between-subjective analysis – video calling and texting

6.5.1.2 Within-subjects analysis

To explore if adding vibrotactile stimuli to MST gestures matters, we conducted the paired sample t-test when the difference value follows the normal distribution [222], and if not, we conducted the Wilcoxon rank test [197]. All data sets conformed to normal distribution (p>0.05) except for perceived messaging understanding in video calling (p=0.001).

Figure 6.9 showed that MST gestures with vibrotactile stimuli provided significantly higher co-presence, perceived behaviour interdependence, perceived affective understanding, and perceived emotional interdependence than MST gestures without vibrotactile stimuli (p<0.05). No significant differences could be found in perceived message understanding and attentional allocation of social presence (p>0.05).

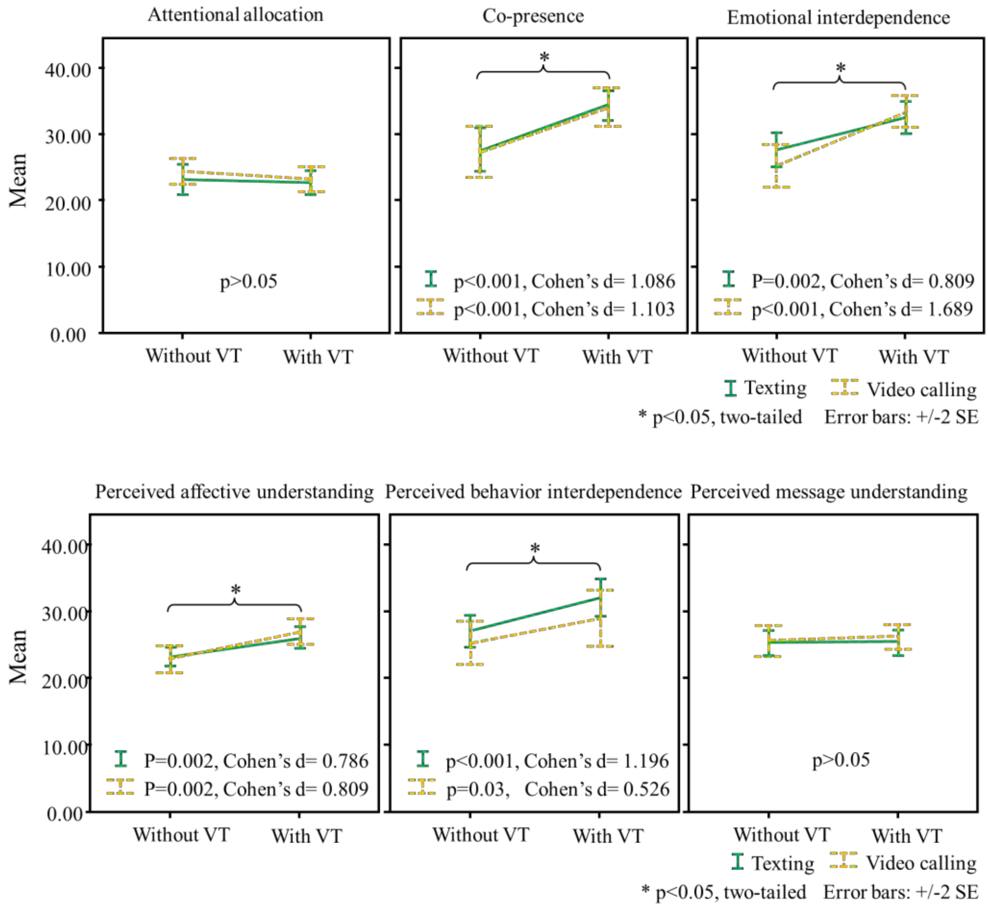


Figure 6.9 Dimensions of social presence. Within-subjects analysis – with VT and without VT (VT = vibrotactile stimuli)

6.5.2 Qualitative results

6.5.2.1 Thematic analysis

We conducted a thematic analysis [223] for qualitative analysis. We recorded the voices of participants during the interview and the recordings were transcribed as qualitative data. After familiarizing with the transcripts of participants' ideas (phase 1 in [223]), we provided initial codes (descriptive sentences in Table 6.8 and Table 6.9) based on participants' interviews (phase 2 in [223]). We inducted themes (phase 3 to phase 5 in [223]). We will provide iterative recommendations for improvement based on the quantitative analysis (phase 6 in [223]) in the later Discussion section.

6.5.2.2 Texting

For the first question about if participants could feel touching or being touched by other people via MST signals when texting, participants mainly provided three types of answers (Table 6.8). Eight participants said they could feel touching or being touched via this function. Six participants mentioned they could touch others by MST signals, but it was difficult to be touched via this function. P6 and P9 said that they felt they could touch others via MST signals. When receiving the MST signals, they just felt vibrations on their hands, or the mobile phone was vibrating. This suggests that gestures with vibrotactile stimuli and visual information might make the touch more real. Six participants could not feel touching or being touched via this function. Two of them said that this function provided a way to express their emotional state rather than send touch. One participant could feel the vibration when interacting with the touchscreen, but that vibration could not be regarded as social touch. The rest of the participants compared their experience to just interacting with the touchscreen or with an electronic pet, or just inputting some gestures on a photo, which could not make them feel touching or being touched by others via MST signals.

For the second question regarding if participants would use this function in online communication, three types of answers were provided (Table 6.8). Nine participants mentioned that they would use this function in online communication. Eight participants said that they would use this function with conditions. Participants mentioned that they would be attracted more by a more straightforward and more intuitive interactive interface, and more types of interesting MST signals. Furthermore, they wanted to customize virtual and cartoon avatars. One participant mentioned that he/she would use this function with familiar people. For unfamiliar people, texting with words was enough. Two participants said that they got used to using only words rather than MST signals, emoji, or stickers during texting.

For answers to the open questions, we found six themes, including Touch, Interactive interface, Avatar, Multimodal MST signals, Customized demands, and other factors (Table 6.8). The Touch theme has four dimensions, including Type, Position, Visual sticker, and Vibrotactile stimuli (Table 6.8). Table 6.8 shows the themes and descriptions.

6.5.2.3 Video calls

For the first question about if participants could feel touching or being touched by other people via MST signals during video calls, participants mainly provided four types of answers (Table 6.9). Nine participants said they could feel touching or being touched by this function. Two participants mentioned they could feel touching other people via MST signals, but it was difficult to be touched via MST signals. P9 said she could 'Hug' and 'Stroke', but the 'Hit' was too gentle. Eight participants could not feel touching or being touched via this function. Four of them said they could feel vibrations, which could not be regarded as social touch. Two of them mentioned they could feel strong emotional expressions rather than social touch. Two participants mentioned that the right hand was performing gestures, but the left hand felt vibrations, which made it difficult to feel touching or being touched via this function.

For the second question regarding if participants would use this function in online communication, two types of answers were provided (Table 6.9). Eighteen participants would use this function in online communication. Two participants would use this function with conditions. One of them mentioned they would use this function with familiar people. The other one said he would use it if the application could be designed better.

For answers to the open questions, we found six themes, including Touch, Interface layout, Emotional expression, Multimodal MST signals, Customized demands, and other factors (Table 6.9). The Touch theme has four dimensions, including Type, Position, Visual sticker, and Vibrotactile stimuli (Table 6.9). Table 6.9 shows the themes and descriptions.

