Representing Interpersonal Touch Directions by Tactile Apparent Motion Using Smart Bracelets

Taku Hachisu and Kenji Suzuki, *Member, IEEE*

***Abstract*—We present a novel haptic interaction to vibrotactually connect an interpersonal touch using bracelet devices. A pair of bracelet devices identifies the user who is actively touching and the other who is passively touched, defining the direction as being from the former to the latter. By controlling the vibrational feedback, the pair induces a tactile apparent motion representing the direction between two hands. The bracelets are comprised of our developed interpersonal body area network module, an acceleration sensor, and a vibrator. The devices communicate with each other through electrical current flowing along the hands to identify the direction by sharing accelerations just before a touch and to synchronize the feedback in less than ten milliseconds. Experiment 1 demonstrates that the vibration propagated from a bracelet device to the wearer's hand is perceivable by another. Experiment 2 determines sets of optimal actuation parameters, stimulus onset asynchrony, and duration of vibration to induce the tactile apparent motion based on a psychophysical approach. In addition, vibration propagation between hands is observed. Experiment 3 demonstrates the capability of the developed device to present the haptic interaction.**

***Index Terms*—EnhancedTouch, direction of touch, interpersonal body area network, tactile apparent motion, touch communication.**

I. Introduction

INTERPERSONAL touch interactions perform a social behavior modulation effect. Servers in a restaurant, for instance, were instructed either to touch customers or not to touch them while returning their change. The customers gave significantly greater tips under the with-touch condition than the without-touch condition [1]. A similar effect has also been noted in several situations in which people behave generously [2]–[4], tend to comply with a request [5]–[7], and help /collaborate with someone [8]–[10]. However, context, such as gender, nationality, and relationship, is likely to affect the interpretation of and reaction to touch [11]–[15]. There have also been a variety of discussions over an effect of awareness of touch, that is, whether a touched person notices / remembers being touched. Joule and Guéguen showed that participants who had noticed a touch tended to comply with a request more than those who had not noticed [16]. Thus, enhancing touch awareness can facilitate social interactions between peers.

We have developed a bracelet device, called EnhancedTouch (ET), which can measure a hand-to-hand physical contact using interpersonal body area network (BAN) technology [17], [18]. The device can also represent a touch by real-time visual and vibrational feedback. Because the device can be worn without the need to attach it to a fixed sensor on the skin of a hand or use a connecting wire, it can be comfortably used for activities in daily life.

This study in a part of the ET project presents a novel representation technique used to expand the freedom of interpersonal touch interaction design (Fig. 1). Here, we define a direction of touch as being from one hand actively touching to another being touched (passive). The technique represents the direction through a direction of vibrotactile sensation, which is expected to provide user awareness of the touch direction. The technique employs a tactile apparent motion (TAM) to induce the vibrotactile direction between two people's hands [19]. Because vibration provided by the bracelet propagates from one hand to the other, actuators are not required to be present between hands. This also enables two people to share the haptic experience.

We identified a direction of touch as a key issue that has not been explored in touch communication after discussions with therapists specializing in children with special needs. While investigating how touch contributes to the social behavior of humans represents future work, we believe that the present technique will lead to a new research branch associated with interpersonal touch supported by information technologies because active / passive touch has become a topic of interest in the research field of discriminative touch since Gibson first introduced it [20].

A. Contributions

There are four main contributions of this paper.

(1) Implementation of wireless wearable devices that represent a direction of touch with TAM
(2) Demonstration of the vibration propagated from a bracelet device to a hand
(3) Demonstration of the propagated vibration inducing a TAM

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The authors are with the Faculty of Engineering, Information and Systems, University of Tsukuba, Tsukuba, Ibaraki 305-8573, Japan.
(e-mail: hachisu@aiiit.tsukuba.ac.jp; kenji@ieee.org).

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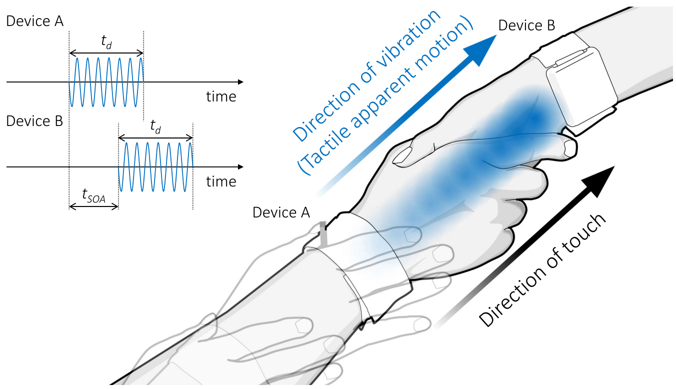

Fig. 1. Interpersonal touch direction represented by vibrotactile direction (tactile apparent motion) between hands wearing smart bracelets.

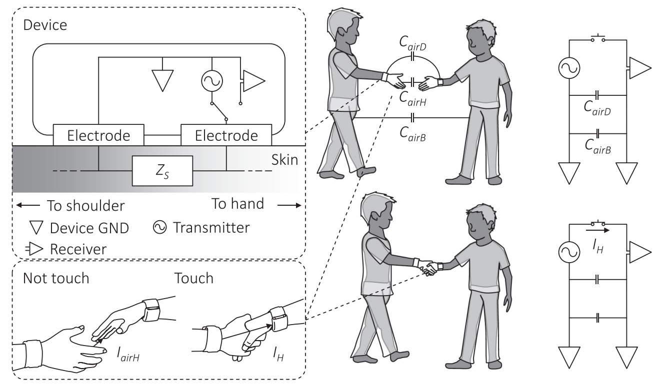

Fig. 2. Model of the touch sensing system with ET [17], [18].

(4) Demonstration of the capabilities of the developed devices

We verified the concept of TAM with the wired condition[1] and developed bracelet devices with the capability of identifying a direction of touch [18]. To implement the present interaction to the bracelet devices, a main technical challenge is to implement new software that synchronizes vibration (turning on and off) between two devices with the accuracy on the order of less than ten milliseconds to induce TAM towards identified direction of touch.

The remainder of this paper is organized as follows. First, we review the literature on touch sensing including ET, TAM, and vibration propagation on a hand to describe the details of the contributions. Next, we describe the implementation of the bracelet devices. Then, we describe three experiments to demonstrate the present technique. Finally, we conclude the paper and discuss directions for future research.

II. Related Work

A. Touch Sensing

Various touch sensing techniques have been developed in the field of human-computer interaction. To measure bare skin to bare skin contact, researchers have employed sound/vibration processing techniques [21]–[23], computer-vision/photo sensor techniques [24]–[26], and capacitive sensing techniques [27]–[29]. These techniques are primarily applied to touch input to a computer and for detecting intrapersonal touches. Researchers have explored various modalities of a touch, such as a stroke, rub, and clap, to enrich human-computer interaction.

