Interpersonal Vibrotactile Feedback via Waves Transmitted through the Skin: Mechanics and Perception

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***Abstract*— Interpersonal touch is critical for health, development, and social relationships. An emerging opportunity in haptics is to design methods for augmenting interpersonal touch. Recently, we presented an actuated smart bracelet for transmitting vibrations through the hand of one person, as feedback to the hand of a second person, during a social interaction such as a handshake. Here, we present an investigation of human factors of vibrotactile feedback provided between people. In two experiments, we studied mechanical transmission of vibrations through a first person (the transmitter) and the perception of these vibrations by a second person (the receiver) who is touching the transmitter's hand. We found that a receiver could readily perceive vibrotactile feedback when touching different locations on the transmitter's hand. The magnitude of the transmitter's skin acceleration was highly correlated with intensity the receiver perceived (Pearson's R = 0.737). We found both perception and mechanics to depend on the driving signal characteristics and the direction in which the transmitter's skin was actuated (at the wrist) to produce the vibrations. Low-frequency vibrations (50 and 100 Hz) were more readily perceived than higher frequencies (200 Hz). Vibrations produced by normal-direction actuation elicited perceptual responses that were less variable than those produced by tangential actuation. In addition, vibrations produced by tangential actuation at the wrist were felt to be very strong when a receiver touches the palm or base of the transmitter's hand, but were felt to be weaker near the transmitter's fingers. This study elucidates human factors for vibrotactile feedback between two people, and holds implications for the design of haptic technologies for the augmentation of interpersonal touch.**

I. INTRODUCTION

Interpersonal touch interactions can be important indices of soundness of body and mind. In early development, touch, especially between a child and a parent, is essential for healthy growth [1], [2], [3]. Physiological studies have also revealed positive effects in reducing blood pressure and heart rate [4], [5], [6]. Touch can also encourage people to comply with requests [7], [8], [9], can be used to signal emotional state [10], [11], [12], and can create bonds [13], among many other important social functions. Thus, interpersonal touch holds considerable potential for haptic design.

Touch varies systematically between individuals from different nations. For example, in northeast Asian countries, such as China, Japan, and Korea, levels of tactile interaction between people are relatively low [14]. This suggests that there may be opportunities for designing interactions to facilitate positive effects of interpersonal touch for populations that may not experience as many benefits as others do, due to social circumstances or health effects (as noted below). Because the awareness of touch (whether a person notices or remembers being touched) plays an important role in many effects, such as compliance [8], [9], one way to facilitate beneficial effects of interpersonal touch may be to enhance awareness of it, such as by haptically augmenting touch interactions.

Motivated by these considerations, we are interested in designing new haptic methods for augmenting interpersonal touch interactions in daily life. We previously developed a haptic smart bracelet capable of sensing hand-to-hand physical contacts and of providing real-time sensory feedback (Fig. 1A) [15], [16]. The visual feedback was designed to enhance awareness of touch in a manner in which at least two people would need to engage in order to experience the augmented interaction. We demonstrated that the even simple visual feedback was able to facilitate increased social interactions among children with autism during recreation time [15]. We also showed that the devices held potential for use as interfaces for social augmented reality games in which players must touch each other to achieve a goal [16].

We next expanded the design space for these devices by endowing them with the ability to provide vibrotactile feedback during interpersonal touch, based on a tactile apparent motion effect provided between people [17]. The technique we used employs the hands as a medium for transmitting vibrations to the touched hand of another person (Fig. 1B). This technique enables the haptic actuator to be located at the wrist, where it does not interfere with the skin to skin contact between people. This also makes the device compatible with activities in daily life.

Despite these promising results, there has been little human factors research that might guide the design of such systems for haptically augmenting interpersonal touch. To address this, this paper presents two experiments in which we studied mechanical transmission of vibrations via the hand of a first person (transmitter) and the perception of these vibrations by a second person (receiver) who is touching the transmitter's hand (Fig. 1B). To clarify human factors affecting the usability of wrist-worn haptic devices, we investigated how the mechanical transmission and perception were affected by the direction in which the wrist is actuated in order to produce the vibrations (normal or tangential to the wrist skin), the frequency of vibration (50, 100, and 200 Hz), and the distance from the wrist to the location at which the vibrations are felt by the receiver. This study sheds light on the haptic engineering for augmenting social interactions performed by people who have physical contact with each other.