Table 6.8 Qualitative analysis of texting

Possibility to touch or be touched?	I could feel that I was touching or being touched by other people (8). I could feel that I was touching the other person, but I could not feel the other person touching me (6). I could not feel that I was touching or being touched by other people (6).		
Use this function or not?	I will use this function (9). I will use this function with some conditions (8). I will not use this function (3).		
Open questions	Touch	Type	Too few types (4).
		Position	Positions of MST gestures were too close and not flexible, the positions could not be remembered (3); Gesture recognition could be considered (1).
		Visual sticker	The meaning of the stickers could not be remembered (1); The stickers were simple (1); Gif animation or special effects may be better (1).
		Vibrotactile stimuli	No big differences among these vibrotactile stimuli (9); The meaning of vibrotactile stimuli could not be remembered (2); The likelihood to be understood as a specific touch for some vibrotactile stimuli was low (2).
	Interactive interface		It was not convenient to jump to another page when using this function (7).
	Avatar		It was strange to input MST gestures on the picture of a person (5); It was interesting to input MST gestures on the picture of a person (2); A dynamic virtual avatar could be considered (1).
	Multimodal MST signals		Visual information was dominant and vibrotactile information is auxiliary (2); Vibrotactile stimuli helped to differentiate indistinguishable visual stickers (1).
	Customized demands		Provide users with a chance to choose whether to apply the vibrotactile stimuli or not. Customizing the avatar size and position and MST types and positions could be considered. Page preview could be considered (3).
	Other factors		Context (1); Familiarity with chatting partner (3); Culture (1).

Table 6.9 Qualitative analysis of video calling

Possibility to touch or be touched?	I could feel that I was touching or being touched by other people (9). I could feel I was touching other people to some extent, not full extent (1). I could feel that I was touching the other person, but I could not feel the other person touching me (2) I could not feel that I was touching or being touched by other people (8).		
Use this function or not?	I will use this function (18). I will use this function with some conditions (2).		
Open questions	Touch	Type	Too few types (3).
		Position	Positions of MST gestures were too close and not flexible, the position could not be remembered (5); Gesture recognition could be considered (2).
		Visual sticker	Gif animations or special effects may be better (3);
		Vibrotactile stimuli	It was easy to attract other people's attention (2); There were no big differences among these vibrotactile stimuli (6); It was difficult to differentiate the touch between the participant and the experimenter (4); The likelihood to be understood as a specific touch for some vibrotactile stimuli was low (2); Vibrotactile stimuli increased the interactive feelings (1); Participants were not used to the right hand performing gestures while the left felt touch (2).
	Interface layout		Focus on the full screen, ignore the small box in the upper right corner (3); Notice the small box in the upper right corner with vibrotactile stimuli, or cannot notice it (1).
	Emotional expression		It was easy to express emotion (4); Participants felt more emotional expressions in sending than they could receive (1).
	Multimodal MST signals		Visual information was dominant and vibrotactile information was auxiliary (1); Audio feedback could be considered (1).
	Customized demands		Social touch type and position, sticker preview (3).
	Other factors		Culture (1).

6.6 Discussion

6.6.1 MST gestures with vibrotactile stimuli and social presence

The research results showed that MST gestures with vibrotactile stimuli increased the social presence in general. This result conforms to previous studies about social presence, which indicates that haptic stimuli help increase social presence in remote communication in different contexts [32], [33], [37], [38], [39], [40], [41], [211], [212], [213].

In this study, we further analysed different dimensions of social presence. Adding vibrotactile stimuli to MST gestures helped increase social presence in co-presence, perceived behaviour interdependence, perceived affective understanding, and perceived emotional interdependence. Adding vibrotactile stimuli to MST gestures caused no significant differences in social presence from attentional allocation and perceived message understanding. We discuss each dimension as follows:

1) Attentional allocation means the amount of attention the user allocates to and receives from an interactant [221]. There were no significant differences in attentional allocation, no matter if there were vibrotactile stimuli or not, in both video calling and texting. Possible reasons are as follows:
   - *For using MST in video calling, participants' attention was mostly on inputting MST gestures, which might lead to no significant differences in attentional allocation.* Many participants mentioned that they paid more attention to their own manipulations. They did not pay much attention to MST signals sent from the other person. The size of the right upper box showing their own images (Figure 6.3) was possibly too small to be noticed no matter if there were vibrations or not.
   - *For video calling, the hard-to-differentiate vibrotactile stimuli might cause no significant differences in attentional allocation.* Many participants mentioned the vibrotactile stimuli for each MST gesture were difficult to differentiate. Sometimes, the dyads were sending MST signals to each other simultaneously. They just felt the mobile device was vibrating, but they did not know who triggered these vibrations. The vibrotactile stimuli could not work well in this dimension. The confusion might result in similar attentional allocation no matter if there were vibrations or not.
   - *For texting, the interaction – 'going to the next page' may cause no big differences in attentional allocation*. The haptic icon led participants to the next page for inputting and perceiving the MST signals. Many participants mentioned that it was inconvenient to press a button and go to the next page for further interaction. Participants wanted to input or

receive MST signals just on the texting page directly. If participants went to another page, the process – 'going to the next page' might get their attention rather than the vibrotactile stimuli.

- *For texting, the interaction – inputting MST gestures on the picture of a person may affect participants' attentional allocation*. Many participants mentioned that inputting MST gestures on the picture of a person was strange, which might have caught too much of attention. This situation might cause no significant differences in this dimension during texting.

2) For perceived message understanding, MST signals are also presented with stickers in this study. No matter if there were vibrotactile stimuli or not, participants could easily know what the other person wanted to express.
3) For co-presence, many participants mentioned that MST gestures with vibrotactile stimuli was interesting. Although many participants said that they could not differentiate the vibrotactile stimuli during video calling since sometimes the vibrotactile stimuli triggered by the participant and the experimenter was displayed simultaneously, the vibrotactile stimuli could still make them feel something.
4) For perceived affective understanding and perceived affective interdependence, the results showed that MST gestures with vibrotactile stimuli provided significantly higher social presence than MST gestures without vibrotactile stimuli in these two dimensions. This result conforms to other related studies, which have demonstrated that vibrotactile stimuli help express emotions better [99], [88], [224], [225].
5) For perceived behavioural interdependence, many participants mentioned that they would like to use MST signals with vibrotactile stimuli to express their emotions, which could be a new way for them to express emotion.

6.6.2 Communication mode and social presence

Other studies mainly focused on one communication mode (e.g., phone calls [19], [48], [21], [22], texting [88], or video calling [211]). This study applied two communication modes together and compared whether MST caused differences in these two communication modes.

The result showed no significant differences between texting and video calling when applying MST signals in online communication. Although there might be limitations in the current design, interview results showed that most participants found the interaction interesting and were willing to use it.

For future design, we need to have a deeper insight into users' needs of MST signals in different communication modes. We could apply the MST signals to different modes based on the users' possible different needs.

6.6.3 Implications for future design

We discuss implications for future design based on participants' interview results, from the perspective of vibrotactile stimuli, visual design, interface design, and interface structure.