On the other hand, we are aware of only a few studies focused on measuring interpersonal touches. Canat *et al.*, for example, applied a swept frequency capacitive sensing method to detect different touch patterns [27] to facilitate interpersonal touches between two players, and designed a collaborative game [30]. In addition, Marshall and Tennent applied an impedance sensing technique to an arcade game that is controlled by gentle touching between the body parts of two players [31]. Although these sensing techniques are promising to measure bare skin-to-skin touch, they require a wired-connection to a large ground plane or to the earth for stable measurements, which would represent a problem for some wearable applications. An overview of capacitive sensing and the importance of the ground connection is discussed in [32].

1) EnhancedTouch: Fig. 2 shows a model of the touch sensing system of two ET devices using the interpersonal BAN technique [17], [18]. While the device is categorized as an active transmit + receive mode (intrabody coupling) system according to the taxonomy of [32], the device does not measure the displacement current I_{airH} flowing through the capacitive coupling C_{airH} between the hands, but instead measures the electric current I_H flowing through the pair of hands touching each other. As mentioned earlier, creating a ground path is crucial for wearable applications [32]. Transmitting a signal by electrical current requires two paths, that is, a signal path and ground path, where the human body is regarded as a single conductive wire. If the human body is used as the signal path by attaching a signal electrode on the wrist, the ground path will be established only by the capacitive coupling C_{airD} in the air between the devices. However, C_{airD} is too weak to transmit or receive the current, even while a pair of hands is touching each other. In our previous studies [17], [18], we implemented the method designed by Doi and Nishimura [33], in which a ground electrode is also attached to the wrist as well as the signal electrode to improve connectivity. Thus, the device has two electrodes. The body is divided into signal and ground paths by the electric impedance Z_S of the skin between the two electrodes. As a result, a large area of the body, such as the torso, works as the ground electrode (gray area of the body in Fig. 2), achieving a significantly stronger capacitive coupling C_{airB} with the body of another user than C_{airD}. Thus, a weak (less than 3 mA) but stable measurable current, I_H, flows between devices only while the user pair is touching each other.

The pair of devices uses the current not only to detect a touch, but also to communicate with each other. For example, exchanging device IDs allows identification of the partner. In addition, sharing the devices' acceleration just before a touch and received signal strength indication enables the devices to

[1] Parts of the second and third contributions were published in [19].

identify the direction of a touch and the type of touch gesture, respectively [18].

In addition to the capability of measurement, the previous devices also have a function of visual and vibrational feedback which is simply turned on and off as soon as it detects the beginning and end of a touch, respectively. Our previous user study showed that the visual feedback motivates children with autism to touch one another [17]. However, this simple on-off feedback limits the flexibility of design for interpersonal touch interactions.

This paper presents an EnhancedTouch+ (ETP) device that uses the previously developed hardware [18] with the newly implemented software that synchronizes the stimuli between the two devices as well as identifies a direction of touch (Section III-B). This enables the devices to represent a direction of a touch through TAM. There are three technical challenges. First is to achieve accuracy on the order of less than ten milliseconds for synchronization purposes. According to previous studies on TAM (see Section II-C), several dozens of milliseconds error results in either perception of a single merged stimulus or perception of a series of successive discrete stimuli instead of a continuous tactile motion. Second, a pair of ETP devices is not controlled by a host computer, which is unlike the system described in Section III-A. This means that the two devices need to communicate directly with each other to synchronize vibration timing. In addition, because one of our design requirements is that the devices must be worn by more than two people, it is difficult to predetermine master and slave devices. Third, a pair of devices must synchronize not only when turning on but also when turning off their vibrators. This means that the devices need to remain synchronized as long as a touch continues, which is a different requirement from the previous ET device [17], [18]. Experiment 3 (Section IV-E and IV-F) demonstrates that the developed device is capable of providing three types of perception: 1) a single static stimulus; 2) a series of static successive stimuli; and 3) a continuous moving stimulus, by controlling the vibration timing on each device.

B. Hand as a Medium for Vibration Propagation

Some studies measured acceleration on the side of a finger pad when a vibration stimulated the finger pad [34], [35]. The results showed that the skin allowed 100- to 300-Hz vibrations while attenuating other frequencies. This attribute contributes to tactile perception. Even after the cutaneous afferent of a finger is abolished by trauma or pharmacological intervention, humans can still discriminate the roughness of an object while exploring its surface with their fingertip [36]. The findings suggest that the vibration resulting from the exploration propagates through the finger toward the hand, wrists, and forearm, which contain tactile mechanoreceptors. Subsequent studies have investigated how vibrations propagate throughout the hand [37], [38].

Although the direction of propagation is opposite to that in our case, these studies indicate that hand tissue can convey vibration stimuli from a wrist to a hand and fingers. To demonstrate this, we measure the vibration propagated from the wrist to the hand and fingers in Experiment 1 (Section IV-A and IV-B).

C. Tactile Apparent Motion

Since TAM was studied in the early 1900s [39], [40], several studies have investigated different stimulation variables, such as time, distance, and intensity [39], as well as types of stimuli, such as pressure, vibration, and electrical stimulation [41], [42], for inducing and controlling a TAM. In particular, the two temporal variables, duration t_d and stimulus on set asynchrony (SOA) t_{SOA}, have been reported as critical to induce illusionary motion [41], [43]. With a constant t_d, a small t_{SOA} causes a pair of stimuli to be felt simultaneously as a single stimulus, because the subsequent stimulus will overlap the prior stimulus. A large t_{SOA}, conversely, causes the pair to be felt discretely as a series of successive stimuli. An intermediate t_{SOA} causes the two stimuli to be felt as a continuous tactile motion. Basically, accuracy on the order of less than ten milliseconds when synchronizing vibration timing is required to induce TAM.

The studies mentioned above have investigated TAM on some sites of contiguous parts of a body, such as a forearm or a thigh. Furthermore, tactile displays for enriching the experience in a virtual environment, such as a video game, have been developed and present TAMs on the back [44], [45], abdomen, and even within the body [46]. Because it is possible to induce a tactile sensation on a site where there are no stimulators by applying a TAM, the number of stimulators can be reduced. This can be considered an advantage in our approach, because we do not need to install a stimulator on the contact area, which would otherwise prevent skin-to-skin contact.

A TAM can also be observed between discrete sites of the body, such as from one hand to the other. Zhao *et al.* developed a tablet device with embedded vibrators, which provides a TAM between the hands holding it [47]. The tablet device works as a medium for extending and connecting discrete sites of the body, that is, the hands. Pittera *et al.* demonstrated intermanual TAM without a medium using two handheld devices with embedded vibrators [48]. Through other major tactile illusions, which are the phantom sensation / funneling [49] and cutaneous rabbit illusion / saltation [50], various studies have found that the illusionary tactile sensation travels between the discrete sites of the body [51], [52] or outside of the body [53]–[56]. To induce these illusionary sensations, these studies suggest that it is necessary to focus the attention of the observer on the site by providing a dummy stimulator at the site or providing a visual cue.