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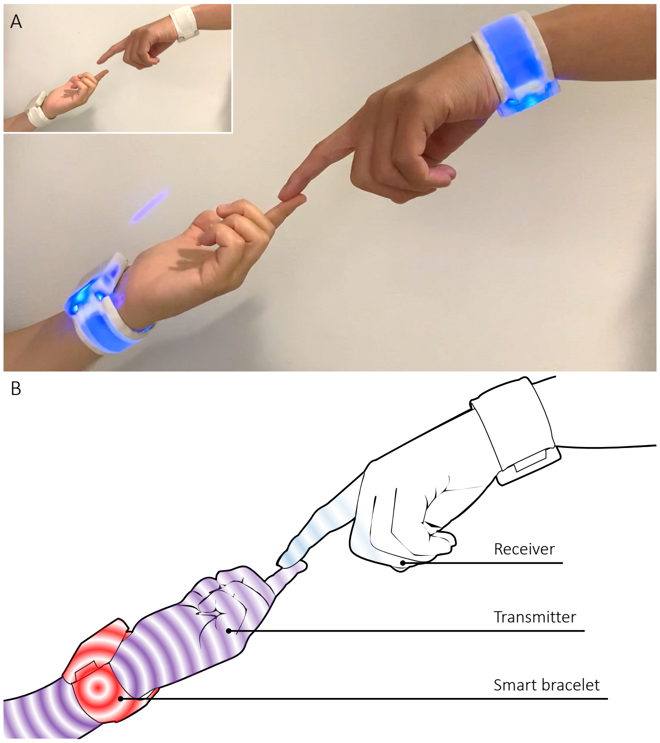

Fig. 1. Augmentation of interpersonal touch interaction with the smart bracelets [16]: (A) Sensing hand-to-hand physical contacts and providing real-time visual and vibrotactile feedback; (B) Waves are transmitted through the skin of one user (the transmitter) to another (the receiver) providing interpersonal vibrotactile feedback.

A. Related Work

Understanding vibration transmission in the body has attracted attention in many fields, including occupational health [18], [19], [20], perception [21], [22], [23], [24], and human-computer interaction [25], [26]. Because the skin is viscoelastic, energy applied to the skin is not only absorbed, but is also transmitted to large distances through soft tissues, including the skin [27], [28], [29], with frequency dependent damping [30]. This propagation also depends on the mechanical properties of the skin, including the site and manner of stimulation [31]. Thus, the stimulation frequency, the direction of stimulation, and contact conditions of a vibration source with the skin and the contactor influence how vibrations are transmitted [32]. These complex continuum mechanical processes make it very challenging to develop a universal model of vibration transmission in the skin.

Many researchers have investigated relations between the mechanical propagation and vibrotactile perception, including studies by von Békésy, who investigated similarities between mechanical signals underlying tactile sensations in the skin and auditory sensations in the ear [28]. However, there have been few perceptual studies on interpersonal vibrotactile transmission, including vibrotactile perception of a receiver touching the skin of a transmitter, as we investigate here. Numerous studies have been used to assess vibrotactile perception, including psychophysical studies of the effects of displacement, frequency, body location, or other factors on subjective perceptual intensity. For example, Verrillo measured the perceptual magnitude of suprathreshold vibrations on the thenar eminence using the method of magnitude estimation, with displacement as the independent factor [33]. Miyaoka reported differences in vibrotactile sensitivity with the directions of applied vibration, that is, normal and tangential directions applied to the skin [34]. While these and other results on vibrotactile perception are relevant to the present work, an important difference here is that the stimulus is felt via the skin of the transmitter, rather than by a rigid contact. This setting involves a closer match between the impedance of the surfaces at the contact, and can be expected to alter perception. For example, from mechanics, the nearly matched impedance between the hands is expected to yield more efficient transmission of vibrations to the skin of the receiver. The viscous nature of the transmitter's skin at the contact will also effect the felt stimulus. When the contact location changes, the position-dependent transmission of vibrations within the transmitter's hand can be expected to play an important role. For example, it has been observed that frequency-dependent damping can cause large distance-dependent effects [30]. Together, these make it challenging to anticipate how vibrations applied in the setting of our study will be perceived as a function of the location in which they are felt.

