Effect of vibration frequency mismatch on apparent tactile motion*

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***Abstract*— Most studies of haptic illusions assume that the actuators used are identical and therefore produce vibrations with the same frequency. We ran two experiments to investigate the effect of mismatched vibratory frequencies on the perception of apparent tactile motion. We simulated having actuators with different properties by changing the frequency and amplitude of vibrations produced by a wideband actuator. We varied frequencies from 50 to 250 Hz with adjusted amplitudes to normalize the perceived intensity. The results suggest that the apparent tactile motion illusion is robust to mismatches in the resonant frequency of actuators and that it can therefore be produced by pairs of haptic devices with different specifications.**

I. INTRODUCTION

It is increasingly common to simultaneously wear and interact with multiple haptic devices in our daily life. We may, for example, have a phone in our pocket, a watch on our wrist, and a game controller in our hands, all with advanced haptic capabilities. A coordinated use of these haptic devices could produce valuable user experiences and improve our interactions with technology (e.g., [1], [2], [3], [4]). A sequence of vibrations from a smartwatch to a handheld controller (Figure 1a) or from a smartphone to a smartwatch (Figure 1b) could, for example, create an impression of flow or other haptic effects in a game.

Such combined use of haptic devices can leverage known perceptual illusions to create more complex tactile effects. By carefully controlling the timing and amplitude of a sequence of vibrations at two locations on the body [5], it is for example possible to give the impression of a vibration that occurs between the two actuators (phantom tactile sensation [6]) or the illusion of a flow from one actuator to the other (apparent tactile motion [7], [8]). However, most prior work assumes that both actuators are identical, which may not be the case in practical situations where the haptic devices used are manufactured independently, with varying specifications.

In this work, we investigate whether the illusion of apparent tactile motion can be produced by actuators with mismatched resonant frequencies, and how much impact this mismatch has on the quality of the illusion. We hypothesized that detecting the direction of apparent tactile motion would become increasingly difficult as the mismatch in frequency of the vibration pulses increases.

We ran two experiments to verify this hypothesis. The illusion was produced between two commonly-used stimulation locations, the forearm and the wrist. We simulated having actuators with different resonant frequencies by changing the frequency and amplitude of vibrations produced by wideband actuators. More precisely, we normalized the perceived intensity of the vibration pulses, and varied their frequency between 50 and 250 Hz. Our results suggest that a difference in frequency of the two vibration pulses does not affect the perception of apparent tactile motion, and therefore that the illusion appears to be robust to mismatches in actuator resonant frequencies.