This paper aims to induce a TAM between the hands of a pair of people wearing bracelet devices. From the perspective of one person, it is easy to feel the vibration provided by the device being worn. However, the vibration provided by the device that the other person is wearing is significantly attenuated because it is propagated via soft tissue along the user's entire hand. We conduct a psychophysical study to determine

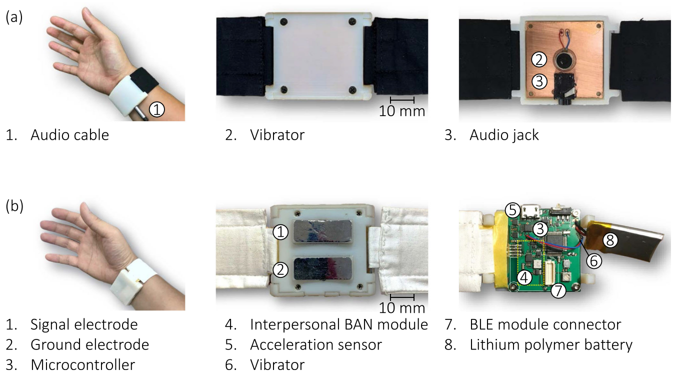

Fig. 3. (a) Wired prototype and (b) ETP device revised from the previous version of ET [18].

the optimal ranges of t_d and t_{SOA} in our case and observe the vibration propagation between hands in Experiment 2 (Section IV-C and IV-D).

III. Material

This section describes two systems. One is a wired prototype, which includes two wired bracelet devices and precisely controls the vibration feedback in Experiments 1 and 2. The other is a system consisting of wireless bracelet devices, ETPs, which are a revised version of our previously developed ET device [18].

A. Wired Prototype

The wired prototype consists of a computer, a vibrator driver unit, and a pair of bracelet devices. The computer executes a program that, through serial communication, orders the driver unit to set temporal variables of vibration, which are t_d and t_{SOA}, with 1 ms resolution.

The driver unit consists of a microcontroller (mbed LPC1768, NXP Semiconductors), two linear resonant actuator (LRA) driver ICs (DRV2603, Texas Instruments), and two audio jacks. The microcontroller controls the ICs according to commands from the computer. The outputs from the ICs are connected to the audio jacks.

As shown in Fig. 3a, a bracelet device of the wired prototype consists of an audio jack and an LRA-type vibrator (C08-001, Precision Microdrives) embedded in a 3D-printed housing, and Velcro straps. The device is worn with the housing on the palm side of the wrist as described in the next section. The device connects to the driver unit via an audio cable with audio plugs to transmit an output signal from the ICs on the driver unit to the vibrator in the device.

B. EnhancedTouch+

The ETP device uses the previously developed hardware [18]. This section describes a novel software that synchronizes vibration feedback as well as identifies a direction of a touch simultaneously, and reviews the existing features of ET.

1) Hardware: Fig. 3b shows the developed ETP device. It consists of two electrodes, a printed circuit board (PCB), a lithium polymer (LiPo) battery, a 3D-printed plastic housing, and Velcro straps. As shown in Fig. 2, one electrode (the signal electrode) connects to a transmitter or a receiver via an analog switch while the other (the ground electrode) connects to the ground point of the PCB. While the device can be worn with the housing on either the palm or back side of a wrist, users in this paper wore it on the palm side of the wrist. This is because hairs on the back side prevent the electrodes from contacting the skin directly. The PCB has a microcontroller (LPC1549, NXP Semiconductors), an interpersonal BAN module, a three-axis digital acceleration sensor (MMA8653FC, Freescale Semiconductor), a vibration unit, and a Bluetooth Low Energy (BLE) module (ZEAL-LE0, ADC Technology).

The interpersonal BAN module modulates a universal asynchronous receiver transmitter (UART) signal from the microcontroller by a carrier wave using on-off keying. Frequency and peak-to-peak voltage of the sinusoidal carrier wave are set to 10.7 MHz and 3.3 V, respectively. The baud rate of the UART is set to 9600. The acceleration sensor is used to measure the direction of a touch. The device monitors values of the sensor at a 10-Hz sampling rate. When communication is established with another device, the pair of devices shares and compares values. Based on the comparison, the pair determines which one was passively touched or actively touched by the other. See the next section for more details.

The device provides vibrational as well as visual feedback. The vibration unit consists of an LRA-type vibrator (C08-001, Precision Microdrives) and a driver IC (DRV2605, Texas Instruments). DRV2605 has similar functions to those of DRV2603, but is controlled by the inter-integrated circuit (I^2C) protocol. This reduces the number of tracks on the PCB, reducing its dimensions. Additionally, an LED driver (NCP5623B, ON Semiconductors) and the acceleration sensor were controlled by the I^2C protocol with a 20-MHz clock frequency. The refresh rate of both visual and vibrational feedback was set to 1 kHz.

2) Software: This section describes how a pair of devices presents TAMs toward the direction of a touch. Although the direction identification is based on our previous technique [18], the software for the device has been revised from our previous work [17], [18].

While not detecting a touch event ("standby"), the device calculates the difference between the root mean square (RMS) of the present acceleration and the RMS of the prior acceleration. In addition, the device calculates the average, a_{avg}, of the ten most recent differences, which is used for the measurement of the direction of a subsequent touch.

For bi-directional communication through a single path using an electric current signal, we used time division to enable transmission and reception in alternating time slots (half-duplex communication). Fig. 4 shows an example of the communication procedure between two devices, namely Device A and Device B. A packet consists of a 2-byte

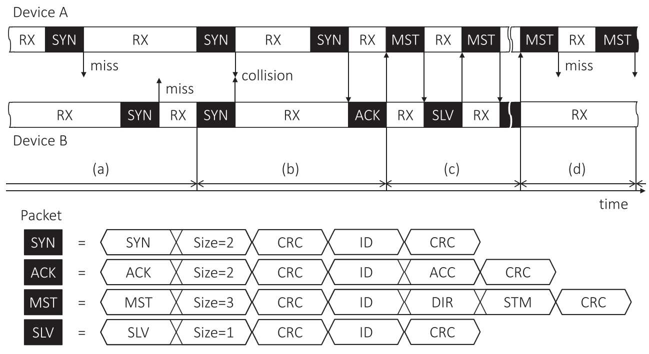

Fig. 4. Communication procedure between Device A and Device B.

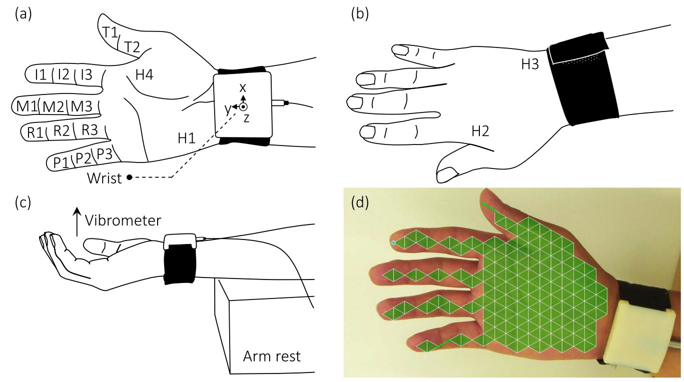

Fig. 5. Setup for Experiment 1. (a) and (b) show the 18 areas of the hand which contact the hand of a partner during a handshake [57] and the wrist to which the housing of the device was fixed. (c) Measurement of vibration acceleration using a scanning vibrometer. (d) View from the vibrometer, which measured the vibration velocity at 163 points.

header, 1- to 3-bytes of data, and a 2-byte cyclic redundancy check (CRC). The header consists of a command byte, that is, a synchronization request (SYN), request acknowledgement (ACK), master request (MST), slave acknowledgement (SLV), and the data size (Size). The data includes a device ID (ID), a_{avg} (ACC), the direction of touch (DIR), and a stimulation request (STM).