6.6.3.1 Vibrotactile stimuli for MST gestures

Regarding the vibrotactile stimuli for MST gestures, we provided the following implications for future design based on our findings:

- More compound waveform composition types [216], [192] are needed. Many participants felt that the vibrotactile stimuli were similar. They could only feel the length difference (long and short). These comments on vibrotactile stimuli suggested that participants might need more interesting and changing vibrotactile stimuli than a simple short pulse or long and unchanging vibrotactile stimuli.
- Applying multi-modal stimuli to enhance the perception of MST signals is necessary. We should notice that people may not have the same perception of the same MST signal in different contexts or different communication modes. This result conforms to the previous study [77], which shows that vibrotactile stimuli could be more pleasant and less arousing in the bus than in the laboratory. We suggest enhancing the perception of MST signals in other ways such as using multi-modal stimuli (haptic, visual, audio, thermal, et al.) as Wilson and Brewster [99] have demonstrated that multi-modal stimuli increase the available range of perception. For example, researchers developed Multi-moji [99], which combined vibrotactile, visual, and thermal stimuli together, and VibEmoji [95], which provided vibrotactile stimuli, animation effects, and emotion stickers together in mobile communication.
- Making the vibrotactile stimuli and visual stickers more matched in a specific context and communication mode is needed. In this study, we added visual information and context. Ernst and Banks [133] mentioned that vision and touch both provided information for estimating the MST signals. Visual information is helpful when judging size, shape, or position [133]. The dominant channel to feel the MST signals may be different between the only vibrotactile stimuli condition [216] and the vibrotactile stimuli along with visual and context information in this study. The vibrotactile stimuli were

designed based on metaphorical cues, while the visual stickers were designed based on gesture movements. This difference may have caused confusion. The possible solutions are iterating the vibrotactile stimuli or the visual stickers to make them more matched in a specific context and communication mode. For example, in this study, the vibrotactile stimulus for 'Hug' was designed to express a feeling of force exerted on other people [216]. However, the visual sticker of 'Hug' comes from emoji, which may not express the feeling of force. We may add varying colours or a progress bar to express a metaphorical force change rather than a simple touch sticker.

- We consider designing and iterating vibrotactile stimuli in a specific context with a specific communication mode. Some participants said they focused more on sending MST signals. In this condition, the sense of touch was stronger while participants performed gestures and actively felt the vibrotactile stimuli. In contrast, when receiving MST signals, participants passively felt the vibrotactile stimuli without gestures. However, we tested vibrotactile stimuli in these two situations - sending with gestures and receiving without gestures [226]. There were no significant differences between these two conditions on the likelihood to understand as a specific MST gesture. These contradictory situations show that the context plays an important role in MST communication. In our earlier study [226], there was no context (no video calling or texting). Participants were asked to press the graphic button on the touchscreen, triggering vibrotactile stimuli. Participants could focus more on the vibrotactile stimuli. In this study, more contexts and visual information required attention and participants could not focus as much on the vibrotactile stimuli. Iterating and testing vibrotactile stimuli in a specific context with a specific communication mode may improve the design.

6.6.3.2 Visual design of MST gesture

About the visual design of MST gestures, we suggested the following:

- Richer visual design is needed. In the user study, we applied simple hand gesture stickers in the application. However, many participants said that the visual design of MST gesture could be more interesting. For example, 3D effects could be considered.
- Customization is needed. Some participants suggested cuter stickers. "Cute" is a concept that can be culture related, and it may suggest that the cultural background should be taken into consideration. Customized MST types and visual stickers could contribute to this point. For example, Memoji and

Digital Touch in iMessage allow users customize their stickers and touch gestures.

6.6.3.3 Interface design

We identify the following design opportunities related to the interface design, the layout, a preview function, and the possibility for customization:

- The layout of the video calling interface needs further iteration. The box showing the participants' picture and received MST signals in the right upper corner (Figure 6.3) was too small to notice. Future interface design could include enlarging the small box to solve this problem, making, for example, the size of two split screens equal.
- Pre-viewing MST gestures before sending is needed. Many participants said they could not remember the MST's positions on the interface as all MST gestures were invisible at first. We could present participants a pre-view window for MST gestures.
- Participants also wanted to customize the MST gesture's types and positions. We only set six typical MST gestures and provided fixed positions for each MST gesture in this study. Some participants said that the present MST signals could not express some of their feelings and they hoped the positions could be more flexible. We designed 23 MST gestures and provided at least one CWC form of vibrotactile stimuli for each MST gesture in [216]. We could consider adding the lists of MST gestures and tactile stimuli and allow participants to choose their preferred and frequently used MST gestures with vibrotactile stimuli.

6.6.3.4 Interface structure

Interface structure needs further improvements as follows:

- In texting, we need to integrate the MST gestures sending and receiving function in the texting interface rather than creating a separate interface. Many participants mentioned that "going to the next page" was not convenient. However, the existing texting interface already has a clear layout for users to send and receive text. We need to consider how to integrate the MST signals functions in this layout.
- There should be a time difference between the vibrotactile stimuli triggered simultaneously by the two people in the communication during video calling. Participants said it was difficult to differentiate whether the vibrotactile stimuli were from themselves or the experimenter. It would be good to provide a time difference between the vibrotactile stimuli triggered by the

two people in the communication so that users can perceive them more clearly.

6.6.4 Limitations

Some participants mentioned that they could feel the vibrotactile stimuli on their left hand (holding the mobile device). Their right hand performed gestures but could not feel much of the vibrotactile stimuli. For vibrotactile stimuli, it is difficult to solve this problem only on a smartphone. Maybe wearables could solve this problem, but use of the wearables means additional load for the users. Another possible way to solve this problem is to consider audio together with visual and vibrotactile stimuli. The richer modalities may help people not focus on a single modality, making the MST signals more realistic. Our test device has an LRA, which could provide vibrotactile and audio stimuli together. Based on our system, we have already investigated how to design vibrotactile and audio stimuli together [192]. We can consider combining the audio stimuli in future designs.

Our user study was based on the selected six MST gestures, which could be frequently used and covered rich emotional expressions. The results indicate that our approach is effective based on these six MST gestures. There are still seventeen more MST gestures that we can include in our test. In future research, we will consider providing more choices and allowing users to experience more MST gestures.

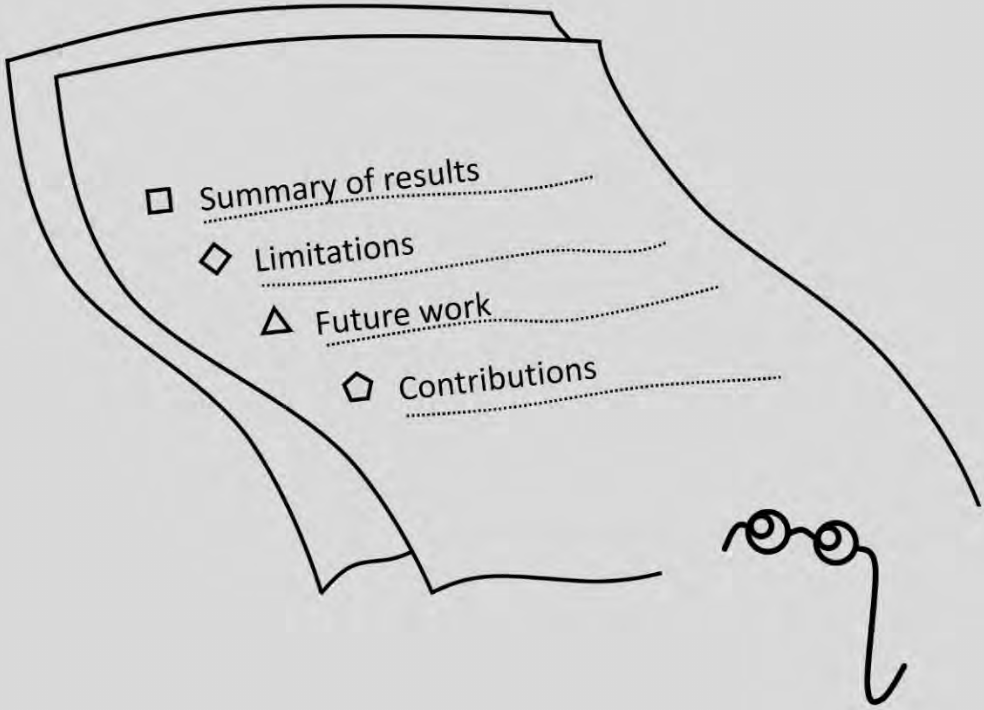
6.7 Conclusion and future work

This study applied MST gestures with vibrotactile stimuli in mobile communication (texting and video calling). We conducted a user study and found no significant difference in perceived social presence between texting and video calling when applying MST signals in online communication. We found that adding vibrotactile stimuli to MST gestures helps increase social presence in the aspects of co-presence, perceived behaviour interdependence, perceived affective understanding, and perceived emotional interdependence. Adding vibrotactile stimuli to MST gestures causes no significant differences in attentional allocation and perceived message understanding. Participants thought MST gestures with vibrotactile stimuli was attractive and they were willing to use it, but the application design should be improved based on users' needs.

