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PhantomFolds: Exploring Unobtrusive Spatial Tactile Feedback Produced by Two Fingernail Mounted LRAs for In-Air and On-Surface Mixed Reality Applications

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ABSTRACT

To support seamless mixed reality (MR) interactions without obstructing natural touch, we introduce PhantomFolds, a nail-mounted device featuring two linear resonant actuators (LRAs) at the lateral nail folds that provide spatio-tactile feedback for in-air as well as on-surface interactions in MR. In three studies, we investigate the perception of spatio-tactile feedback produced by PhantomFolds. Our results show that (1) PhantomFolds can leverage the funneling illusion to produce spatio-tactile feedback at the finger for in-air as well as on-surface interactions, (2) tactile feedback produced with PhantomFolds can successfully increase the perceived realism in MR applications without impeding user interaction, (3) phantom sensations, are perceived more localized when users touch a surface, and (4) while participants could not consistently feel touch illusions below the finger when touching a surface as described by prior work, our results indicate that a per-user calibration could increase the success rate of this effect in the future.

KEYWORDS

Tactile feedback; mixed reality; unobtrusive; illusion; finger

1. Introduction

From typing on a keyboard to picking up an object, we rely heavily on our sense of touch at our hands when performing everyday tasks in the physical world (Abraira & Ginty, 2013a; MacLean, 2008). Researchers have therefore investigated how to produce artificial touch feedback to also support user interaction in digital environments. Prior work demonstrated that tactile feedback can help to enrich interaction in a virtual environment (VE) by providing more natural and intuitive feedback (Kuchenbecker et al., 2006; Ramsamy et al., 2006; Ziat et al., 2014), reducing cognitive load (Leung et al., 2007; Meier et al., 2015; Oakley et al., 2000), improving task performance (Hoggan et al., 2008; Ma et al., 2015) and enhancing the overall user experience (Bermejo & Hui, 2021; Elvitigala et al., 2022).

In typical virtual reality applications the user mostly interacts in-air. For interaction, users often hold physical controllers or wear gloves, which enable for user input and tactile feedback. However, these and many other tactile feedback devices tend to cover the user's finger pad to produce expressive touch feedback (Chinello et al., 2015; Gabardi et al., 2016; Khurshid et al., 2017; Leonardis et al., 2017; Pacchierotti et al., 2017). This is problematic for user interactions in a mixed reality environment (MRE). The tactile feedback devices designed for a VE, obscure natural touch experiences at the finger pad when the user interacts with objects and surfaces in the physical world. A key challenge to enhance a MRE with tactile feedback therefore lies in providing expressive touch sensations at the finger without

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impeding the user's natural sense of touch when interacting with physical objects and surfaces (Maisto et al., 2017; Mueller et al., 2020; Nittala et al., 2019).

Prior work has proposed different ways to address this problem. One approach is to shrink the device's size to a minimum and providing "feel-through" capabilities. Withana et al. fabricated a very thin layer of electrodes to limit the degree the skin-covering device can impede the natural touch experience (Withana et al., 2018). Another approach is *Touch & Fold* where a finger-mounted device uses a vibration motor attached to a moving frame that quickly folds back when the user touches the physical environment (Teng et al., 2021). Hsieh et al. (2016) and Ando et al. (2007) proposed using vibration motors mounted at the finger nail to produce tactile feedback while leaving the finger pad free to allow the user to seamlessly interact with the physical world. Here, Hsieh et al. (2016) investigated the discrimination of spatio-temporal patterns using sequential actuation of *multiple vibration motors*. The sensations of the spatial feedback are felt at the location of the actuators in a temporal pattern sequence. *They focused on ERM vibration motors and did not investigate creating phantom sensations between the actuators by leveraging the funneling-illusion. Furthermore they did not explore the effect of on-surface vs. in-air MR interaction spaces*. On the other hand, Ando et al. (2007) work revealed that feedback from *a single nail-mounted LRA vibration motor* can produce the illusion of touch below the finger when moving along a surface. Yet, it is unknown if multiple nail-mounted LRAs could use parallel actuation patterns to exploit the funneling illusion and create phantom sensations between the actuators. Furthermore, it remains an open question whether two nail-mounted LRA actuators at the finger nail can evoke phantom sensations below the finger. The combination of both could enable a more effective way to provide expressive feedback for MR applications using unobtrusive technology.