In phase (a), the users are not touching. Each device attempts to synchronize with other devices by transmitting a SYN packet at intervals selected randomly from five alternatives (1, 2, 3, 4, and 5 ms). Using the random intervals helps to avoid collisions between multiple transmitted signals. When the device is not transmitting, it waits to receive signals from other devices. In this phase, the state of both devices is “standby.”

In phase (b), the users are touching. However, first, synchronization initially fails because of a collision between transmissions while the transmission path is established. Then, Device A succeeds in transmitting the SYN packet to Device B. Device B immediately responds with an ACK packet.

In phase (c), Device A receives the ACK packet from Device B. First, Device A compares its own a_{avg} to the received a_{avg}. If its own a_{avg} is greater, the state of Device A changes from “standby” to “active.” If not, the state of Device A changes to “passive.” Then, Device A responds to Device B with an MST packet. When Device B receives the MST packet, Device B changes from “standby” to either “passive” or “active” depending on the received DIR byte. In addition, Device B controls the visual and vibrational feedback according to the received STM byte.

In phase (d), the users stop touching. Device A attempts to transmit MST packets several times once it no longer receives the SLV packet. After a certain period of time, the state of Device A changes to “standby” and returns to phase (a). Similarly, after a certain period of time without receiving the MST packet, Device B also changes to “standby” state and returns to phase (a).

We informally confirmed the performance of identification of the direction of a touch. The devices worked as well as our previous work [18], in which the result of a laboratory experiment demonstrated 95% accuracy. This current study, on the other hand, requires the capability of not only real-time identification but also feedback synchronization for representing the direction of a touch with TAM, which is evaluated in Experiment 3 (Section IV-E and IV-F).

IV. Experiments

A. Experiment 1A: Intensity of Vibration Propagated From Wrist to Hand

The purpose of this experiment is to show that the vibration propagated from the bracelet device on a wrist of one person is perceivable by another person.

1) Setup: In this experiment, we used one of the wired prototype bracelets. Six participants (three males and three females, ages 28 to 32) took part in the experiment. Each participant wore a device on the right wrist. Figs. 5a and b show 18 areas and the wrist area during a handshake [57]. Each participant was instructed to sit on a chair and place his forearm comfortably on the armrest with the wrist and hand floating. We measured the vibration propagation using an acceleration sensor. A digital output pin of the microcontroller, which triggered the driver IC, was used to trigger the sensors. The driver unit drove the vibrator for 120-ms.

We used a three-axis acceleration sensor (MMA7361, Freescale Semiconductor) whose outputs were monitored by a voltage input module (NI 9205, National Instruments) with a universal serial bus data acquisition chassis (NI cDAQ-9174, National Instruments) and a computer. The sensor was fixed between the wrist and the housing of the device, or on one of the other 18 areas, with thin double-sided tape with y- and z-axes aligned along the distal direction of the hand and on a normal line to the surface of the skin, respectively. After three acceleration measurements, the sensor was fixed to another area and the measurements were repeated.

2) Results and Discussion: Fig. 6a shows an example of the temporal profiles of the acceleration measured on the wrist of one participant. The response included a transient response of 20-30 ms. The frequency of the vibration, which is a resonant frequency, was 230 Hz. Although the vibrator is uniaxial, (propagates a signal along the z-axis), a negligible but infinite acceleration was observed along the x- and y-axes. This was observed in the other participants as well. Possible reasons for the off-axis components are the low assembly accuracy in

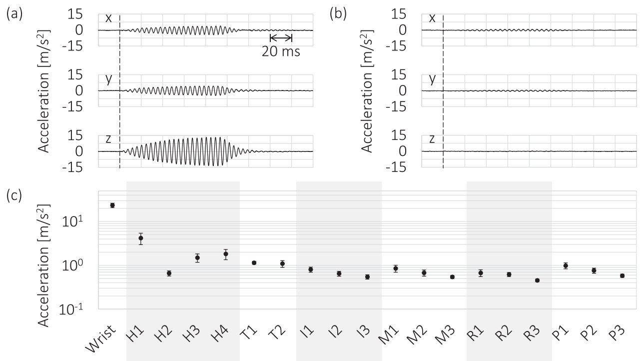

Fig. 6. Measured acceleration. (a) and (b) show examples of temporal profiles of the acceleration on the wrist and T1 of one participant, respectively. Dashed lines indicate the start time of the vibrator driver. (c) Ms and SEs of the maximum RMS for the 19 areas.

manufacturing the actuator, device creation, acceleration sensor installation, or a combination of these.

Fig. 6b shows an example of the temporal profiles of the acceleration on T1 for one participant. As expected, a significantly attenuated vibration was measured on the hand. Interestingly, the greatest amplitude of the acceleration was found on axes other than the z-axis. While a similar tendency was observed in most of the other areas among participants, variations of the dominant axis were observed. In addition to the low assembly accuracy, this may have resulted from hand postures, anisotropy of the complex hand tissue, and differences among propagation characteristics between transverse and longitudinal waves. This is a limitation in the current study because a more careful setup would be required to pinpoint the cause(s).

We computed the averages of the three maximum RMS values of the three-axis acceleration of each area for each participant and used them for further analysis. Fig. 6c shows the means (Ms) and standard errors (SEs) for the 19 areas. On the Wrist, 23.560-m/s^2 average RMS vibration was observed. Compared to the Apple Watch Series 4 from Apple, where we observed 10-30 m/s^2 at the wrist using a similar setup, the developed device provides a similar level of vibration. While significant attenuation was observed along the entire hand, a similar tendency was observed among all participants. On the finger, the greatest amplitude of acceleration was found on the distal phalanx followed by the middle phalanx and proximal phalanx. This could be because a finger behaves like a cantilever beam whose open end has the largest displacement while it is oscillating. Although the amplitude was reduced, the acceleration in all areas is sufficiently above the absolute threshold needed to perceive vibrations [58]. Therefore, while a pair of people holds each other's hand, a vibration produced by a bracelet worn by one person can be perceived by the other.

B. Experiment 1B: Spatiotemporal Propagation From Wrist to Hand

The purpose of this experiment is to visualize the spatial and temporal behavior of the propagation along an entire hand to validate the design principle. In addition, it also demonstrates the possibility of application to different types of touch other than a handshake, such as a fist bump or a high-five.

1) Setup: We recruited one male participant (30 years old). Although it is required to recruit more participants to see variance, we thought that one participant was enough for the purpose because the previous results were similar among all participants. The setup was the same as the previous experiment, except that we used a scanning laser Doppler vibrometer (PSV-500-1D, Polytec) instead of the acceleration sensor to measure the spatiotemporal propagation along the skin. It is noteworthy that the vibrometer only measures one axis, normal to the vibromater. As shown in Fig. 5c, the participant was first asked to fix the device to the palm side up area to measure the propagation along the palm while the vibrometer was installed approximately 50 cm above the hand. As shown in Fig. 5d, we measured the vibration velocity at 163 points. The vibrometer was set to the time domain mode with 3-time averaging, using a 0.002–2000-Hz bandpass filter, and 2500 samples at 5 kSps. Additionally, we measured the vibration velocity at 139 points on the back side of the hand.