Vibrations propagate in body tissues as mechanical waves that possess not only magnitude but also directionality – that is, they are vectorial waves. Thus, to characterize the vibration that is elicited at remote areas of the skin (the transmitter's hand, in our study), it is important to measure vibrations along three axes at each location of interest. Today, small, lightweight MEMS acceleration sensors with large frequency bandwidth are commercially available and well suited to such measurements [24], [35], [36].

B. Contributions

This paper contributes human factors knowledge for the design of vibrotactile feedback augmenting interpersonal interactions. For the reasons mentioned above, it is challenging to predict the mechanical transmission attributes and perceptual attributes from first principles or prior studies. Nonetheless, it is reasonable to assume that the receiver's perceptual magnitude will be positively correlated with the amplitude of vibrations (such as, acceleration magnitude) at a location touched on the transmitter's skin. The contributions of this study include: 1) measurements and analysis of mechanical transmission from the wrist functions of the actuation direction, signal frequency, and location in the hand; 2) measurements and analysis of the psychophysics of vibration feedback felt during interpersonal touch; and 3) analyses of the relation between mechanical signals and the perceived magnitude of the vibrations.

II. METHODS

In two experiments, we measured both mechanical signals in the hand of one person (the transmitter) and the perception

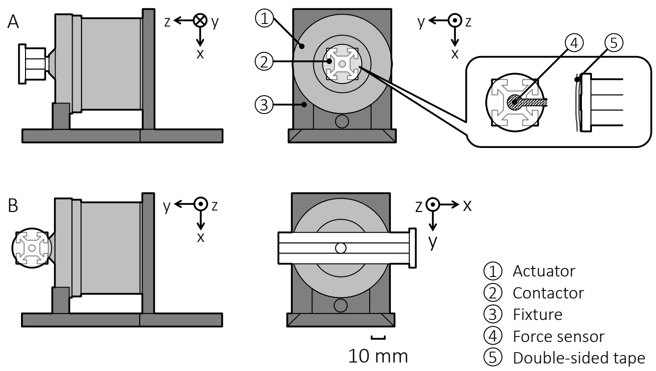

Fig. 2. Vibrator unit consisting of a contactor, an electrodynamic actuator, and a fixture. There were two types of contactors for generating vibration in (A) the normal and (B) the tangential direction to the skin

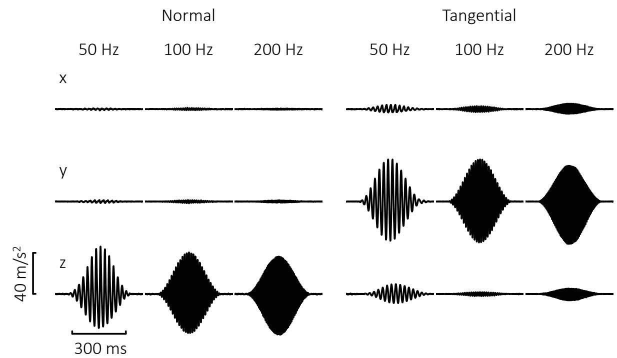

Fig. 3. Empirically measured six vibrations, with 300-ms Hanning window, were used in the experiments: two actuating directions (normal and tangential) × three frequencies (50, 100, and 200 Hz).

of the same signals by a second person (the receiver) while vibrations applied at the transmitter's palmar wrist.