With this paper we, therefore, aim to extend the work of Hsieh et al. (2016) and Ando et al. (2007) by exploring the capability of two LRA actuators mounted at the lateral nail folds to produce unobtrusive spatial tactile feedback between the actuators and below the finger for in-air as well as on-surface interaction spaces. We call our proposed approach PhantomFolds (Figure 1). In three separate studies we investigate one of the following research questions each: *RQ1: How well can PhantomFolds produce spatial feedback between the actuators for in-air and on-surface interactions by leveraging the funneling illusion? RQ2: How reliably can PhantomFolds create the illusion of touch below the finger on surfaces and what factors lead to a higher success rate?* Finally, we validate the benefit of PhantomFolds for MR applications by looking at three different use cases and investigating *RQ3: How well can PhantomFolds increase realism in MR applications in an unobtrusive way?*.

Our findings provide insights on the capability of nail mounted vibration motors to render spatial feedback in MR in an unobtrusive way and the potential influence of surface contact on the tactile perception. We find (1) two LRAs mounted at the lateral nail folds (PhantomFolds) can leverage the funneling illusion to produce spatio-tactile feedback at the finger for in-air as well as on-surface interactions, (2) tactile feedback produced with PhantomFolds can successfully increase the perceived realism in MR applications without impeding user interaction, (3) phantom sensations (created by the funneling illusion) are perceived more localized when users touch a surface, and (4) while participants could not consistently feel touch illusions below the finger when touching a surface, our results reveal a

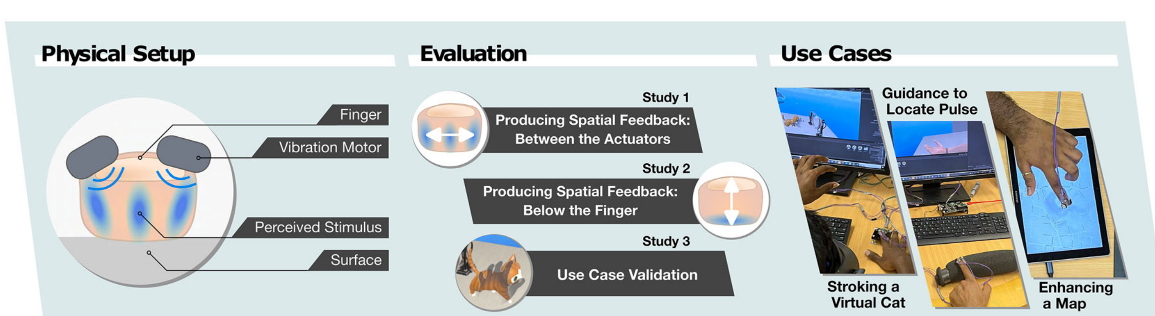

Figure 1. *PhantomFolds* comprises two vibration motors (LRAs) mounted on top of the finger at the lateral nail folds. This way, it augments the user's finger with spatial tactile feedback during in-air and on-surface interactions. The setup minimizes interference with surface interactions performed using fingertips in MR. We conducted several studies to understand the performance and benefit of *PhantomFolds* across various conditions and use cases.

significant positive correlation between fingernail size and participants stating to perceive the sensations below the finger – indicating that a per-user calibration could potentially increase the success rate of this effect in the future. We discuss our findings along with the limitations of PhantomFolds at the end of our paper.

In summary, we contribute:

- An artifact, PhantomFolds, which consists of two LRAs mounted at the lateral nail folds to produce unobtrusive spatial tactile feedback for MREs.
- Empirical findings of two studies that shed light on (1) the ability of two nail mounted actuators to produce spatial tactile feedback, (2) the influence of surface contact on the acuity of perceived phantom sensation locations, (3) potential factors increasing the success rate of producing the illusion of touch below the finger for surface interactions.
- A use case validation using PhantomFolds that illustrate the potential benefit of nail mounted actuators to produce unobtrusive spatial tactile feedback and increase perceived realism for MREs.

2. Background & related work

2.1. On-body haptic feedback and mixed reality

Extensive research has focused on ways to provide haptic feedback around the hand and fingers for VR applications (Fang et al., 2023; Pacchierotti et al., 2017; Shilkrot et al., 2015). The researchers investigated how to produce tactile and kinaesthetic feedback (In et al., 2011; 2015; Iqbal et al., 2015; Khurshid et al., 2017; Pierce et al., 2014), lateral skin stretch (Leonardis et al., 2015, 2017; Minamizawa et al., 2007; Muthukumarana et al., 2019; Tsetserukou et al., 2014), as well as shear forces through moving platforms (Chinello et al., 2015; Gabardi et al., 2016; Pacchierotti et al., 2014). However, many of these devices are bulky and impede natural touch sensations of the user that are needed for MR interactions.