2) Results and Discussion: Fig. 7 shows one cycle (approximately 4 ms) of the spatiotemporal propagation with four-frame intervals (800 μs). See the attached videos (Sup. 1a and b) for additional details. Note that the velocity scale was set to be able to observe the low vibration. On both sides of the hand, concentric propagation was not observed. This could be because the hand consists of various tissues with different mechanical impedance, which can distort and reflect vibrations. While large attenuation was observed around the wrist, the vibration propagated along the entire hand. This implies that one person touching another's hand can perceive the vibration for various types of contact other than a handshake.

On the palm side (a), the greatest vibration was found on the lower palm and first propagated to a thenar and hypothenar eminence. Then, it propagated to the upper palm or thumb and to the middle palm and to the fingers. On the back side (b), the greatest vibration was found on the lower back side. It propagated to the middle back side followed by the upper back side and the fingers. As in the previous experiment, a relatively large vibration was observed in each distal phalanx.

There are some limitations with this experiment, which result in artifacts present in the results. Even though we used an armrest, the participant unintentionally moved or rotated the hand and wrist, which may have resulted in one of the largest artifacts. While one solution would be to immobilize the hand and finger, it would change the hand's physical properties, such as mass. This is also a limitation caused by an acceleration sensor that needs to be in contact with the skin. In addition, during a handshake, for example, a muscle will contract, which may also change the hand's properties. Another limitation derives from the device that generates vibrations with a negligible but infinite variance. Because the device can basically have an extreme resonance peak, it is also impossible to study the frequency response characteristics. While the purpose of this experiment was achieved by

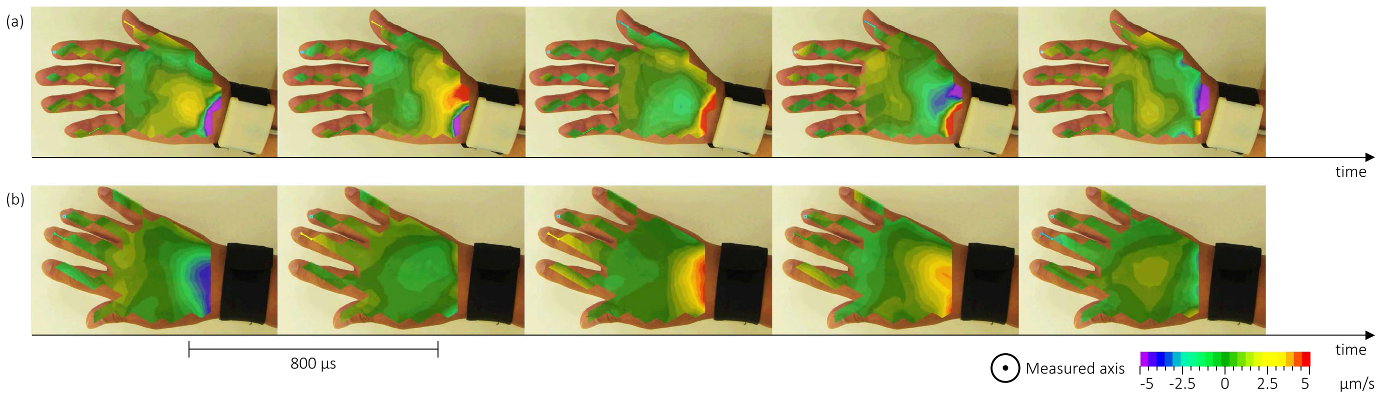

Fig. 7. Four-millisecond measured spatiotemporal propagation of vibration whose frequency and duration are 230 Hz and 120 ms, respectively, on (a) the palm and (b) the back side of a hand. See the attached videos (Sup. 1a and b) for details.

this setup, a more sophisticated setup would be required to observe the full details of vibration propagation from a bracelet device to a hand.

C. Experiment 2A: Optimal Pairs of Duration and SOA

The purpose of this experiment is to find the optimal range of t_{SOA} that induces a TAM between hands holding each other under a constant t_d. Based on the experimental design of previous studies [44], [45], we measure t_{SOA} values that make participants feel: 1) continuous tactile motion; 2) a clear start and end; 3) a single semantic unit that cannot be subdivided; and 4) motion with varying velocity, using a psychophysical approach.

1) Setup: Wired prototype bracelets were used in this experiment.

2) Staircase Method: To measure the range of t_{SOA} under a constant t_d, the t_{SOA} was controlled according to a weighted staircase algorithm [59] which is a modified staircase algorithm and results in a 75% just-noticeable difference (JND). In this experiment, we measured two kinds of JNDs: one is an upper threshold in which observers do not feel a series of two vibrations as discrete stimuli, while the other is a lower threshold in which observers do not feel a series of two vibrations as a single stimulus.

In the measurement of the upper threshold, an observer was asked “do you feel individual discrete vibration?” and answered ‘yes’ or ‘no’ (a two-alternative forced-choice). Each ‘yes’ response caused the t_{SOA} value to decrease by the three-time base step size, while each ‘no’ response caused the t_{SOA} value to increase by the base step size. A ‘yes’ response after a ‘no’ response or a ‘no’ response after a ‘yes’ response is called a reversal, as the increasing or decreasing direction of the staircase is reversed. The step size, initially 32 ms, was halved at each reversal to a minimum step size of 1 ms. This continued until a total of eight reversals occurred. We recorded the t_{SOA} value in the previous trial of the eighth reversal, which resulted in a convergence at 75% JND. A similar protocol was used for the lower threshold measurement with the question “do you feel vibration merged as one?”, with a three-time base size increase in t_{SOA} for a ‘yes’ response, and a base step size decrease in t_{SOA} for a ‘no’ response. The staircase began with 0- and 255-ms t_{SOA} in the lower and upper threshold measurements, respectively. These values were determined based on a preliminary test.

3) Design: In addition to the threshold condition (upper and lower), we set the duration (t_d = 120 or 240 ms) and direction (distal or proximal) conditions. Thus, there were eight conditions in total.

4) Procedure: Five pairs (ten males, ages 22 to 25) of participants took part in the experiment. One participant of each pair became an observer. Before the experiment, an experimenter obtained informed consent after explaining the purpose and procedure of the experiment to each pair of participants. First, a pair sitting on chairs wore the bracelet devices on their right wrists and clasped right hands similar to a handshake. Although grip force and details of posture were not controlled, each pair was asked to clasp hands comfortably. White noise was presented to the observer via earphones to mask audio cues. Then, the computer executed the staircase pattern with one of the eight conditions and displayed the appropriate question on the monitor and the observer chose the response using a keyboard. The observer could experience a series of two vibrations as many times as he wanted by pressing a key to replay the vibrations. After one staircase exercise was completed, the computer executed a new staircase under a different condition. The order of the conditions was randomized and each condition was presented three times. Thus, 24 staircases were executed for each observer. After the 24 staircases, the pair switched roles and the process was repeated. After completing all measurements, each pair answered a questionnaire asking personal information and subjective feelings regarding the TAM.