A. Participants

Twelve participants (6 males and 6 females, mean (standard deviation, SD) age was 27.3 (2.7) years old; mean (SD) hand length was 18.0 (1.4) cm) participated in the experiment and gave their written, informed consent. The experiment protocol was approved by the University of California, Santa Barbara Human Subjects Committee (Protocol Number: 9-19-0680). All participants played the role of the receiver while a male experimenter (32 years old; hand length was 19.2 cm) played the role of a transmitter (Fig. 4B). No participants reported impaired tactile sensation of their hands.

B. Apparatus

The system consisted of a computer, a microcontroller, and a vibrator unit. The microcontroller (mbed LPC1768, NXP Semiconductors) generated a signal via an amplifier (PA-138, Labworks) for the vibrator unit consisting of a contactor, an electrodynamic actuator (Type 4810, Brüel & Kjaer), and a fixture, controlled by the computer. There were two types of contactors: one generated vibration in a normal direction to the wrist of the experimenter (Fig. 2A) while the other generated vibration in a tangential (proximal-distal axis) direction (Fig. 2B). We refer to the y- and z-axes as the tangential and normal directions of the palmar surface of the left wrist, respectively (see Fig. 4A). Both contactors were fixed to the actuator through a rigid aluminum frame. Both the contactors were in contact with the wrist skin via double sided tape and a 3-cm diameter acrylic disk on which a film-type force sensor (S8-10N, Pressure Profile Systems) was fixed. The sensor value was read by the microcontroller, which represented the value through four light emitting diodes (LEDs).

Six sinusoidal vibrations (two directions × three frequencies) were used in the experiments (Fig. 3). A 300-ms Hanning window enveloped the signals. The frequencies were set to 50, 100, and 200 Hz, because these matched typical frequencies for commercially available linear resonant actuators, like that used in our smart bracelet device.

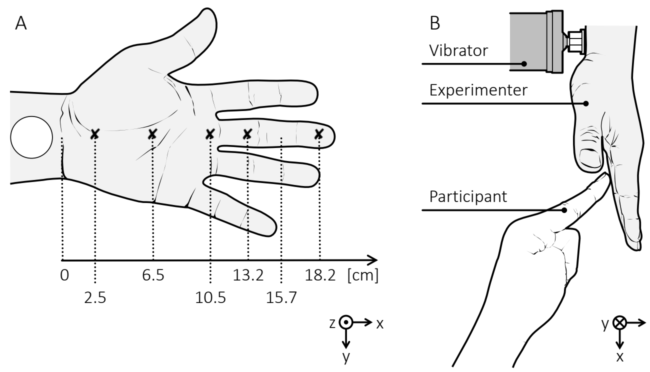

Fig. 4. Configuration of the vibrator unit and the hands of the experimenter and the participant: (A) The hand of the experimenter whose palmar wrist was in contact with the contactor. The six positions on which the acceleration sensors were attached and the five positions (cross marks) which participants touched; (B) The participant touched the hand of the experimenter with the left index finger pad while vibration was presented in the perceptual test.

These settings also allowed us to avoid exciting any large resonant frequencies of the combined system that might alter the results. The nominal amplitude of each vibration was such that a 40 m/s^2 acceleration of the contactor resulted when it was not loaded by the skin.

The experimenter placed his left palmar wrist on the contactor (Fig. 4A) and maintained a contact force of 1 to 2 N by using feedback from the LEDs in both the experiments. This force was selected as representative of on a typical contact force between wrists and smart watches.

C. Mechanical Measurement

We measured the skin acceleration (vibration) at locations on the hand that resulted from applying vibrations at the experimenter's wrist. We used a sensor array developed in our previous work [36] to simultaneously record at multiple locations. It is comprised of six three-axis digital acceleration sensors (LIS3DSH, ST Microelectronics) that connected with each other with a light and flexible print circuit board made of Kapton. Sensors were attached to the six points of the hand of the experimenter via double sided tape (Fig. 4A). Sensor values were acquired by a field-programmable gate array (XC7A75T, Artix-7 series, Xilinx). The sampling rate was 1.3 kHz. In total, there were 36 conditions (2 directions $\times$ 3 frequencies $\times$ 6 positions).