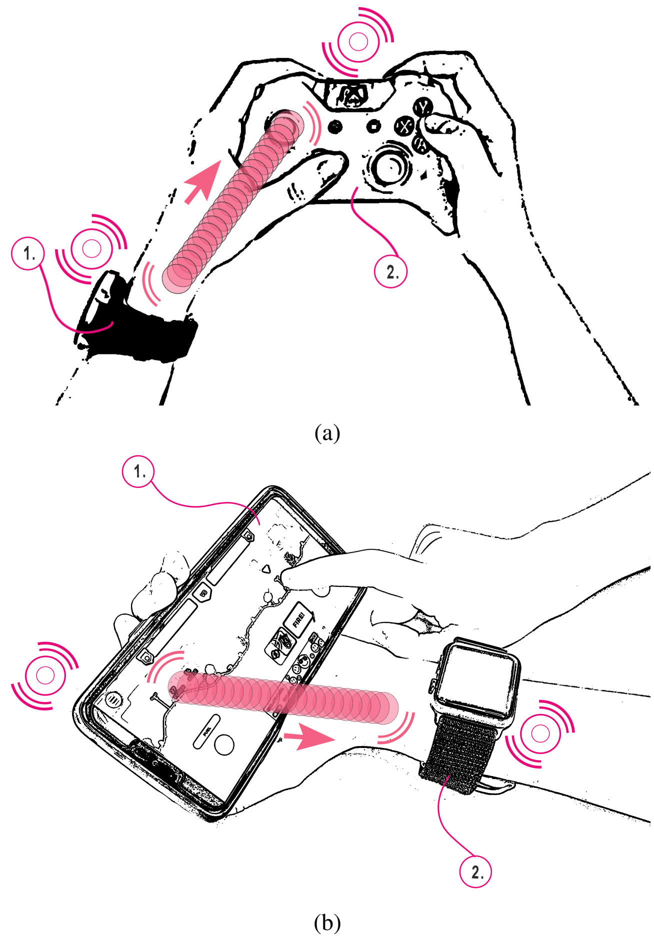

Fig. 1: Conceptual examples of applications of apparent tactile motion between off-the-shelf devices: a smartwatch and (a) a handheld controller or (b) a mobile phone.

II. RELATED WORK

Apparent tactile motion creates the illusion of a continuously moving vibration as two actuators at different body

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sites produce temporally overlapping vibration pulses [7], [8]. The illusion is created by carefully controlling parameters such as the timing and duration of the vibration pulses, without which a single stationary vibration or two discrete, stationary vibrations may be felt. The effect on apparent tactile motion of various parameters (e.g., timing, frequency, amplitude, body sites, and actuator characteristics) has been studied extensively in the literature.

The duration of the vibration pulses (stimulus duration; SD) and the time between the start of one pulse and the start of the next (stimulus onset asynchrony; SOA) are known to be critical to produce apparent tactile motion [9], [10], and their effect has been studied extensively (e.g., [11], [7], [12], [13], [14], [5]). [15], for example, has found that the quality of apparent tactile motion depends on the timing parameters. Others have found that the optimal SOA varies with SD [5], [8], and have proposed a formula to optimize the timing parameters: $SOA = 0.32 \times SD + 47.3$. Kohli et al. [13] similarly proposed specific pairs of SOA and SD values to produce apparent tactile motion at three different speeds.

The effect of the frequency of vibration pulses has also been investigated. For example, [16] found that varying frequency in the range of 100 to 250 Hz does not impact the localization accuracy of vibrations produced by an array of actuators on the forearm. [5] has similarly found that variations of vibration frequencies (200 and 270 Hz) and intensities (20 and 25 dB) do not affect the optimal range of SOA values for apparent tactile motion. In contrast, [8] observed that variations of vibration frequencies (150, 200, 270 Hz) impacted the optimal range of SOA values, and that the lowest frequency (150 Hz) produced more continuous apparent tactile motion.

To our knowledge, [17] presents the only study of the effect of having vibration pulses of different frequency on apparent tactile motion. They studied variations in frequencies (10, 20, 40, 100 and 200 Hz) and SOA values (0 and 400 ms) on apparent tactile motion between two locations on the fingertip. They found that apparent tactile motion can be felt whenever one of the vibration pulses is at 40 Hz, even if the two vibration pulses have a different frequency. Apparent tactile motion was also felt in all low-frequency and high-frequency combinations.

The effect of vibration amplitude has also been investigated. [18] created a linearly moving tactile sensation similar to apparent tactile motion by linearly or logarithmically modulating the activation amplitude of two actuators on a handheld mobile device. [19] studied the impact of various factors on the perceived intensity of a vibration.

The influence of the type of actuators and their distance was also studied. [20] found that apparent tactile motion could be felt with a distance between actuators of 4 to 20 cm on the forearm. Optimal SOA values were independent of the distance, but the relation between SD and SOA was more linear with increased distance. [21], [14] found that a voice-coil type tactor (VCT) could produce apparent tactile motion for a broader range of SOA and SD values than a DC actuator-based tactor (DCT).

This prior work informed the design of our experiments, including the selection of timing parameters and actuator positions. This literature review also reveals a need for further investigation of the effect of mismatched vibration frequencies on the illusion of apparent tactile motion.

III. Experimental Setup

The experimental setup consisted of two vibrotactile actuators mounted on the forearm and wrist, an external sound card for signal generation, a custom interface device for communication with the participants, and a computer (see Figure 2).