5) Results and Discussion: We computed the averages of the three converged t_{SOA} of each condition for each observer and used them for further analysis. Fig. 8 shows the Ms and SEs of the measured t_{SOA}. A three-way analysis of variance (ANOVA) was performed on the results and a post-hoc power analysis was performed on significant results. The within-participants factors were Threshold (upper vs lower), Duration (120 ms vs 240 ms),

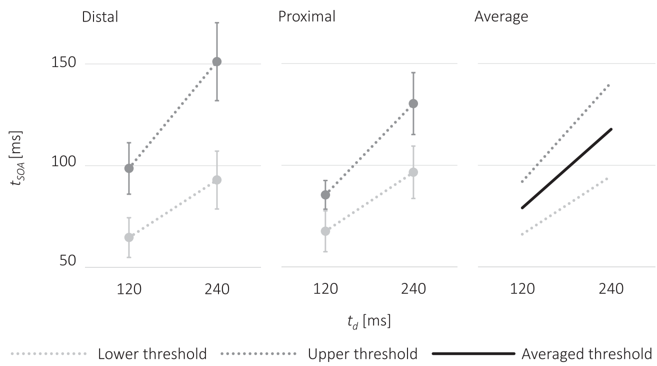

Fig. 8. The data points and error bars show the Ms and SEs of the measured t_{SOA} plotted against the Duration condition in the distal condition (left panel) and the proximal condition (middle panel). The right panel shows lines indicating averaged upper and lower thresholds and a line for near-optimal t_{SOA} for TAM. The light- and dark-gray dotted lines show lower and upper thresholds, respectively. The black solid line shows the line for near-optimal t_{SOA}.

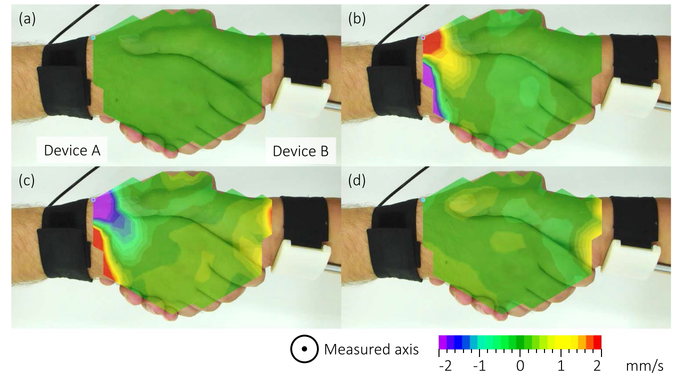

Fig. 9. Measured spatiotemporal propagation of vibration with 180-ms t_d and 98-ms t_{SOA}: (a) the 191 measured points; (b), (c), and (d) are only Device A, both devices, and only Device B vibrating, respectively. See the attached video (Sup. 1c) for details.

and Direction (distal vs proximal). There were no significant interaction effects for Threshold × Duration × Direction ($F(1,9) = 0.184$, $p = 0.678$, $\eta^2_G = 0.001$), Threshold × Duration ($F(1,9) = 3.181$, $p = 0.108$, $\eta^2_G = 0.016$), Threshold × Direction ($F(1,9) = 3.261$, $p = 0.104$, $\eta^2_G = 0.016$), or Duration × Direction ($F(1,9) = 0.147, p = 0.710, \eta^2_G = 0.001$).

There was a significant main effect for Threshold ($F(1,9) = 15.533$, $p = 0.003$, $\eta^2_G = 0.173$, $1 - \beta = 0.841$). This indicates that there is a range of t_{SOA} in which observers felt neither discrete nor merged vibration(s). There was a significant main effect for Duration ($F(1,9) = 87.166, p < 0.001, \eta^2_G = 0.195$, $1 - \beta = 0.828$). This indicates that both the upper and lower thresholds increased as t_d increased. This behavior is similar to previous studies of TAM investigated on another body site [41], [43]–[45]. There was no significant main effect for Direction ($F(1,9) = 1.9326$, $p = 0.198$, $\eta^2_G = 0.008$). This indicates that a consistent direction of the TAM can be perceived between a pair.

We calculated the averages of the upper and lower thresholds on the two Duration conditions. As a result, when t_d is 120 or 240 ms, the average t_{SOA} is 79 or 118 ms, respectively. We obtained a linear relationship between t_d and t_{SOA} as:

$$t_{SOA} = 0.32 t_d + 40.0. \tag{1}$$

This linear equation defines the near-optimal t_{SOA} control to achieve robust apparent tactile motion.

We collected the comments on subjective feelings of the TAM made by the participants of this experiment and from a preliminary test. While the participants were asked if the series of vibrations felt were discrete or merged in the experiment, most reported that they sometimes felt a line or the motion of a vibration between their hands. Interestingly, one participant described "I felt as if my hand merged with the hand of my partner and the vibration went through our arms and hands and felt like a line." This implies that the hand of the partner worked as a medium for perceptually extending and connecting the body of one participant to the body of his partner. We suppose that a handshake provides context and modulates the perception as if the vibration moved between hands and along arms.

D. *Experiment 2B: Spatiotemporal Propagation Between Hands*

The purpose of this experiment is to visualize the spatial and temporal manner of the propagation between hands while a pair of the bracelet devices is inducing a TAM to validate the design principle.

1) Setup: We recruited a pair of male participants (Participant A and B, ages 26 and 30). Although it is required to recruit more pairs to see variance, we thought that one pair was enough for the purpose because the results in Experiment 1A (Section IV-A) were similar among all participants. The setup was the same as in Experiment 1B (Section IV-B), but we used a pair of wired prototype bracelets. As shown in Fig. 9a, the participants were asked to clasp each other's hand like during a handshake with their forearms on armrests while the vibrometer measured the vibration velocity at 191 points. The values t_d and t_{SOA} were 180 and 98 ms, respectively. The value of t_d was intermediate between the values used in the previous experiment and t_{SOA} was determined according to Equation (1).

2) Results and Discussion: Fig. 9 shows the spatiotemporal propagation of the vibration measured by the vibrometer (see the attached video (Sup. 1c) for details). There were four phases: a) no device vibrates; b) only Device A vibrates; c) both devices vibrate; and d) only Device B vibrates, where the participants with the devices felt a TAM between their hands.