For future work, we need to improve the design of vibrotactile stimuli for some MST gestures, visual designs of the MST gestures, and interface design for different communication modes. We could also consider integrating vibrotactile, visual and audio stimuli together to create a richer MST signal effect. Future work will also include providing more MST signals and allowing users to experience more MST signals in mobile communication.

Chapter 7

Conclusion



This Ph.D. research aims to investigate how mediated social touch (MST) could be expressed, perceived, and recognized for increasing social presence in mobile communication. To achieve this goal, we conducted studies as follows:

- As presented in **Chapter 2**, we conducted a literature review to comprehensively understand the state of the art of MST designs and evaluations for mobile devices. We explored which actuators, parameters, and prototypes researchers used to express and communicate MST signals with mobile devices and how they evaluated their designs. We also derived guidelines for future work. Based on those findings, we summarized the key elements from the aspects of technology, design, and applications for this Ph.D. research.
- The work presented in **Chapter 3** aimed to understand MST gestures comprehensively. We applied the elicitation study [145] to explore the user-defined MST gestures on the touchscreen and capture related touch properties. Those findings guided the MST signal design (Chapter 5) and the application design (Chapter 6).
- **In Chapter 4**, we presented a generation method to instantiate a wide range of vibrotactile stimuli. We generated and selected drive signals with varying envelope shapes, superposition methods, compound waveform composition (CWC) forms, durations, and frequencies. We studied the perceived depth and roughness of rendered graphical buttons, which would be connected to the skin deformation and pressure applied to the skin for MST gestures on touchscreens, as presented in Chapter 5.
- **In Chapter 5**, we presented a generation method for MST signals on smartphones. We proposed a function to transfer MST gesture pressure to MST signal frequency. We set the duration and created different CWC forms for MST signals. We conducted user studies to evaluate the designed MST signals. The MST signals would be selected for the experiment with online communication, as presented in Chapter 6. We also derived design guidelines for MST signals.
- **In Chapter 6**, we applied MST signals designed from Chapter 5 in two online communication modes – asynchronous and synchronous communication (texting and video calling) to enhance social presence for mobile communication. We first designed the application that included the visuals of MST gestures, the vibrotactile stimuli for MST gestures, and the interface for texting and video calling. Then, we conducted a user study to explore if the MST gestures with vibrotactile stimuli could increase social presence in texting and video calling compared to MST gestures without vibrotactile stimuli. We also explored whether the communication modes significantly

affected social presence when applying MST signals.

In this chapter, we summarize the results of each chapter, answer the research questions, discuss the limitations and future work, and conclude the contributions of this Ph.D. research.

7.1 Summary of results

This thesis mainly addresses this research question: How could MST be expressed, perceived, and recognized for increasing social presence in mobile communication? To address this question, we first got an overview of MST designs and evaluations through literature reviews. Then, we divide the main research question into several specific questions. This section mainly describes the results that answer research questions.

7.1.1 Summary of results in Chapter 2: An overview of the designs and evaluations of mediated social touch

Chapter 2 presents an overview of MST designs and evaluations on mobile devices based on selected 52 articles. We summarize (1) the MST design from typical haptic input and output based on the different actuators and parameters, (2) the overview of mediated social touch and emotion that social touch communicates studied in the selected papers, (3) three typical prototypes researchers developed for MST gestures and signals, namely, actuators, accessories, and connected devices, (4) the evaluation of MST research from the perspective of participants, experiment design, and data collection, and (5) what conclusions benefit future research, especially in the aspects of signal design, multimodal stimuli, evaluation of gesture, MST signals in the application, communication concepts, contexts, and special users.

We propose three main aspects for further study based on the above findings. **Technology**: (1) We can choose the smartphone embedded with one linear resonant actuator since Rognon et al. [16] have found that mobile devices are popular for users use to communicate social touch. (2) We focus on users engaging with smartphones and interacting with touchscreens to explore how to express MST gestures. The insights gained from this investigation can inform and guide MST signal design. **Design**: (1) A generation method for vibrotactile stimuli can be proposed. Then, we can study how parameters affect the users in perceiving vibrotactile stimuli on touchscreens, offering valuable insights for informing MST signal design choices. (2) We can create a generation method for MST signals as many existing studies have mainly developed prototypes for MST signal transmission instead of bringing about generation methods. (3) A rich set of MST signals can be created since only a limited number of MST signals have been considered in previous studies. This will help us understand how well the designed MST signals can be recognized and understood.

Application: We can apply the designed MST signals in an online social application to explore if social presence be increased with them.

7.1.2 Summary of results in Chapter 3: Answers to research question 1

RQ1: How to express MST with hand gestures on a touchscreen?

As we design MST signals for smartphones, we need to know how users express MST gestures on the smartphone touchscreens and collect related touch properties. We conducted an elicitation study to explore the user-defined MST gestures on touchscreens, as presented in Chapter 3.

We developed a user-defined gesture set considering touch properties and context to display how participants expressed MST with hand gestures through the touchscreen. Furthermore, we collected the duration and pressure of each MST gesture and obtained different hand/finger movements. We also found that MST gestures with shorter duration were easier for participants to perform; participants were inclined to use social touch with an easier gesture more often.

Those findings guided the MST signal design in Chapter 5. Specifically, we select frequency, duration, and CWC forms based on the pressure, duration, and finger/hand movements collected from this chapter. In Chapter 6's mobile application, we also utilize finger/hand movements to design visuals for MST signals.

7.1.3 Summary of results in Chapter 4: Answers to research question 2

RQ2: How do signal parameters affect the users in perceiving vibrotactile stimuli on touchscreens?

As we use the smartphone as a tool and apply the linear resonance actuator (LRA) to render vibrotactile stimuli, we first need to know the physical effects the system can produce between humans and the touchscreen. As presented in Chapter 4, we studied parameters such as frequency, duration, envelope shapes, superposition methods, and CWC forms. We took graphical buttons on touchscreens as the carrier and explored how these parameters affected the perceived depth and roughness of rendered graphical buttons. We generated and selected drive signals to render vibrotactile stimuli for graphical buttons through varying parameters.

Research results indicated that the selected frequencies, durations, and the designed CWC forms significantly affect the users in perceiving vibrotactile stimuli. Specifically, the perceived depth and roughness of graphical buttons increase when the frequency approaches the resonant frequency. Conversely, perceived depth and roughness decrease when the frequency moves away from the resonant frequency.

Furthermore, a longer duration of vibrotactile stimuli and adding the number of pulses could increase the perceived depth and roughness. Additionally, perceived depth and roughness have a similar trend with varying frequencies at a fixed duration.

Those findings indicated that the selected frequencies, durations, and the designed CWC forms affected the users in perceiving vibrotactile stimuli. We adjust these parameters to design MST signals in Chapter 5.

7.1.4 Summary of results in Chapter 5: Answers to research question 3

RQ3: To which extent could users recognize the designed MST signals?