Several approaches have been proposed to produce tactile feedback in a less obtrusive way over the past years. One notable approach is *Tacttoo*, which aims to limit the degree to which the natural sense of touch is impeded by the overlaying technology at the finger pad by using a thin layer of electrodes (Withana et al., 2018). Another approach, proposed by Kajimoto et al. (2004), involves a device that acts as a second skin with input and output capabilities, enabling it to sense the surface and replay it to the finger (Kajimoto et al., 2004). This approach allows for injecting virtual elements and even filtering part of the real world, offering an interesting means of fully controlling the perceived sensation. Both of these approaches still introduce an extra layer that has a certain thickness, which can impede the natural sense of touch as it creates an offset between the finger and surface. Therefore, the authors of *Touch & Fold* proposed a smart finger-mounted device with a vibration motor that provides feedback at the finger pad in mid-air and quickly folds back when the user touches the physical environment (Teng et al., 2021).

In the past, vibration motors have been largely proposed for providing on-body haptic feedback for several reasons. They are low-cost, easily perceivable, afford simple integration and can come in compact form factors. There are two main types of vibration motors. ERM (Eccentric Rotating Mass) motors depict the most conventional type of vibration motors. They are easily perceivable as they generate vibration by spinning an unbalanced weight, thereby stimulating many receptors in a larger area in the skin. On the other hand, Linear Resonant Actuators (LRAs) operate on a principle similar to that of a loudspeaker: an alternating current drives a coil, which interacts with a magnetic mass attached to a spring, causing it to oscillate at its resonant frequency. The advantage of LRAs is that they provide a much cleaner, more precise, and more smooth vibration. Many studies have shown how multiple vibration motors and exploiting tactile illusions can allow to render spatial feedback more effectively on the body which we review in greater detail in the following.

2.2. Spatio-tactile feedback using multiple vibration motors

Several studies have been conducted to explore the use of multiple actuators to render information spatially on the body. These studies investigate the design parameters and the efficiency of various approaches to enhance the limitations of haptic feedback devices. Lee et al. (2015) conducted experiments on a watch-back tactile display (WBTD) consisting of a 3×3 array of tactors. They explored the design space of a WBTD and demonstrated that the type, temporal pattern, and locus of stimuli significantly affect the efficiency of the display. Chen et al. (2008) investigated the localization of a single vibration on the wrist using a 3×3 tactor array. They found that participants could accurately identify only 2 locations on either the dorsal or volar side of the wrist, and 4 locations when arrays were placed on both sides. Jones and Ray (2008) evaluated tactile localization and pattern recognition on the torso using one-dimensional and two-dimensional tactor displays. They discovered that an 8-tactor array around the waist allowed for precise spatial mapping, while a 16-tactor array on the back was found to be inadequate. Additionally, they identified tactile patterns with high accuracy, suggesting the ability to convey navigational and instructional commands on the torso. Oakley et al. (2006) investigated the feasibility of forearm-mounted vibrotactile displays for mobile computing. They examined different spatial arrangements of tactors and found that performance varied significantly. They also explored the influence of adjusting the size of the vibrated area on perceived intensity. Lindeman and Yanagida (2003) conducted experiments on vibrotactile cues for near-field haptics in virtual environments. They tested subjects' ability to identify the location of an one-second vibrotactile stimulus on their back using a 3×3 tactor array. They achieved an 84% correct identification rate. Their study also examined the matching of intensity between different locations. More recently, Kim et al. investigated a row of four actuators to provide multimodal feedback combining vibration, pressure, and shear force (Kim et al., 2019). Several other studies investigated the perception of matrices of vibration motors on different parts of the body, such as thigh, torso, arm and hand palm (Alvina et al., 2015; Carcedo et al., 2016; Elsayed et al., 2020, 2023). Most of these approaches try to produce sensations at the location where the actuators are located themself. However, several studies showed that researchers can fool our perception and e.g., produce the illusion of touch between two vibration motors. We discuss the most commonly known illusions and related work in the next section.