In phase (b), a relatively large vibration was observed on the back side of Participant B's hand in contact with the proximal phalanges of Participant A's hand. Contrarily, less vibration was observed in the parts of the palm side of Participant B's hand, i.e., the thenar eminence and lower palm. In phase (d), vibration propagation was observed on the back side of Participant A's hand while Device B was solely vibrating. This might be because the back side of the hand is in contact with the proximal phalanges of a partner's hand, in which a

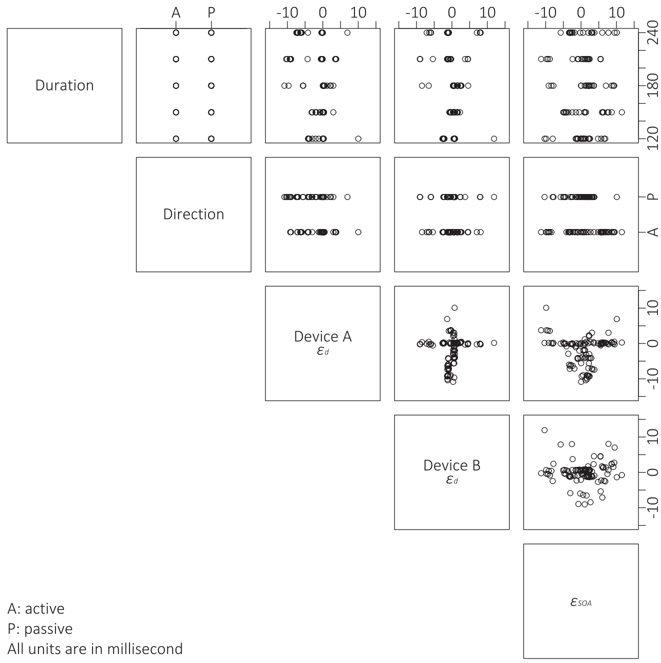

Fig. 10. Scatter plots of two conditions (Duration and Direction) and three errors (ϵ_d of Devices A and B and ϵ_{SOA}).

relatively large vibration was observed in Experiment 1. While a limitation of this experiment is that the hypothenar, middle palm, upper palm, and several fingers are invisible to the vibrometer, the vibration propagation between hands, more specifically, between proximal phalanges and the back side of a hand, was observed. As in the case for Experiment 1B, another limitation is that the vibrometer only measured vibration along the single axis normal to itself, so the major components of measured vibration are transverse waves.

E. Experiment 3A: Evaluation of Developed Device

The purpose of this experiment is to evaluate the capability for temporal synchronization between a pair of ETP devices for presenting TAM.

1) Setup: The evaluation system consisted of a pair of developed ETP devices (Devices A and B), two phototransistors (PT-350, Sharp), a microcontroller (mbed LPC1768, NXP Semiconductors), and a computer. The devices were set to provide both visual and vibrational feedback simultaneously. Phototransistors were fixed on the housing of the devices to sense the visual feedback with black tape covering them to filter environmental light. The microcontroller monitored the phototransistors and measured the t_d and t_{SOA} of the two devices. The measurements were sent to the computer in microsecond intervals.

2) Design: We set the parameter conditions (t_d = 120, 150, 180, 210, 240 ms with t_{SOA} determined according to Equation (1)) and the direction condition (active and passive from the perspective of Device A) to evaluate the performance of the devices. There were ten conditions in total. We computed the error ϵ_d of Devices A and B and error ϵ_{SOA} by subtracting measured values from command values.

3) Procedure: One pair (one male and one female, 31 years old) of participants took part in the experiment. The pair wore the bracelet devices on their right wrist. During the experiment, touch was limited to a handshake. The participant with Device A was asked to actively touch his partner ten times while the participant with Device B was asked not to move his hand. Subsequently, the participant with Device B was asked to perform the same number of touches. This procedure was repeated for all t_d values. Thus, there were 100 touches in total.

4) Results and Discussion: Fig. 10 shows scatter plots of two conditions (Duration and Direction) and three errors (ϵ_d of Devices A and B, and ϵ_{SOA}). The three errors were almost within ± 10 ms, regardless of the value of t_d and direction. Any variance would likely be caused by the communication protocol. As in Section III-B2 and Fig. 4, an MST packet consisting of seven bytes of data plays a key role for synchronization. Because the baud rate was set to 9600, it takes a device approximately 6 ms to send a packet. It also takes the partner device a certain amount of time to receive the packet and refresh the state of the LED and the vibrator. In addition, if the transmission fails, it takes two or more attempts to accomplish the function. Thus, most of the delay is considered to come from the device receiving the MST packet. This is reflected by the cross-shaped points in the scatter plots representing ϵ_d of Device A and the corresponding ϵ_d of Device B. The cross shape indicates that one device precisely provides the commanded t_d with almost 0 ms of ϵ_d while the other does so less precisely.

We computed the Ms and 95% confidence intervals (CIs) of the overall errors obtained in the experiment. The Ms (95% CI) values of ϵ_d and ϵ_{SOA} are -1.031 (± 7.369) and 0.719 (± 9.793) ms, respectively. This indicates that the developed device can accurately control the temporal intervals of the feedback on the order of less than 10 ms. While the precision and accuracy are sufficient for the current study (see the next experiment), it would be possible to improve the temporal resolution by increasing the baud rate and/or optimizing the data package.

F. Experiment 3B: Evaluation of Tactile Apparent Motion Presented by Developed Device

The purpose of this experiment is to demonstrate the capability of a pair of ETP devices for presenting TAM in the direction of a touch. In addition, we study whether the developed device is capable of providing other types of perceptions, which are feelings of a single static stimulus and a series of successive static stimuli, by controlling the vibration timing of the two vibrators.

1) Setup: In addition to a pair of the developed ETP devices, we used three tablet computers: one as a controlling terminal for switching the type of vibration feedback and the other two answering terminals for participants to input an evaluation.

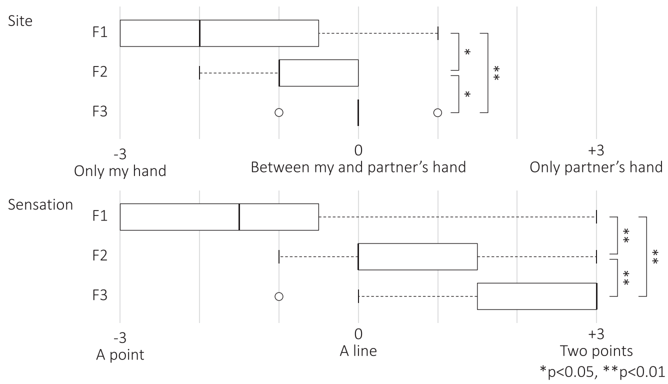

Fig. 11. Boxes, whiskers, and points showing the Meds and IQRs, the 1.5 × IQRs, and the outliers of the site and sensation rating for the three types of vibration feedback.

2) Design: We set three types of vibration feedback (F1, F2, and F3). The values (t_d, t_{SOA}) of F1, F2, and F3 were (180, 49), (180, 98), and (180, 196) ms, respectively. The t_{SOA} value of F2 was the near-optimal value to induce a TAM according to Equation (1). The t_{SOA} values of F1 and F3 are half and double that of F2, respectively, which were set for comparison purposes. While the devices were not in "standby", they provided vibration feedback once per second.

Participants were asked to rate each feedback based on the perceived site and sensation. Asked "where do you feel vibration feedback?", participants rated the site on a 7-point Likert scale: -3 = Only my hand; 0 = Between my and my partner's hands; +3 = Only my partner's hand. Asked "how do you feel vibration feedback?", participants rated the sensation on a 7-point Likert scale: -3 = as a point; 0 = as a line; +3 = as two points. Instead of using the expressions used in the previous experiment (merge, continuous), we employed terms based on the comments made by the participants of Experiment 2A.