Having studied how the users would express MST gestures and perceive vibrotactile stimuli, we start to create the vibrotactile stimuli in Chapter 4 with the touch properties presented in Chapter 3 to represent MST gestures. In Chapter 5, we present a generation method for MST signals on smartphones. We conducted user studies to evaluate the designed MST signals.

Results showed that around 70% of designed MST signals could be recognized above a precision of 25%, which was two times better than the random recognition rate. These concrete measures can be referenced when designing MST signals.

The designed MST signals in this chapter would be selected for the experiment with online communication in Chapter 6.

7.1.5 Summary of results in Chapter 6: Answers to research question 4

RQ4: Can MST signals increase social presence in mobile communication?

After designing MST signals, we tried to apply them to an online application. As presented in Chapter 6, we applied MST signals in an application with two online communication modes – asynchronous and synchronous communication (texting and video calling). We conducted a user study to evaluate the application.

The quantitative data analysis shows that adding vibrotactile stimuli to MST helps to increase social presence in the aspects of co-presence, perceived behavior interdependence, perceived affective understanding, and perceived emotional interdependence. Adding vibrotactile stimuli to MST causes no significant differences in attentional allocation and perceived message understanding. There is no significant difference between texting and video calling when applying MST signals in online social communication. The qualitative data analysis showed that participants thought MST with vibrotactile stimuli was interesting, and they were willing to use it in mobile communication, but the application design should be future improved based on their feedback. The improvements could include: (1) More CWC forms, multimodal stimuli, and a better match of visual-haptic stimuli could be considered to understand MST signals in online communication better. (2) Richer visual design and customization of visual icons are needed. (3) A better layout of video and texting with MST signals, a preview of MST gestures before sending, and customization of MST gestures' position and types are needed. (4) A time difference between the vibrotactile stimuli triggered by the two people in the communication during video calls should be considered.

7.2 Limitations and Future work

We mainly summarized the limitations and suggested future work from four aspects: signal design, application design, measurement, and other concerns.

7.2.1 Signal design

1) Parameters and actuators

We only considered parameters such as frequency, duration, and CWC forms when designing MST signals based on LRAs. However, parameters and actuators are not just limited to those used in this thesis. For example, current and voltage are parameters that should be considered when piezoelectric and electromagnetic actuators are used to produce certain social touch [23]. We could consider more types of parameters or actuators, trying to explore various MST effects for users.

2) Signal design and context

In the work presented in Chapter 4, we did not consider the context when designing vibrotactile stimuli. However, the same vibrotactile stimuli might lead to different perceptions for users in different contexts. For example, Salminen et al. [77] have demonstrated that users have different emotional ratings of haptic stimuli in different contexts (i.e., laboratory and bus conditions). The same haptic stimuli were rated as less arousing in noisy environments such as on buses [77]. Thus, in a noisy context, users may need stronger vibrotactile stimuli when pressing a graphical button on a touchscreen. Conversely, weaker vibrotactile stimuli are enough for users in a quiet space.

As presented in Chapter 5, we focused on a single generation method for the MST signals without considering the context and applications. However, there might be other potential generation methods that could be simpler considering the context and applications. We can improve the generation method by iterating it, considering the context and applications, and aiming for better efficiency.

In our initial design of the MST signals as described in Chapter 5, we didn't consider specific applications when designing MST signals. However, incorporating

MST signals in online social communication, using MST visual icons, and adding audio information could positively affect how participants perceive and recognize the MST signals.

3) Generation methods

We proposed a generation method in this thesis for MST signals. However, we only evaluated the MST signals generated through this generation method. We did not evaluate the generation method itself. Providing a better generation method may help to increase the effectiveness of design for MST signals, which may lead to a higher recognition of MST signals. We could consider experimenting with more generation methods, evaluate them, and select more effective ones to improve the MST design.

4) Social cues

There are no social cues in Chapter 4, but we used a parametric design method to better understand how users perceive vibrotactile stimuli. This understanding allows us to better deliver social cues to vibrotactile stimuli in Chapter 5. To create social cues, we made assumptions, connecting the perceived depth and roughness of graphic buttons in Chapter 4 to the skin deformation and pressure applied to the skin for MST gestures in Chapter 5, as Thompson and Paredis [227] indicated that design decisions could be made based on rational assumptions in the design process. However, not validating these assumptions or decisions could affect research because the chosen design action depends on the outcomes of previous design process decisions [227]. Future design should consider validating the assumptions first to make the results more solid.

5) Multimodal stimuli

The employed LRA in this research can generate both haptic and audio stimuli simultaneously, but we only evaluated stimuli on the haptic level. We found that sometimes small changes to the drive signal had little effect on the haptic output but significantly impacted the audio output. By exploring the combined audio and haptic aspects, we may enhance the overall quality of the stimuli generated by the LRA.

7.2.2 Application design

In this research, we used MST signals in texting and video calling for evaluation. The research findings were mainly derived based on these two applications. However, it would be interesting to integrate MST signals into more mobile applications. One such example is mobile augmented reality games, which have shown a demand for haptic feedback during usage [228]. It has the potential to integrate MST signals into other mobile applications.

7.2.3 Measurement

In this research, we collected both quantitative and qualitative data, as presented in Chapter 6. Chapter 3 primarily focused on behavior analysis, where we recorded hand gestures. In Chapter 4 and Chapter 5, we mainly used Likert scale assessments to evaluate the designed vibrotactile stimuli with different parameters. We discovered that it might be more beneficial to collect participants' comments on why they expressed MST gestures like that in Chapter 3 and their experiences regarding the perception of vibrotactile stimuli in Chapters 4 and Chapter 5. The reason is that in-depth interviews, designed to obtain detailed and insightful information, have proven to offer valuable insights in this domain [229].

By considering both quantitative and qualitative data, we can address the research questions and better understand the reasons behind specific outcomes. This approach helps researchers develop clearer iterations based on the collected data. For example, as presented in Chapter 5, a designed MST signal – 'Pinch' received the lowest scores for being understood and recognition performance. We suggested an initial iteration based on the definition in the Touch Dictionary [130]. However, collecting detailed comments from participants about why they gave 'Pinch' low scores would offer a clearer path for improvement of the MST signal based on users' perceptions.

7.2.4 Other concerns

1) Age groups

There are some limitations due to the age group of participants. We mainly recruited participants from the campus. We did not consider the age group under 22 or over 38. Teenagers or older people may offer different insights in performing MST gestures on touchscreens. Furthermore, they may have different perception of vibration because the mechanical properties of the skin changes along with the age, incurring touch sensitivity changes [230]. Although participants we recruited were also active users in social media, and they could still cover a specific spectrum, we could have considered a wider range of age group when studying MST signals for them.

2) User needs

In this research, we directly provided the participants with a mobile application with MST signals to evaluate. However, we did not consider the detailed user needs before designing the application. Although the mobile application in this research was designed based on the current popular applications such as WhatsApp and WeChat, which should meet the needs of users to some extent, we could still have considered doing a survey and exploring users' deeper needs when using MST signals in mobile communication before developing the mobile application. For example, users in romantic relationships may need to express affection more, while colleagues focus more on business communication, which leads to different MST gestures and signals in mobile communication.

7.3 Contributions

This research explores how to design and apply MST signals in mobile communication. We conducted one literature review and four main studies to answer four detailed research questions. The main contributions are as follows:

1) An overview of the MST designs and evaluations on mobile devices.

We provide an overview of MST designs and evaluations on mobile devices, enhancing the completeness of mobile MST research fields. While existing studies have mainly focused on reviewing the applications and the effects of social touch across various tools such as wearables, virtual agents, and other haptic devices [50], [36], [4], [51], our research mainly focuses on mobile devices and how MST gestures and signals are designed, prototyped, and evaluated, serving as an effective guideline for researchers to create their desired MST gestures and signals. We also summarize valuable insights for future MST design and research directions. Referring to our summarized findings will help researchers design MST gestures and signals for mobile devices efficiently and effectively.