2.3. Vibro-tactile illusions

Exploiting tactile illusions by actuating multiple vibration motors in a deliberate way has shown to be useful to furthermore increase the expressiveness of devices while limiting the required amount of actuators. The three most commonly known tactile illusions are (1) the *Sensory Funneling Illusion*, also known as *Phantom Sensation*, (2) the *Sensory Saltation Illusion*, often referred to as *The Cutaneous Rabbit*, and (3) *Apparent Tactile Motion*.

The Cutaneous Rabbit was first described by *Geldard and Sherrick* (Geldard & Sherrick, 1972). Multiple stimuli at different locations create moving sensations between them, like a hopping rabbit. They are still felt as separate stimuli, not one object. In contrast, *Apparent Tactile Motion*, creates the illusion of one continuous motion moving between two vibration motors that are actuated in sequence with a partially overlapping actuation time window (Burtt, 1917; Sherrick & Rogers, 1966). While the latter two approaches work by actuating vibration motors sequentially, the phenomenon of *Phantom Sensations* is created by simultaneously actuating two neighboring vibration motors. When both vibration motors are actuated with the same amplitude, a "phantom sensation" is perceived at the center between both actuators (Alles, 1970). When actuating one actuator at a stronger amplitude, the perceived sensation is perceived closer to (funneled towards) the stronger vibration. A large amount of work has focused on recreating this illusion in 1D, 2D, and even creating moving stimuli (Park & Choi, 2018). de Vlam et al. propose a method to correct distortion of the wave propagation of a sparse array of actuators to improve the localization of perceived sensations through the funneling illusion (de Vlam et al., 2023).

Tactile Brush presents a prominent approach where the authors combine *Phantom Sensations* with *Apparent Tactile Motion* (Israr & Poupyrev, 2011). Further studies showed that also illusions beyond spatial vibrotactile feedback along the skin can be created using vibration motors. In *Traxion* the authors were able to create the illusion of forces at the finger using asynchronous vibration (Rekimoto, 2014). Moreover, researchers have demonstrated how to produce body-penetrating phantom sensations at the torso (Kim et al., 2020), or even extend phantom sensations outside the body (Berger & Gonzalez-Franco, 2018). Kim et al. (2017); Baik et al. (2020) built up on *Tactile Brush* and *Traxion* and investigated how to render moving stimuli and forces using arrays of piezo actuators around the finger. Lederman and Jones provide a comprehensive overview about different haptic and tactile illusions (Lederman & Jones, 2011).

Exploiting tactile illusions does not only allow to produce more expressive on-body feedback using vibration motors, it can furthermore allow to generate tactile feedback in a less obtrusive way. Many studies have explored producing tactile illusions at different body parts with different properties. However, *it is yet to be investigated whether tactile illusions can be produced around the fingernail* which provides a promising body location to implement technology in an unobtrusive way for MR interactions.

2.4. Unobtrusive technology at the finger nail

As researchers strive to develop unobtrusive body-worn devices for mobile interactions and MR environments, the fingernail has attracted considerable attention in recent years. It depicts part of the body that is mostly unused and provides a platform to mount devices securely to the users finger without disturbing user interactions. As technological miniaturization progresses, researchers have been able to incorporate an increasing amount of technology around the fingernail. Vega and Fuks suggest that technology could be integrated on artificial nails, which are already used by many as a form of self-expression (Vega & Fuks, 2014). They demonstrate this concept by embedding passive RFID tags in their "Beauty Tech Nails." Other studies have explored the potential of using the fingernail as an input surface (Kao et al., 2015) and as a visual output display (Su et al., 2013). On one side, the nail has been recognized as a promising location to apply sensors to sense the finger state and, on the other side, to provide haptic feedback to the finger.

While most approaches focus on plain vibro-tactile feedback for VR (Hsieh et al., 2016; Preechayasomboon & Rombokas, 2021; Tamaki & Iwasaki, 2014), some have investigated multi modal feedback including pressure induced by direct contact (Teng et al., 2021) or pulling forces by exploiting haptic illusions created through asymmetric vibration techniques (Kim et al., 2018; Niwa et al., 2010). *Tactile echoes* propose a finger worn I/O device that senses tactile vibration of natural sensations at the finger nail with the help of a piezo actuator and augments the finger through playing it back to the finger using an actuator at the back of the finger (Kawazoe et al., 2019). Also Tran et al. combine input and output. They augment on-body touch input with tactile feedback using a single actuator at the fingernail (Tran et al., 2023).