The three vibrations were presented followed by pauses of 200-ms duration to ensure the skin vibrations completely decayed before each subsequent measurement. Each measurement was repeated ten times for each direction condition. Thus, ten sets of time-varying three-axis acceleration values were obtained for each condition.

D. Perceptual Experiment

The experiment was based on the method of magnitude estimation. In each trial, participants rated magnitude of the intensity of the stimulus. Participants used their left index finger pad to touch one of five cross marks on the experimenter's hand (Fig. 4) while maintaining 1 to 2 N contact force. One position (15.7 cm) was omitted to reduce the time of the experiment. The participant's right hand was used to interact with the computer using a mouse. The computer provided instructions for the touching position, and allowed participants to play the vibration, rate its perceptual magnitude, and enter the rating. One of the six vibration was played (Fig. 3) 500 milliseconds after the user pressed "play". The rating was entered using a scale bar (resolution: 1024 steps) whose left and right ends were labelled "No Vibration" and "Strongest Imaginable", respectively. The rating was entered by clicking another button. The scale bar was activated after the vibration was played at least one time. The rating could be entered after the scale bar control was moved at least one step. The vibrator unit and the mouse were on the different tables so that no vibrations were transmitted via the table. In total, there were 30 conditions (2 directions $\times$ 3 frequencies $\times$ 5 positions). The stimuli were assumed to minimize the possibility of sensory adaptation, because their duration was short (300 ms), their magnitude was small, and the inter-stimulus interval (during response collection) was several seconds.

The experimenter explained the procedure and obtained informed consent from the participants. Participants were trained to apply an appropriate amount of force (1 - 2 N) to the experimenter's hand using the force sensor and the LED indicator. Because the participants directly touched the experimenter's hand, we could not measure the force and provide sensor feedback during the experiment.

Participants completed one block of practice trials (15 conditions under one direction condition) to get familiar with the GUI and the range of the stimuli. The experimenter instructed participants to avoid touching the table on which the vibrator unit was installed. Participants were told to rate the intensity of vibration they felt on each trial. They were told to avoid rating the initial stimulus too low. They were told that if a stimulus felt twice as intense as another stimulus, they should give it a rating twice as high.

The experimental design was a within-participants randomized block design, in which each participant completed 10 blocks of each direction condition with a 5-minute break in between. The orders of the direction condition were counter-balanced between the participants. Participants wore earplugs and headphones to mask any mechanical sounds generated by the vibrator unit. The participants were able to play each vibration as many times as necessary. After the trials were completed, participants completed a short survey recording their gender, age, and hand length. The total duration was around one hour.

E. Analysis

The time-varying vector (three-axis) acceleration had a duration of 300-ms vibration. After DC (gravity) subtraction this yielded three components, $a_x(i), a_y(i), a_z(i)$, where i is a sample index. We measured the acceleration root mean square (RMS) magnitude for the overall acceleration S_O, normal direction acceleration S_N, and tangential direction acceleration S_T, as follows:

$$S_O = \sqrt{\frac{1}{n}\sum_{i=1}^{n} a_x(i)^2 + a_y(i)^2 + a_z(i)^2}, \quad (1)$$

$$S_N = \sqrt{\frac{1}{n}\sum_{i=1}^{n} a_z(i)^2}, \quad (2)$$

$$S_T = \sqrt{\frac{1}{n}\sum_{i=1}^{n} a_x(i)^2 + a_y(i)^2}. \quad (3)$$

where, n is the number of samples (n=518) for each vibration. The values were averaged over ten trials. This was repeated for each distance, vibration frequency, and actuation direction.

The perceptual ratings were transformed into z-score for each participant, and a mean z-scores, p, for perceptual magnitude were computed for each condition. The means of p for all the participants were plotted as functions of position for each frequency condition and each direction condition. A mixed analysis of variance (ANOVA) was used to evaluate the significance of differences between conditions. The within-participants factors were Direction, Frequency, and Position while the between-participants factor was Order of Actuation (normal or tangential actuation first).