2) User-defined MST gestures

We studied user-defined MST gestures, addressing a noticeable gap in the research for social context on smartphone touchscreens. While many gestures have been defined primarily for manipulating mobile devices, such as commands for touchscreens interaction [145], [150], [151], we obtain a set of user-defined MST gestures on the touchscreens of smartphones and collect their touch properties (e.g., pressure and duration). These results could be the design foundation for computer-mediated social interaction, which in our case involved mobile devices.

The MST signal forms and intensities could be designed based on user-defined gestures and their touch properties. For example, we used short pulses for 'Hit' and 'Pat' because users quickly touch the touchscreen with their fingers in user-defined gestures. To provide effective feedback, 'Hit' is accompanied by strong vibration, while 'Pat' is gentler. These decisions are based on the collected pressure data, where 'Hit' corresponds to strong pressure and 'Pat' to gentle pressure.

The recorded touch properties (e.g., pressure and duration) could be a foundation for future gesture recognition research, just similar to the work of Jung et al. [122]. Specifically, they created the Corpus of Social Touch [122], containing pressure and duration data of social touch gestures. They received good results in developing and evaluating gesture recognition using these data.

User-defined gestures can serve as commands on the touchscreen to trigger MST signals in mobile applications. For example, the gesture 'Nuzzle' moves fingers back and forth. During the mobile communication application, we utilized this 'moves fingers back and forth' around the other person's nose to trigger 'Nuzzle,' which made the computer-mediated social interaction more natural.

3) Generation methods for MST signals

We introduce a generation method for MST signals. In contrast to existing studies that mainly develop prototypes for MST signal transmission, our research focuses on the generation method of MST signals. This detailed generation method shows how to select the frequency (i.e., transferred by pressure), duration (i.e., recorded in user-defined gestures), and CWC forms (i.e., proposed based on skin pressure and deformation) in MST signals design. Researchers can follow our proposed process to design MST signals, especially the mathematical method that converts MST gesture pressure to MST signal frequency. Researchers can calculate the corresponding frequency and get the appropriate vibration intensity for the MST gestures based on the desired pressure. This approach has proven efficient in our practice for MST signal design for mobile communication.

Furthermore, we design a rich set of MST signals utilizing our proposed generation method. This contribution enhances the current research field of MST signal design, as previous studies have considered only a limited number of MST signals. Additionally, these MST signals can be integrated into mobile communication applications to increase social presence.

4) Application for MST signals

We applied MST signals in online social communication (i.e., text and video calls). The application we developed in this research is a preliminary exploration of using MST signals in mobile communications. We derived some guidelines and improvement suggestions from the user study. Other applications (e.g., mobile augmented game) with better integrated MST signals could be explored based on our findings.

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Appendix

Fifty-two selected articles for literature review in Chapter 2.

Studies		Design					Evaluation			
Ref	Date	Actuator	Related parameters	Haptic input	Haptic output	Mediated social touch and emotion	Participants	Independent variables	Collected data	Dependent variables
[82]	2022	Air pump, inflatable surface	Air pressure of the airbag	Touch gestures	Pressure	Pull, pinch, press	12 participants (3 women, 9 men)	2 input techniques (pinch-and-pull vs. press) × 6 pressure levels (Level 1 to 6)	Game tasks results + interview	The accuracy of controlling pressure input and general experiences
[86]	2022	Others *	Rhythms and patterns, intensity	Graphic user interface	Vibration	Hand/finger movement; emotional expression	3 couples	N/A	Interview + observation	N/A
[95]	2022	Taptic Engine	Rhythm, frequency, waveform, and envelope structure	Pre-defined parameters	Vibration	Haptic stimuli for emotional expressions	20 participants (12 females, 8 males, 10 pairs)	Multi-modal emoticons vs. static emoticons	Unstructured feedback + system logs + interview + subjective scales	Engagement, fun, expressiveness, and general experiences.
[26]	2021	Linear stepper motors	Position, velocity, acceleration, the sequence of actuators	Touch gestures	Pressure	Kiss	50 couples (study 1), 50 pairs (strangers, 57 males, study 2), 26 couples (study 3)	Real kiss vs. mediated kiss (study 1); 2 Genders (male vs. female) × 2 kissing devices (with vs. without kissing device) × 2 communication ways (chatbox vs. human) (study 2)	Verified questionnaire + calculated data + interview	The hedonic and pragmatic qualities, winning rate, satisfaction, perceived stress
[49]	2021	Servo driver; A 12V DC vacuum pump	Orientation of the phone, activate movement (hand interaction); Air	Touch gesture	Pressure	Handshakes, hold hands, tap, high-five, hand/finger movement	136 participants (46% female, 52% male, 2%	Mediated (i.e., handshakes with SansTouch) vs. substituted with other forms (i.e., waving	Observation + subjective scales + interview	The frequency and the forms of social touch for different relationship categories,

			source to inflate airbags				preferred not to say) (study 1); 6 stranger pairs, 3 females (study 2)	hands, without SansTouch) (study 2)		similarity to the real touch and general experiences
[97]	2021	Voice-coil motor	Recorded signals	Touch gestures	Vibration	Joy, anger, sadness, relaxation	7 individuals (3 males)	Preset haptic stimuli	Subjective scales + calculated data	Affective ratings in the emotion dimension, difficulty rating results, accuracy rate
[60]	2020	Haptuator Mark II	Amplitude, carrier frequency, duration	Pre-defined parameters	Vibration	Haptic stimuli for emotional expressions	20 individuals (10 females, study 1), 20 individuals (9 females, study 2)	3 amplitudes × 3 frequencies × 2 durations (study 1); Preset haptic stimuli (study 2)	Subjective scales	Recognition and affective ratings in the emotion dimension
[79]	2020	Tactile-emoji apparatus using a 3D printer.	Dot ratio, resolution, dimension	Pre-defined parameters	Other tangible output	Happiness, sadness, surprise, anger, scare, affection	30 individuals (16 males)	Preset haptic stimuli (study A); Image-based vs. non-image-based emojis, 2 visual impairment status (congenital vs. acquired) × 2 education levels (below compulsory vs. above compulsory education) (study B); With vs. without the image-based tactile emojis (study C)	Calculated data	Message intention recognition, accuracy, the clarity of the intended message
[92]	2020	Linear resonant actuator	Frequency, amplitude, and envelope shapes of accelerations	Pre-defined parameters	Vibration	Knock, stroke, hug, hit	16 individuals (4 males)	2 contact time (long vs. short) × 2 gestures traits (dynamic vs. static)	Subjective scales	General experiences