In many cases, the applications focus on mobile interactions and VR applications leveraging ERM and LRA motors. However, few work has verified to which degree tactile feedback using finger-nail mounted vibration motors can actually increase realism in MR applications in an unobtrusive way.

2.5. Tactile sensations at the finger pad using nail-mounted actuators for MR surface interactions

Researchers discovered a phenomenon that makes the implementation of LRAs on the back of the finger particularly interesting for MR applications on surfaces. Ando et al. (2002) were the first who showed that touch sensations could be produced at the finger pad using a nail-mounted LRA while moving the finger across a surface (Ando et al., 2002). The first thorough study of the proposed method and explanation of underlying phenomenon was described by Ando et al. five years later (Ando et al., 2007).

The authors explain that when a perpendicular vibration stimulus is applied to the finger (with the help of LRAs), stress is induced between the finger pad and the surface. As a result, the sensation is perceived predominantly at the finger pad. A supporting factor is that few mechanoreceptors are located close to the finger nail. Consequently, the user feels the sensation at the finger pad and has the illusion that the sensation is caused by the surface texture.

The phenomenon has also been reproduced at the toe in a static condition (Sakai et al., 2017). Sakai et al. propose that this method of providing feedback could help support gait related applications. A similar approach without vibration motors but using two rotary motors to expand or retract the skin at the finger pad by stretching the skin at the sides of the finger has been recently proposed by Maeda et al. (2022). In *FingerTac*, Hulin et al. (2020) investigated a nail worn device that uses two LRAs with transmission elements that transfer the vibrations and stimulate the lower sides of the finger. They asked participants if they could discriminate sensations produced by FingerTac and a single external actuator. They found that when playing vibrations from FingerTac, users can sometimes confuse them with the external actuator which would be a desired outcome. Prior work, hence, highlights the potential benefit of using finger nail mounted actuators to produce feedback for MR surface interactions. However, *the influence of the interaction space (in-air vs. on-surface) on the perception of finger mounted feedback devices has not been explored yet*. It is furthermore still open *how well the illusion of touch can be created at different locations at the finger using multiple actuators by exploiting the funneling illusion*. This also includes the creation of touch illusions below the finger as proposed by Ando et al.

Based on these research gaps we developed PhantomFolds. Unlike prior work PhantomFolds aims to not impede surface interactions in MR by using nail mounted actuators and using multiple LRAs to render spatial tactile feedback at different locations. With the help of PhantomFolds we sought to explore the following in this work: *RQ1: How well can PhantomFolds produce spatial feedback between the actuators for in-air and on-surface interactions by leveraging the funneling illusion?*, *RQ2: How reliably can PhantomFolds create the illusion of touch below the finger on surfaces and what factors lead to a higher success rate?*, and finally, *RQ3: How well can PhantomFolds increase realism in MR applications in an unobtrusive way?* (Figure 2).