To analyze the relation between the RMS acceleration S and the perceptual magnitude p the Pearson correlation coefficients R were computed between one of the three RMS accelerations (logarithm of mean S_O, S_N, and S_T excluding the data with the 15.7-cm point) and one of the three perceptual magnitudes (mean p of all the direction conditions p_O, only normal-direction actuation condition p_N, and only tangential-direction actuation condition p_T; $p_O = p_N \bigcup p_T$) for each participant. Thus, nine coefficients were obtained. For each perceptual magnitude, the statistical significance of differences between the coefficients under the different RMS accelerations was evaluated by Wilcoxon signed-rank tests with Bonferroni correction. In addition, a pair of the RMS values (mean S_O, S_N, and S_T) and the perceptual magnitudes (i.e., mean p_N and p_T) was plotted.

The probability criterion for significance was set to $\alpha = 0.05$. Where significance was found, the effect size, η_G^2 for

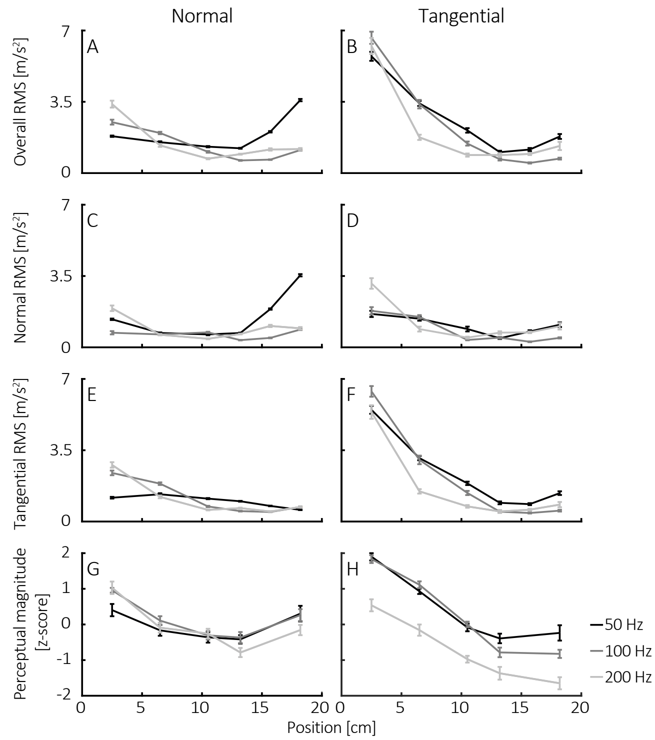

Fig. 5. The RMS acceleration and the perceptual magnitude of vibrations transmitted from the experimenter's wrist to hand: The horizontal axis shows position on the experimenter's hand while the vertical axis corresponds to (A and B) the mean overall RMS values, S_O, (C and D) the mean normal RMS values, S_N, (E and F) the mean tangential RMS acceleration, S_T, or (G and H) the mean perceptual magnitudes (z-scores). The small vertical bar indicates one standard error. The left and right panels show the normal and tangential actuation, respectively.

the ANOVA and r value for the Wilcoxon signed-rank test, was computed.

III. RESULTS

The results of the mechanical measurement revealed different characteristics between RMS accelerations that depended on the actuation direction of vibration application. At the 2.5-cm point, the normal actuation elicited skin vibrations with smaller RMS acceleration, S_O, than that elicited by vibration applied in the tangential actuation (Fig. 5A and B). The vibration generated by the normal actuation gradually attenuating on the palm ($\leq$10.5 cm) and increasing on the finger ($\geq$13.2 cm). In particular, the vibration with 50 Hz generated the largest intensity at the finger pad (18.2 cm), which seems to derive from the normal RMS acceleration, S_N (Fig. 5C). The vibration generated by the tangential actuation rapidly attenuated on the palm and slightly increasing on the finger at 50 and 100 Hz. These characteristics seem to derive from the tangential RMS acceleration, S_T (Fig. 5F).