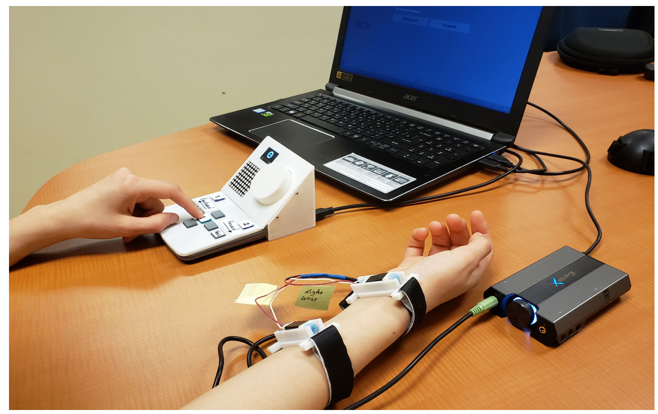
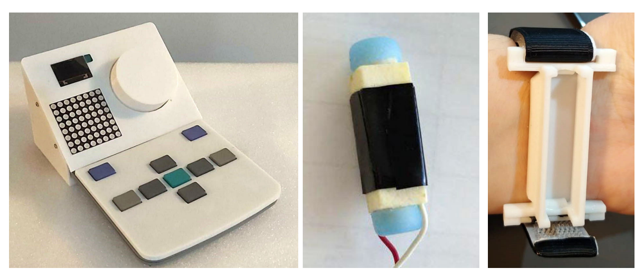


Fig. 2: Experimental setup: computer, custom interface device, external sound card, and vibrotactile actuators mounted on the wrist and forearm.

The vibrations were produced by Haptuator MM3C-HF actuators (Tactile Labs, Montreal, Canada; Figure 3b). These vibrotactile actuators from the voice coil family can produce vibrations in a wide range of frequencies, and thereby imitate various actuators found in commercial products.Their highest mechanical resonance is between 85 and 125 Hz, with a peak at 96 Hz.



(a) (b) (c)

Fig. 3: Components of the experimental setup: (a) custom interface device with displays, buttons and a dial; (b) Haptuator MM3C-HF actuator; and (c) custom mounting bracket for actuator.

The vibrotactile actuators were fastened to the wrist and forearm using custom wristbands designed for comfort, contact with the skin, and transmission of vibrations (Figure 3c). After several iterations, the final design mounts the actuator in a 3D-printed plastic bracket (20 × 40 × 60 mm) attached to the dorsal wrist or forearm with a fabric strap (Figure 4). We found that a solid plastic bracket produced a more uniform distribution of vibrations on the skin than alternatives.

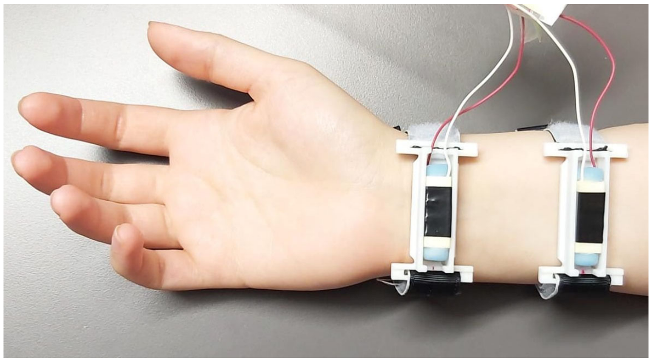


Fig. 4: Close-up on the actuators mounted on the forearm and wrist with custom wristbands.

The driving signals were generated by a high-performance USB sound card (BlasterX G6, Creative Labs) capable of producing a high gain without signal interference with discrete amplification circuits for the stereo channels in dual mono configuration.

We also designed a custom integrated interface device to receive inputs from and send outputs to the participants (Figure 3a). The device allowed participants to easily adjust the intensity of vibrations with their non-dominant hand while their other arm wears the haptic devices. It has buttons and a knob for input and an OLED and Matrix LED display for output.