3) Procedure: Nine pairs (14 males and 4 females, ages 21 to 32) of participants took part in the experiment. None of these participants took part in the previous experiments. Before the experiment, an experimenter obtained informed consent after explaining the purpose and procedure of the experiment to each pair. Each pair wore the bracelet devices on their right wrist during the experiments, and touch was limited to clasping hands similar to a handshake.

First, a pair experienced visual feedback representing the direction of a touch by repeatedly touching hands. In this phase, vibration feedback was not provided. This phase was continued until the pair understood the concept of the direction of a touch.

Next, the pair was exposed to the three types of vibration feedback (F1, F2, and F3). The feedback type could be switched by pushing buttons on the host terminal. The pair was allowed to switch the feedback and clasp hands as much as they wanted to. The pair rated all feedback types by using the answering terminals. In this phase, visual feedback was not provided. In addition, white noise was not presented in order to allow the pair to discuss how to hold hands. However, they were not allowed to discuss rating of the feedback.

Then, the pair rated the devices on the degree to which the devices accurately measured a direction of touch using a 10-point Likert scale: 0 = 0%; 10 = 100%, by using the answering terminals. Responses were used to check the performance of the devices during the experiment.

4) Results and Discussion: Regarding the accuracy rating, the average accuracy rating of one pair showed a relatively lower accuracy rate of 40%. After the experiment by this pair, the experimenter found that the battery of one device was not fully charged. For the following analysis, we do not consider data obtained from this pair. The median (MED) and interquartile range (IQR) of the accuracy rating are 90% and 10%, respectively. This result is comparable to that of our previous study [18].

Fig. 11 shows the MEDs, the IQRs, 1.5 × IQRs, and outliers of the site and sensation ratings for the three types of vibrotactile feedback. Regarding the site ratings, the MEDs of F1, F2, and F3 were -2, 0, and 0, respectively. Wilcoxon signed-rank tests with Bonferroni correction was performed on the results and a post-hoc power analysis was performed on significant results. There are significant effects when considering F1 vs F2 ($W = 5$, $Z = -2.416$, $p = 0.049$, $r = 0.427$, $1 - \beta = 0.928$), F1 vs F3 ($W = 6$, $Z = -2.946$, $p = 0.007$, $r = 0.521$, $1 - \beta = 0.926$), and F2 vs F3 ($W = 0$, $Z = -2.801$, $p = 0.023$, $r = 0.495$, $1 - \beta = 0.961$). The results imply that it is difficult to feel the vibration propagated from a partner with a small t_{SOA} value because the propagated vibration may be masked by the vibration provided by the other's device. Conversely, the results indicate that participants felt vibration not only on their own hand, but on the hand of the partner when t_{SOA} was large.

Regarding the sensation rating, the MEDs of F1, F2, and F3 were -1.5, 0, and +3, respectively. The same tests as the site rating performed on the results. There are significant effects for F1 vs F2 ($W = 4$, $Z = -3.169$, $p = 0.003$, $r = 0.560$, $1 - \beta = 0.930$), F1 vs F3 ($W = 0$, $Z = -3.300$, $p = 0.001$, $r = 0.583$, $1 - \beta = 0.892$), and F2 vs F3 ($W = 3.5$, $Z = -3.186$, $p = 0.003$, $r = 0.563$, $1 - \beta = 0.934$). The results indicate that the three types of feedback provided different feelings.

As both the site and sensation ratings of F1 were small, participants tended to feel a point of vibration on their own hand. Both of the ratings for F2 were approximately 0, indicating that participants tended to feel a line of vibration between their own and their partner's hand. In contrast to F2, F3 provides a feeling of two points felt in both their own and their partner's hand more clearly.

In summary, the devices are capable of presenting three kinds of feelings by precisely controlling t_{SOA}. While we used a constant t_d, which was 180 ms, the devices are able to provide various velocities of TAMs by controlling t_d. For example, it is possible to design an interaction in which the faster one user moves his hand toward the other's hand, the faster a TAM flows through the hands. Overall, this study demonstrates the potential of our approach to expand the freedom of design for systems involving interpersonal touch interactions.

The current haptic interaction technique has some limitations. Regarding identification of the direction, the devices employ an acceleration-based method and refer to active and passive touch. Although 90% agreement was observed in this experiment, it is unclear whether the degree to which the identification agrees with human subjectivity in an uncontrolled setting would be similar. In addition, it is necessary to consider a neutral touch, in which a pair of people touches each other in a similar manner. Regarding TAM between individuals, a pair must maintain the touch for at least $t_d + t_{SOA}$ to feel the direction. In addition, while the present study employed a handshake-type touch as an example, it is unclear to what extent changing the style of touch affects a user's perception. Also, it would be interesting to evaluate a similar application to other parts of the body.

V. Conclusion

We presented a novel haptic interaction technique for "vibro-tactually" connecting individuals through a human-human physical touch using bracelet-type wearable devices. A pair of these devices (one per user) identifies a hand that actively touches and a hand that is passively touched by exchanging acceleration data via an interpersonal BAN. The pair of devices provides vibration feedback and induces a TAM from the active to the passive wearer. To demonstrate the interaction technique, we conducted three experiments. Experiment 1 demonstrated that the vibration propagated from a bracelet device through the hand is perceivable by the other person. Experiment 2 determined sets of optimal actuation parameters, t_d and t_{SOA}, that induce TAM. Experiment 3 demonstrated that a pair of the developed ETP devices can represent the direction of a touch through TAM, thus vibrotactually connecting a pair of users.

We foresee three directions for our future research. One direction is to explore the different models for TAM through human-human physical touch. The experiments in this paper limited the number of variables to demonstrate the concept of TAM. We need to consider more variables for the hand of an observer, such as posture, as well as for vibration, such as frequency and amplitude. In addition, we plan to study the directional characteristics of vibration propagation, which should make vibration feedback more effective and efficient. Another direction is to consider other sensory illusions such as the phantom sensation and cutaneous rabbit illusion. This is expected to enrich the freedom of design to further augment interpersonal touch interactions. The third direction is to use the ETP device to evaluate whether the present haptic interaction technique can affect human behaviors.

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Taku Hachisu received the Ph.D. degree in engineering from the University of Electro-Communications, Chofu, Japan, in 2015. He is a Researcher with the University of Tsukuba, Tsukuba, Japan. His research interests include augmented/virtual reality, haptics, human–computer interaction, and wearable devices.

Kenji Suzuki (M'03) received the Ph.D. degree in pure and applied physics from Waseda University, Tokyo, Japan, in 2003. He is currently a Professor with the Faculty of Engineering, Information and Systems, and also the Principal Investigator with the Artificial Intelligence Laboratory, University of Tsukuba, Tsukuba, Japan. Prior to joining the University of Tsukuba in 2005, he was a Research Associate with the Department of Applied Physics, Waseda University. He was also a Visiting Researcher with the Laboratory of Physiology of Perception and Action, College de France, Paris, France, in 2009, and with the Laboratory of Musical Information, University of Genoa, Genoa, Italy, in 1997. His research interests include artificial intelligence, cybernetics, assistive and rehabilitation robotics, computational behavior science, and affective computing.