The results of the perceptual test indicate that there was no significant main effect or interaction effect involving Order of Actuation. Significant interaction effects were found for Direction $\times$ Frequency $\times$ Position ($\eta_G^2 = 0.064$), Direction $\times$ Frequency ($\eta_G^2 = 0.219$), Direction $\times$ Position ($\eta_G^2 = 0.347$), and Frequency $\times$ Position ($\eta_G^2 = 0.056$). Also,

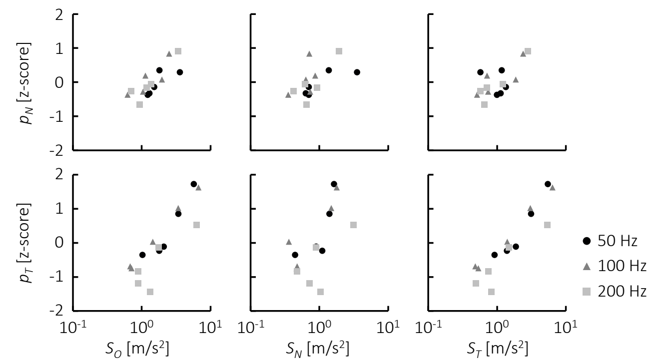

Fig. 6. Relation between the RMS accelerations (mean S_O, S_T, and S_N) and the perceptual magnitudes for each direction condition (mean p_N and p_T)

a significant main effect was found for Frequency ($\eta_G^2 = 0.262$) and Position ($\eta_G^2 = 0.678$), while none was found for Direction.

At the 2.5-cm position, the vibration with normal actuation and high frequency (200 Hz) were felt as stronger (Fig. 5G). The perceptual magnitude, p, then decreased monotonically on the palm ($\leq$10.5 cm). At locations $\geq$13.2 cm in the transmitter's finger, the vibrations with lowest frequencies (50 and 100 Hz) were felt to be stronger. At the 18.2 cm, corresponding to the transmitter's finger pad, the magnitude was higher for all frequencies.

The vibration with tangential actuation and highest frequency (200 Hz) was felt weaker throughout the hand than those with lower frequencies (50 and 100 Hz) (Fig. 5H). At the 2.5-cm position, the larger perceptual magnitudes was induced by the tangential actuation with lower frequency (50 and 100 Hz). Perceptual magnitude decreased monotonically with distance from the source to locations on the palm, while the slope of variation became more gradual in 100 and 200 Hz, changed sign, becoming positive, for the lowest frequency 50 Hz.

Figure 6 reports the mean RMS accelerations (S_O, S_T, and S_N) and the mean perceptual magnitude (p_N and p_T). Table I reports the medians and interquartile ranges of the Pearson's correlation coefficients for all the participants. The following relations were significant: $R(\log S_O, p_O) > R(\log S_N, p_O)$ ($r = 1.221$) and $R(\log S_T, p_O) > R(\log S_N, p_O)$ ($r = 0.759$) in all the actuation conditions, for $R(\log S_O, p_N) > R(\log S_N, p_N)$ ($r = 0.838$) in the only normal-direction actuation condition, and for $R(\log S_O, p_T) > R(\log S_N, p_T)$ ($r = 0.883$) , $R(\log S_T, p_T) > R(\log S_O, p_T)$ ($r = 0.883$), and $R(\log S_T, p_T) > R(\log S_N, p_T)$ ($r = 0.883$) in the only tangential-condition actuation.

IV. DISCUSSION

The analysis of correlation coefficients indicates that the overall RMS acceleration, S_O, provided a good predictor for the perceptual intensity (Table I), as expected. The tangential RMS acceleration , S_T, was also a good predictor not only for the perceptual magnitude for the tangential-direction actuation p_T but also for the overall perceptual magnitude, p_O.

TABLE I
CORRELATION COEFFICIENTS, R, BETWEEN THE MECHANICAL AND PERCEPTUAL INTENSITIES.

	$\log S_O$	$\log S_N$	$\log S_T$
p_O	0.737 (0.178)	0.542 (0.213)	0.787 (0.396)
p_N	0.651 (0.264)	0.453 (0.291)	0.471 (0.210)
p_T	0.828 (0.100)	0.588 (0.134)	0.859 (0.087)

Conversely, the coefficients relating the perceptual magnitude with the normal RMS acceleration, S_N, were significantly smaller than for S_O even when the direction of the actuation was the same as that of the acceleration measurement. These complex relations can be attributed to mode conversion in the complex propagation medium of the hand. They indicate that, in the conditions of this experiment, the tangential RMS acceleration could provide more predictive value for the perception of vibration, although further investigation is required.