IV. Methodology

The goal of the experiments was to better understand the effect on the apparent tactile motion illusion of a difference in frequency between the first and second vibration at the wrist and forearm. We asked participants to detect the direction of the apparent tactile motion in order to see if it has been felt. We ran two pilot tests and two experiments. The participants wore the wristbands on the arm of their dominant hand, with a center-to-center distance of 8 cm between the actuators. The vibration pulses were produced as sinusoidal waveforms using the external sound card. The participants wore headphones playing white noise during the experiment to mask any sound generated by the actuators.

The stimulus onset asynchrony (SOA) is one of the most important factors for apparent tactile motion. The illusion will not be felt if the SOA is below or above a specific range, in which case the vibrations will be perceived either as a single stationary vibration or as two distinct vibrations [5]. Based on [8], [13], we selected a SD of 200 ms and a SOA of 111 ms to create a fast apparent tactile motion. Whenever a sensation of two distinct vibrations was required, we used a SD of 1 s and a SOA of 1.5 s.

Throughout this work, we focus on a set of 9 frequencies from 50 to 250 Hz, with 25 Hz increments (50, 75, 100, 125, 150, 175, 200, 225, and 250 Hz). This set of frequencies exceeds the just-noticeable difference of 10% required to detect a change in vibration frequency [22]. It also covers critical frequencies such as those used in most commercial vibrotactile actuators, those with the lowest detection thresholds (200-300 Hz; [23]), the mechanical resonance range of our actuators (85-125 Hz), and the lower frequencies known to produce continuous apparent tactile motion [8].

All participants signed a consent form and received a 20$ gift card as compensation. The experimental protocol was approved by the ÉTS Research Ethics Committee.

V. Experiments

A. Pilots Studies

We conducted two pilot studies to refine our experimental protocol and determine the number of trials that could be completed in 90 minutes. A total of 10 participants completed the pilot studies.

The two pilot studies began with an experiment designed to normalize the perceived intensity of vibrations at the forearm and wrist, for a given frequency range. Using these normalized vibration intensities, a second experiment was conducted to determine the effect of frequency mismatches on the detection of the direction of apparent tactile motion.

The highest frequencies used in the first pilot study, 275 and 300 Hz, were found to result in the weakest vibrations and were eliminated from the second pilot study and the experiments to increase the normalized perceived intensity for vibration pulses in the selected range (50-250 Hz). The weakest vibration was also found to be consistently felt at the forearm with the highest frequency in this range (250 Hz). We therefore concluded that normalization of the perceived intensity should be done against 250-Hz vibrations on the forearm.

We finally found that conducting both experiments (normalization and apparent tactile motion detection) as part of a single experimental session caused fatigue and did not provide sufficiently accurate normalization data. The two experiments were therefore conducted separately, as described in the next sections.

B. Experiment 1: Normalization of Perceived Intensity

We conducted a first experiment to normalize the perceived intensity of vibration pulses at all frequencies (50, 75, 100, 125, 150, 175, 200, 225, and 250 Hz) and body sites (wrist, forearm). More specifically, our goal was to determine the vibration amplitude for each combination of frequency and body site that would result in the highest perceived intensity achievable at all combinations. Based on the results of the pilot studies, we set this reference stimulus to be the maximum activation of the actuator on the forearm at a frequency of 250 Hz, which we expected to produce the weakest vibration pulse.

The experiment was divided in three sets of two blocks, with a pause of 5 minutes in between each block. In both blocks, the reference stimulus was a vibration pulse at

250 Hz at maximum intensity, on the forearm. The comparison stimuli were vibration pulses on the forearm (block 1) or wrist (block 2) at frequencies in the selected frequency set (50, 75, 100, 125, 150, 175, 200, 225, and 250 Hz). In the first block, the participants were instructed to adjust the intensity of vibration pulses on the forearm until their perceived intensity matched that of the reference stimulus. In the second block, the same procedure was repeated with vibration pulses at the wrist. The order of frequencies was randomized within each block. The process was repeated three times, for a total of 54 trials (3 sets $\times$ 2 body sites $\times$ 9 frequencies $\times$ 2 directions).