			(based on touch gestures)							
[31]	2020	Eccentric motor, Linear electro-mechanical actuators	A specific system code in-accordance with the Braille protocol	Graphic user interface	Vibration	Tap, hand/finger movement	30 individuals with researcher (23 males)	2 hands use (single hand vs. both hands), 2 vibration motors (linear actuators vs. vibration motors), 3 actuation durations × 3 actuation intervals	Calculated data + interview	Recognizing accuracy (stimuli and number)
[105]	2020	A 2-by-2 tactor array - Tectonic Elements	Frequency, duration	Pre-defined parameters	Vibration	Haptic stimuli for emotional expressions	14 individuals (7 females)	Preset haptic stimuli	Subjective scales	Affective ratings in the emotion dimension
[117]	2019	Voice-coil motor	Amplitude, carrier frequency, frequency of envelope, duration	Pre-defined parameters	Vibration	Comfort, haptic stimuli for emotional expressions	11 males	3 waveforms × 4 amplitudes × 4 frequencies × 4 durations × 4 duty ratios	Subjective scales	Affective ratings in the emotion dimension
[20]	2018	Servo motors	Positions, the sequence of motors	Graphic user interface	Shape change	Pat, stroke, tap; Anger, comfort, excitement	51 individuals (11 females)	10 scenarios	Subjective scales + interview	Usefulness, fun
[55]	2018	A vibration motor - Silicon Touch Technology Inc.	Duration, intensity	Pre-defined parameters	Vibration	Cheerfulness, liveliness, quietness	10 individuals	Preset haptic stimuli with different intensities, suspensions, and changes in intensity	Subjective scales	Impressions
[56]	2018	A C2 actuator	Amplitude, carrier frequency, frequency of envelope, envelope attributes	Pre-defined parameters	Vibration	Haptic stimuli for emotional expressions	20 individuals for study 1 (18 females), 22 individuals for study 2 (15 females)	Preset haptic stimuli with different waveforms, tempo, discontinuity, frequency + waveform, waveform + tempo, and irregularity + discontinuity	Subjective scales	Affective ratings in the emotion dimension
[94]	2018	Linear resonant	Frequency, amplitude, and	Pre-defined parameters	Vibration	Happiness, surprise,	20 individuals	Preset haptic stimuli	Interview	General experiences

		actuators	envelope shapes of accelerations (based on breathing patterns)			sadness, anger	(10 females)			
[27]	2017	Linear coin-shaped actuators	Frequency, amplitude, and envelope shapes of accelerations, the sequence of actuators	Shape change	Vibration	Hand/finger movement	9 couples	Communication modes (voice calls vs. video communication)	Subjective scales + interview	Emotional connection, intimacy, general experiences
[37]	2017	Shape memory alloy actuation	Current	Touch gestures	Shape change	Handshakes, high-five, pat, hug, hold hands	28 pairs (stranger pairs and known people pairs), 53% females	2 Tasks with different levels of emotion (low emotion vs. high emotion) × 2 prototypes (ShareTable only vs. SqueezeBands + ShareTable)	Subjective scales + interview + recorded data	Task load, social presence
[75]	2017	N/A	Gestural attributes of size, pressure, speed, position, and stroke width	Touch gestures	Visual information	Surprise, happiness, afraid, anger, sadness, tiredness, mellow, boredom	26 individuals	Gestural attributes of size (small vs. large), pressure (light vs. heavy), speed (fast vs. slow), position (top vs. middle vs. bottom)	Recorded objective data + calculated data	Emotional intensity recognition (e.g., moderately happy, extremely afraid)
[99]	2017	Haptuator Mark II	Amplitude, carrier frequency, duration	Pre-defined parameters	Vibration	Haptic stimuli for emotional expressions	12 individuals (4 females) (study 1); 18 individuals (10 females) (study 2); 12 individuals (9 females)	3 amplitudes × 3 frequencies × 2 durations (study 1); Vibrotactile + thermal vs. vibrotactile + visual vs. visual + thermal (study 2); Trimodal vibrotactile, visual, and thermal stimuli	Subjective scales	Affective ratings in the emotion dimension
[19]	2016	Coin type vibrotactile	Finger motions	Touch gestures	Vibration	Pat, slap, tickle, kiss	30 individuals	4 touch gestures (pat, slap, tickle, kiss) × 3	Subjective scales	The possibility of applying the

		actuators					(17 males)	conditions (Sound only vs. vibrotactile only vs. combined situation) × 2 repetitions		vibration as the social touch
[25]	2016	Servo motor + Others *	Location of gestures	Joystick	Vibration + Shape change	Finger or hand movement. Haptic stimuli for emotional expressions	10 university students	'EMO' vs. mobile phone	Subjective scales interview	Usefulness, easiness-to-use, efficiency, pleasurability, willing to use and other comments
[74]	2016	A flexible display	Dimensionality and 2D form factor	Shape change	Shape change	Anger, calmness, sadness, confusion, boredom, distress, delight, excitement, happiness, love, contentment, fear, haptic stimuli for emotional expressions	10 pairs, strangers, 6 females, study 2	N/A	Observation + calculated data + subjective scales	Affective ratings in the emotion dimension; recognition
[90]	2016	Two degree of freedom arm	Movement of arm	Graphic user interface	Shape change	Pat, stroke	27 male university students	2 genders (male vs. female) × 2 touch use (with touch vs. without touch)	Observation + recorded objective data + subjective scales	The number of actions, the working time, and impressions of performing the task
[76]	2015	Haptuator	Amplitude, carrier frequency, frequency of envelope duration	Pre-defined parameters	Vibration	Haptic stimuli for emotional expressions	24 individuals (12 females)	5 amplitudes × 5 carrier frequencies × 6 durations × 6 envelope frequencies	Subjective scales	Affective ratings in the emotion dimension
[22]	2015	Coil-type	Shape-changing	Joystick	Shape	Haptic stimuli	7 couples	N/A	Field study +	N/A

		SMAs	movements		change	for emotional expressions			interview	
[45]	2014	Piezoelectric actuators	Spatial frequency, magnitude, rhythm, and increasing or decreasing magnitude or frequency across space	Touch gestures	Other tangible output	Hand/finger movement; Anger	6 couples and 6 strangers' pairs	3 applications (haptic text messaging vs. haptic image sharing vs. haptic virtual touch) × 4 preferred communication partners (strangers vs. acquaintances vs. close friends vs. spouse/sig vs. other) × 4 interactions (ease of use vs. fun vs. self-expression vs. understand partner)	Subjective scales	Usability and appeal
[85]	2014	SMA coils	Shape-changing movements	Joystick	Shape change	Hand/finger movement	12 pairs (friends), 24 females	N/A	Field study + interview	N/A
[88]	2014	Others *	Intensity	Graphic user interface	Vibration	Haptic stimuli for emotional expressions	20 individuals with the researchers	Text only vs. text + vibrotactile stimuli vs. text + color stimuli	Subjective scales	Affective ratings in the emotion dimension
[98]	2014	Haptuator II	Amplitude, carrier frequency, frequency of envelope	Pre-defined parameters	Vibration	Haptic stimuli for emotional expressions	18 individuals (9 males) (study 1, study 2, and study 3)	Preset visual icons (study 1); Preset haptic stimuli (study 2); Preset visual icons and haptic stimuli (study 3)	Subjective scales	Affective ratings in the emotion dimension (study 1 and study 2); The degree of congruence (study 3)
[89]	2014	Others *	vibration length, vibration gap, inter-vibration on, and off	Graphic user interface	Vibration	Joy	3 pairs of friends (study 1); 7 known people (1 male)	Focus group (study 1); 2 Busyness (low vs. high) × 2 joy (low vs. high) (study 2)	Focus group + subjective scales + interview	Acceptance and understanding of the application (study 1); User acceptance and attitudes (study 2)
[28]	2013	Minebea Linear	Amplitude, waveform, touch	Touch gestures	Vibration	Squeeze, hand/finger	12 pairs (friends and	2 participant roles (sender vs. receiver)	Observation + subjective	Affective ratings in the emotion