Vibrations with lower frequency induced stronger percepts at almost all positions (Fig. 5G and H). This suggests a trade-off involving the choice of actuation direction. Normal actuation provides less variable (flatter) perceptual magnitudes across these hand locations, but induce weaker percepts when felt at the bottom of the transmitter's palm. Conversely, the tangential actuation induced strong perception at the bottom of the palm, but these percepts decreased faster approaching distal positions in the transmitter's hand.

The mechanical measurement revealed two interesting characteristics of propagation. One is that most of the vibration attenuates on the palm while increases on the finger. This tendency is especially noticeable in 50-Hz vibration applied in the normal actuation. The similar tendency was also observed in [30], in which 40-Hz vibration was applied on the fingertip while its maximum amplitude was found near the base of the finger. While we are not sure of the mechanism, it might be attributed to the behavior of cantilever beam whose open end has the largest acceleration while vibrating.

Despite the interesting findings of this study, the results suggest several opportunities for further research. First, further research is needed in order to understand how the perception of vibrotactile feedback in interpersonal touch might vary with contact conditions at the actuator and at the location of receiver-transmitter contact. While we carefully controlled for normal forces at the actuator, the extent of loading could affect the mechanical transmission. In addition, while the actuator dynamics were well controlled, further research would be needed in order to account for non-ideal actuator characteristics, which may facilitate translating these results to other display devices. It would be particularly interesting to further investigate how the results might vary with hand characteristics and, equally importantly, kinematic pose and state of the hand [32], [37]. For instance, the wrist greatly modulates stiffness and geometry of hand tissues. It would be interesting to understand how this affects mechanical transmission. Such knowledge could elucidate the robustness of these results when applied in everyday conditions. The conditions of contact between the experimenter and the participants were controlled as well as possible without introducing any instrument between the hands (which would have impacted the results). This points to a general challenge in interpersonal haptics, which is to accurately capture contact conditions. Finally, the conditions of this experiment involved only one type of skin-skin contact (touching the hand with a fingertip). It would be interesting and valuable to obtain analogous results for different modes of skin-skin contact with the hands, or with other parts of the body that are commonly involved in social touch.

V. CONCLUSIONS

The goal of this research is to elucidate human factors informing the design of haptic interfaces for augmenting interpersonal touch interactions. To this end, in two experiments, we studied the mechanics and perception of interpersonal vibrotactile transmission in a setting in which vibrations were transmitted from the wrist of one person, through their body, to the skin of another person touching the transmitter's hand. We varied the actuation direction at the transmitter's wrist, vibration frequency, and location of touch contact during the experiment. The results show that the mechanical acceleration was highly correlated with the perceived magnitude of the vibrations (Pearson's R= 0.737), and that the direction of actuation and signal characteristics could all influence transmission and perception. These findings suggest several guidelines for the use of vibrotactile feedback in interpersonal touch. First, low frequency vibrations (50 and 100 Hz) are more readily perceived than high frequency vibrations (200 Hz). Second, vibrations produced by normal-direction actuation elicited perceptual responses that were less variable than those produced by tangential actuation, yielding a "flatter" response amplitude with distance from the source. Third, tangential actuation at the wrist yields especially large perceptual responses at the base of the palm (an area of the hand that is commonly involved in handshakes, for example), but smaller vibrations near the fingertips.

We envisage several promising areas for future work. As discussed above, it would be valuable to extend these results on haptic augmentation of interpersonal touch to a wider repertoire of interpersonal touch conditions, body parts, device configurations, touched locations, and individuals. We also look forward to applying the knowledge developed in this study in order to design wearable devices, including smart bracelets extending our prior work, for haptically augmenting interpersonal touch interactions.

ACKNOWLEDGMENTS

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