In each trial, participants first felt the reference stimulus for 1 s and then, after a pause of 1.5 s, felt the comparison stimulus for 1 s. The participants were instructed to turn a knob on the interface device to increase or reduce the intensity of the comparison stimulus until it matched the intensity of the reference stimulus. They pressed a button to feel the sequence of vibrations again (reference and comparison stimulus), and another button once the intensities were felt to match.

Experiment 1 was conducted with 5 participants (3 female; mean age of 30) and lasted approximately 70 minutes. One participant did not complete the experiment and was removed from analysis.

1) Results: Figure 5 shows the mean of the amplitudes selected to match the perceived intensity of the reference stimulus for each frequency and body location, across all four participants. The amplitudes are shown as a percentage of the maximum voltage that could be produced by our experimental setup. These values can be used as normalization factors to produce a uniform perceived intensity at all frequencies and body locations. As expected, the normalization factor peaked at 100% with the reference stimulus (250 Hz on the forearm). The normalization factors were low in the 50-125 Hz range, and increased gradually in the 125-225 Hz range. It is important to note that the perceived intensity was much above the perception threshold even though the lowest normalization factor was 7% (75 Hz on the wrist).

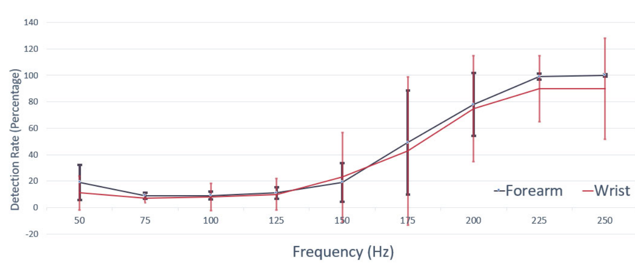


Fig. 5: Mean normalization factors selected by participants at different frequencies on the forearm and the wrist. Error bars show 95% confidence intervals.

C. Experiment 2: Detection of Apparent Tactile Motion

This goal of Experiment 2 was to determine the impact of mismatched vibratory frequencies on the perception of apparent tactile motion. To focus on the effect of frequency alone, the normalization factors determined in the previous experiment were used to produce vibration pulses of the same perceived intensity at all frequencies and body locations.

Participants were asked to detect the direction of apparent tactile motion produced by a sequence of two vibration pulses on the forearm and wrist. The direction was considered to be forward when the motion was felt from the forearm to the wrist, and backward in the reverse direction (see Figure 6).

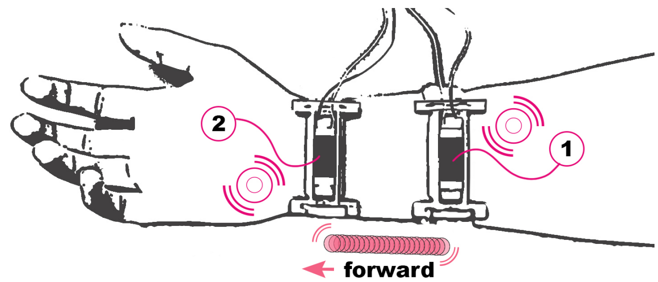


Fig. 6: The direction of motion was considered to be forward when from the forearm (1) to the wrist (2).

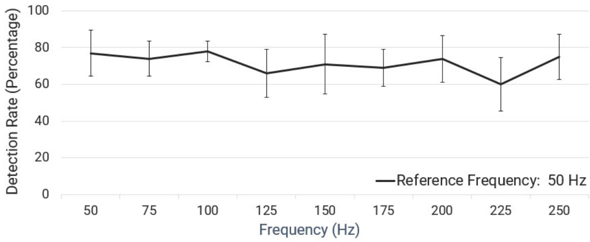
Apparent tactile motion was produced with a stimulus duration (SD) of 200 ms and a stimulus onset asynchrony (SOA) of 111 ms. The first vibration was produced at one of three reference frequencies (50, 150, or 250 Hz). The second vibration was produced at one of 9 frequencies (50, 75, 100, 125, 150, 175, 200, 225, and 250 Hz). A total of 54 vibration pairs were produced (2 directions $\times$ 3 reference frequencies $\times$ 9 frequencies). Each pair of vibration was repeated 5 times, for a total of 270 trials (54 pairs $\times$ 5 repetitions). The order of vibratory pairs was randomized for each participant.