		Vibration Motor actuators	location			movement. Relaxation, haptic stimuli for emotional expressions	couples)	× 2 touch gestures (squeeze vs. finger touch) × 4 emotional intentions (unpleasant vs. pleasant vs. relaxed vs. aroused)	scales + interview	dimension
[48]	2013	Air pump, inflatable surface	Inflation height	Touch gestures	Pressure + Vibration	Tap, poke	3 couples	N/A	Field study + Recorded objective data + interview	N/A
[87]	2013	Others *	Rhythms and patterns	Graphic user interface	Vibration	Tap, hold hands, nudge	4 couples	Mobile only vs. semi-hybrid vs. hybrid	Recorded objective data + subjective scales + interview	Closeness
[102]	2013	An EAP vibrotactile actuator	Frequency, repetitions	Pre-defined parameters	Vibration	Haptic stimuli for emotional expressions	30 individuals	7 patterns × 2 frequencies × 2 repetitions	Subjective scales	Affective ratings in the emotion dimension
[103]	2013	The in-built vibration motor in Nexus One	Frequency, duration, amplitude, envelope shape	Pre-defined parameters	Vibration	Haptic stimuli for emotional expressions	18 participants (5 females) (pilot study); 36 individuals (17 females, study 2)	Preset haptic stimuli (study 1); A neutral laboratory setup vs. an office vs. a bar surrounding (study 2)	Subjective scales	Discriminability, general impression, and functionality (study 1); Affective ratings in the emotion dimension (study 2)
[106]	2013	A micro vibration motor	Duration, current	Pre-defined parameters	Vibration	Affection, boredom, depression, anxiety, concentration, hostility, surprise, haptic stimuli for emotional expressions	21 individuals (13 males)	Preset haptic stimuli	Subjective scales	Affective ratings in the emotion dimension
[47]	2012	Servo motors	The sequence of	Touch	Shape	Kiss	7 couples	Send kiss through	Observation +	Affectivity and co-

			motors	gestures	change + pressure			Kissenger vs. through skype	subjective scales	presence
[18]	2012	Coin type vibrotactile actuators	Finger motions	Touch gestures	Vibration	Tap, hand/finger movement	5 couples	N/A	Field study + interview + Observation	N/A
[23]	2012	Piezoelectric actuators	Moving length in the screen and the moving velocity of the finger	Touch gestures	Other tangible output	Tickle	650 individuals (410 males), exhibitions	N/A	Observation + interview	N/A
[21]	2012	Rotational motor	A preset short burst (50ms)	Touch gestures	Vibration	Squeeze. Anger, affection, surprise, haptic stimuli for emotional expressions	3 couples	2 Interaction loops (basic vs. delay) × 3 feedback modalities (visual vs. vibrotactile vs. visual/vibrotactile)	Recorded objective data + calculated data + interview	User performance
[58]	2012	Minebea Linear Vibration Motor actuators	Amplitude, waveform, touch location	Pre-defined parameters	Vibration	Haptic stimuli for emotional expressions	12 males (study 1), 16 individuals (8 females, study 2)	Concurrent tactile stimulation (speech only vs. speech tactile); The emotional content of the speech (positive vs. negative) (study 1); Design methods (Extract the amplitude changes of the tactile signal from the concurrent speech sample vs. extracted from one of the other speech samples), speech sample content (speech only vs. positive vs. neutral vs. negative) (study 2)	Subjective scales	Affective ratings in the emotion dimension
[57]	2011	Minebea	Amplitude,	Touch	Vibration	Anger,	20	Tactile-only vs.	Subjective	Friendly-hostile,

		Linear Vibration Motor actuators	waveform, touch location	gestures		excitement,	individuals (10 females)	setting vs. sender vs. situation	scales + interview	intense-superficial, socioemotional-task-oriented, and formal-informal
[59]	2011	Minebea Linear Vibration Motor actuators	Amplitude, waveform, touch location	Touch gestures	Vibration	Squeeze, stroke, hand/finger movement	12 individuals	2 output methods (4 actuators vs. 1 actuator) × 3 input methods (move vs. squeeze vs. stroke)	Observation +subjective scales + interview	Applicability, easiness, pleasantness, expressiveness, and reasonability
[78]	2011	Piezoelectric actuators	Rise time (the current), displacement amplitudes (the driving voltage), pulse numbers	Pre-defined parameters	Other tangible output	Haptic stimuli for emotional expressions	14 individuals (7 females)	A between-subjects design. 3 presentation types (haptic only vs. haptic auditory vs. auditory only) × 9 stimuli (3 rise time × 3 amplitudes)	Rank	Affective ratings in the emotion dimension
[107]	2011	Others *	Rhythms and patterns, intensity	Pre-defined parameters	Vibration	Awareness	7 couples	N/A	Field study + observation + interview	N/A
[29]	2010	A DC motor	Pulse Width Modulation (PWM): frequency, magnitude	Pre-defined parameters	Vibration	Normal, happiness, surprise, sadness	20 individuals	Before training vs. after training	Subjective scales	Effectiveness (the success to failure ratio for task completion); Efficiency (the reaction time of a user, the delay time); Satisfaction
[77]	2009	Piezoelectric actuators	Rise time (the current), displacement amplitudes (the driving voltage), pulse numbers	Pre-defined parameters	Vibration	Haptic stimuli for emotional expressions	10 individuals (5 females)	2 amplitudes (2µm vs. 30µm) × 2 rise time (1ms vs. 10ms) × 2 burst number (1 burst vs. 3 bursts) × 2 sessions (laboratory vs. travelling by bus conditions)	Subjective scales	Affective ratings in the emotion dimension
[24]	2009	Ultrasonic distance sensor, stereo	Hand movement, step distance,	Touch gestures	Other tangible output	Tap, tickle, push, caressing, handshakes	Exhibition, not mentioned	N/A	Interview	N/A

		amplifier	frequency, duration, and amplitude				exact participants			
[100]	2009	Minebea Linear Vibration Motor actuators + a C2 actuator	Amplitude, waveform, touch location, carrier frequency	Touch gestures	Vibration	Shake, tap	20 individuals (14 males, study 1), 10 individuals (study 2)	10 scenarios	Subjective scales + interview	The easiness, understandability, and reasonability
[30]	2009	An eccentric-weighted pager motor	Frequency, control over onset, offset	Pre-defined parameters	Other tangible output	Stroke, tap, flick, twist	6 couples	N/A	Field study + interview	N/A
[108]	2008	A low-cost coin motor	PWM (frequency and magnitude)	Pre-defined parameters	Vibration	Happiness, surprise, normal, sadness	10 participants	Before training vs. after training	Subjective scales	Effectiveness (the success to failure ratio for task completion); Efficiency (the reaction time of a user, the delay time); Satisfaction

* Other actuators that did not mention specific type

Publication

Journal

Qianhui Wei*, Min Li, & Jun Hu, "Mediated social touch with mobile devices: a review of designs and evaluations," *IEEE Transactions on Haptics*, pp. 1–20, 2023. https://doi.org/10.1109/TOH.2023.3327506

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Conference

Qianhui Wei*, Min Li, Jun Hu, & Loe Feijs, "Creating mediated touch gestures with vibrotactile stimuli for smart phones," *TEI 2020 - Proceedings of the 14th International Conference on Tangible, Embedded, and Embodied Interaction*, 519 – 526. https://doi.org/10.1145/3374920.3374981

Curriculum Vitae

Qianhui Wei was born on 12th December 1992 in Sichuan, China. In 2015, she earned her bachelor's degree in Industrial Design and was awarded the Outstanding Graduate from Sichuan Province (Top 5%). She was also recommended to pursue a master's degree. In 2018, she completed her master's degree in Industrial Design and Engineering from Southwest Jiaotong University, where she received an Excellent Paper Award for her master's thesis (Top 5%). In the same year, she began her Ph.D. studies at Eindhoven University of Technology, doing research in the field of social haptics under the supervision of dr. Jun Hu and dr. Min Li. This thesis is the result of her Ph.D. project on "Designing Mediated Social Touch for Mobile Communication."

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