The experiment was divided in 4 blocks of 68 trials, with breaks of 10 minutes in between. The duration of the experiment was approximately 70 minutes. The experiment was conducted with 10 participants (3 female; mean age of 30). None of them had participated in Experiment 1.

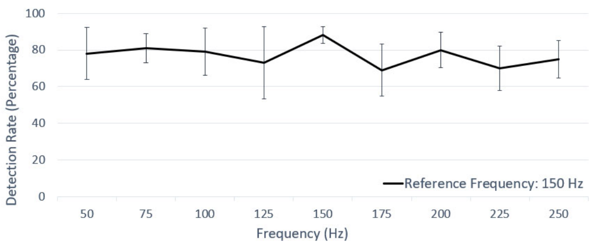
D. Results

1) Reference Frequencies: Figure 7 shows the mean detection rate of apparent tactile motion direction for the three reference frequencies (50, 150 and 250Hz; first vibration) and 9 frequencies (50-250 Hz; second vibration). For each reference frequency, the detection rate appears to be nearly constant over the range of frequencies for the second vibration pulse (50-250 Hz). One-way repeated measure ANOVAs confirm that there is no statistically significant effect of the frequency for each of the three reference frequencies: 50 Hz ($F(8,81) = 1.108, p = 0.366$), 150 Hz ($F(8,81) = 1.186, p = 0.318$) or 250 Hz ($F(8,81) = 0.606, p = 0.77$).

2) Frequency Gaps: We performed a second analysis of the data by re-encoding the direction detection rates as a function of the absolute difference in frequency between the first and second vibration pulses. Figure 8 shows the mean



(a)



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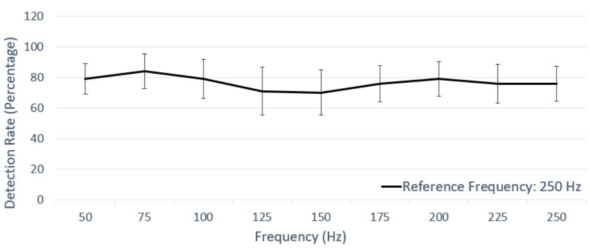

(c)

Fig. 7: Apparent tactile motion direction detection rate as a function of second vibration's frequency for three reference frequencies: (a) 50, (b) 150 and (c) 250 Hz. Error bars show 95% confidence intervals.

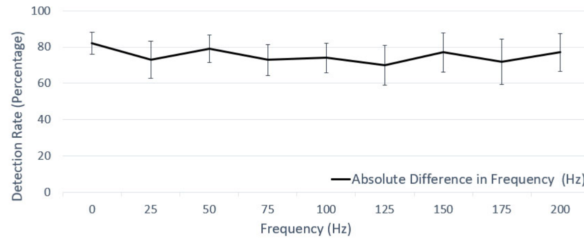

Fig. 8: Apparent tactile motion direction detection rate as a function of the absolute difference in frequency between the first and second vibration pulses. Error bars show 95% confidence intervals.

direction detection rate across participants for frequency differences ranging from 0 to 200 Hz.

Once again, the difference in frequency appears to have little impact on the direction detection rate. We confirmed that the data was normally distributed with the Shapiro–Wilks Test. A one-way repeated measure ANOVA confirmed that there is no statistically significant effect of the difference in frequency on the direction detection rate ($F(8, 81) = 0.642, p = 0.74$).

VI. Discussion

This work focused on the effect of a frequency mismatch on apparent tactile motion. We considered fixed values for timing parameters (SD and SOA) and the distance between actuators. In order to isolate the effect of a frequency mismatch, we ran a first experiment to normalize the perceived intensity of vibrations at two body sites (forearm and wrist) and a set of 9 frequencies (50-250 Hz). We ran a second experiment to determine the effect on the detection of the direction of apparent tactile motion of a frequency mismatch between a first vibration at a reference frequency (50, 150 or 250 Hz) and a second vibration at one of nine frequencies in the 50-250 Hz range.

We hypothesized that the apparent tactile motion illusion would be increasingly difficult to feel as the difference in frequency between the two vibration pulses increased. We found instead that a difference in frequency appears to have no statistically significant impact on the detection of apparent tactile motion. We conclude that apparent tactile motion is perceived even when the vibrations have mismatched frequencies, at least when the vibrations are felt between the wrist and forearm and their perceived intensities are matched.

We note that the perceived intensity was normalized with 1000-ms vibration pulses, while apparent tactile motion was produced with 200-ms pulses. This discrepancy in stimulus duration may have affected the accuracy of the perceived intensity normalization.

It should also be noted that our experiment asked participants to detect the direction of motion of the illusion, rather than the presence of an illusion of continuous movement. It is therefore possible that participants were able to correctly feel the sequence of vibrations without feeling apparent tactile motion. Prior work, however, suggests that apparent tactile motion is typically felt with the spatio-temporal parameters used in the experiment [8], [13]. The participants also reported feeling continuous motion in informal discussions. We are therefore confident that our results apply not only to the detection of the direction of apparent tactile motion, but also to the detection of the illusion itself.

Our results are also consistent with those of a similar experiment performed at the fingertip [17], which found that apparent tactile motion is felt in both high and low frequencies and combinations of the two.

More generally, our results are also consistent with prior findings that some parameters such as timing values and body sites affect the perception of apparent tactile motion, but typically not frequency. As explained by [7], [24], the SD and the SOA are the most important parameters that affect apparent tactile motion perception, and the frequency of the vibration pulses doesn't have a significant effect on the illusion. Similarly, other studies (e.g., [16], [5]) have found that the frequency of the vibration pulses has no impact on the optimal range of SOA. However, [8] mentions that using a lower range of frequency improves the perception of apparent tactile movement.

A possible explanation for the lack of effect of frequency on apparent tactile movement could be found in the cooperation of various mechanoreceptors for vibration perception in a wide range of frequencies [25], [26]. This may explain why participants felt the illusion even with a mix of two different frequencies.

Although not investigated directly in the experiments, our anecdotal evidence suggests that a mismatch in perceived intensity does affect the perception of apparent tactile motion. It may, for example, not be possible to feel apparent tactile motion when one actuator is much stronger than the other. Our preliminary results also suggest that while perceptible, the subjective experience of the apparent tactile motion may be qualitatively different when vibration frequencies are mismatched. Both topics will be investigated in future work.

VII. CONCLUSION

This work investigated the effect of using two different vibratory frequencies on the perception of apparent tactile motion between two body sites. The most critical parameter was the frequency of vibration, which we studied in a range from 50 to 250 Hz. We aimed to focus only on the effect of this parameter. We therefore normalized the amplitude of vibrations such that all vibration pulses had the same perceived intensity, no matter the frequency or body site used. We ran two experiments and found that the difference in frequency between the two actuators did not statistically significantly affect apparent tactile motion detection. We conclude that the illusion of apparent tactile motion is robust to a mismatch in the frequency of vibration pulses. In practice, this result suggests that it is possible to produce the illusion even with mismatched vibratory frequencies as long as the two actuators are matched in perceived intensity.

This work was motivated by the need to improve the experience of illusions when using multiple off-the-shelf haptic devices, such as the movement of a vibration between a smartwatch and a handheld controller. As these devices are manufactured by different companies, we hypothesized that tactile illusions may not be perceive due to differences in their range of vibration frequencies. Our experiments suggest instead the illusion of apparent tactile motion can be perceived with a combination of devices tuned for different resonant frequencies, at least when produced with the same perceived intensity between the forearm and the wrist.

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