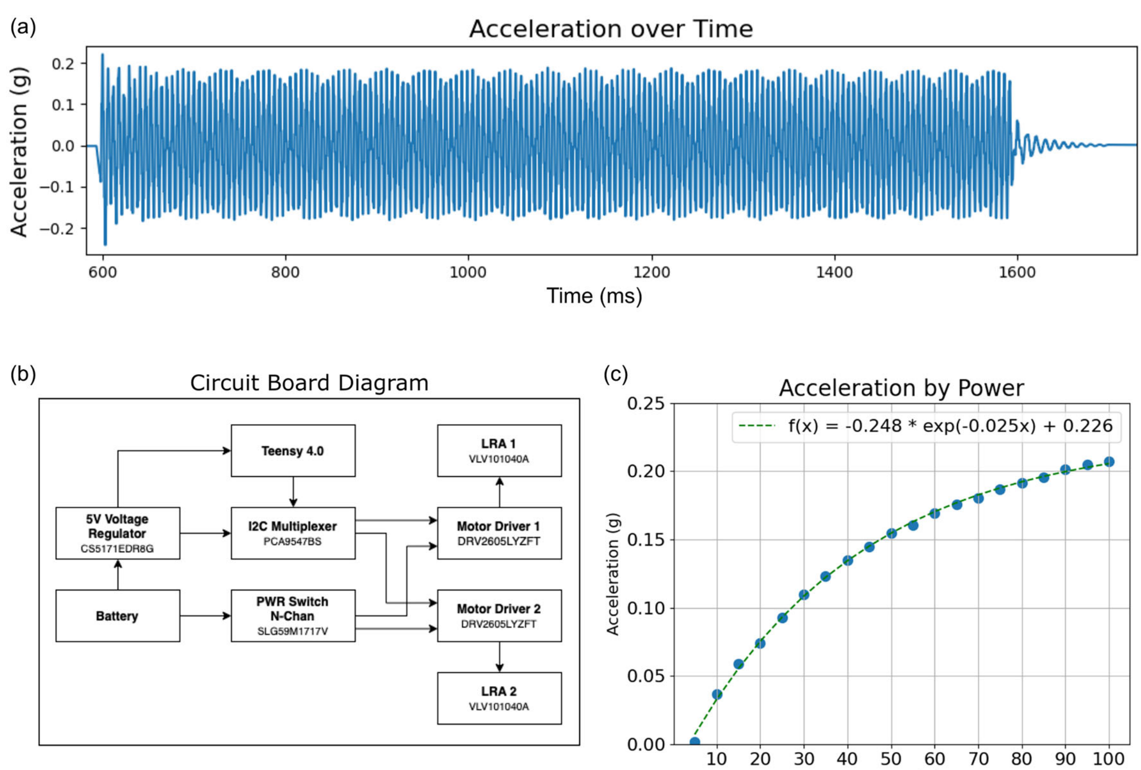

Figure 2. (a) Shows a recorded sample of 1s actuation at 200 *Hz* and 75% power amplitude. (b) Shows the circuit board diagram used to actuate the LRAs. (c) Actuation characteristic of one VLV101040A LRA with our implementation. Acceleration plotted over different power values (blue). The dashed green line shows the fitted function describing the relation between supplied power and acceleration.

3. PhantomFolds apparatus

PhantomFolds uses two LRA vibration motors (VLV101040A) similar to Vo et al. (2023) and Messerschmidt et al. (2025), but mounted at the top of the user's finger. The actuators are attached using double-sided tape (*Scotch Clear Double Sided Mounting Tape*) and centered at the lateral nail folds. The goal of this arrangement was to exploit two haptic illusions and produce spatial tactile feedback at the finger without disturbing user interactions on surfaces in MR (Figure 3(b)). Pilot tests showed that this positioning of the actuators enables simple and symmetrical attachment to the finger and increases the probability that the funneling illusion will be produced.

Unlike *NailTactors* (Hsieh et al., 2016), PhantomFolds uses LRAs instead of ERMs and applies them perpendicular to the finger with the flat surface aligning with the finger nail similar to Ando et al. (2007). However, unlike Ando et al. (2007) PhantomFolds uses two instead of a single actuator. The actuator arrangement aims to support producing phantom sensations at various location areas between the actuators as well as below the finger by leveraging the funneling illusion and the illusion as shown by prior work (Ando et al., 2007).

The actuators are driven by a DRV2605LYFT motor driver which is controlled by a Teensy 4.0. A more detailed circuit diagram is shown in Figure 2(b). We analyzed the actuation characteristics of the VLV101040A with our implementation using an IMU (MPU-9250) attached to one of the LRAs and sandwiching them between two foam sheets. We actuated the LRA at 20 discreet power levels between 0 and 100% with increments of 5 and three repetitions each. Figure 2(a) shows a recorded sample at 75% actuation power which captured the rise and fall time well. We could observe a rising time of $\sim 5ms$ and a falling time of $\sim 100ms$ at $200\,Hz$. We derived a function to describe relation between power and acceleration as follows:

$$f(x) = -0.248 * \exp(-0.025x) + 0.226 \tag{1}$$

A plot of the measured acceleration by power is shown in Figure 2(c). In the following we report on three studies that were carried out to explore our three research question which are to (1) investigate the capability of PhantomFolds to exploit the funneling illusion and produce spatial tactile feedback between the actuators for MR interaction, (2) investigate the capability of PhantomFolds to produce sensations below the finger when touching a surface by leveraging the method as demonstrated by Ando et al. (2007), and (3) to validate the ability of PhantomFolds to increase realism in an unobtrusive way for different MR applications.

4. Study 1: Producing spatial tactile feedback between the actuators

We conducted a first study to explore *RQ1: How well can PhantomFolds produce spatial feedback between the actuators for in-air and on-surface interactions by leveraging the funneling illusion?* Both actuators were actuated at different power levels and participants were asked about the perception when the finger was lifted up in the air and when it was touching a surface.

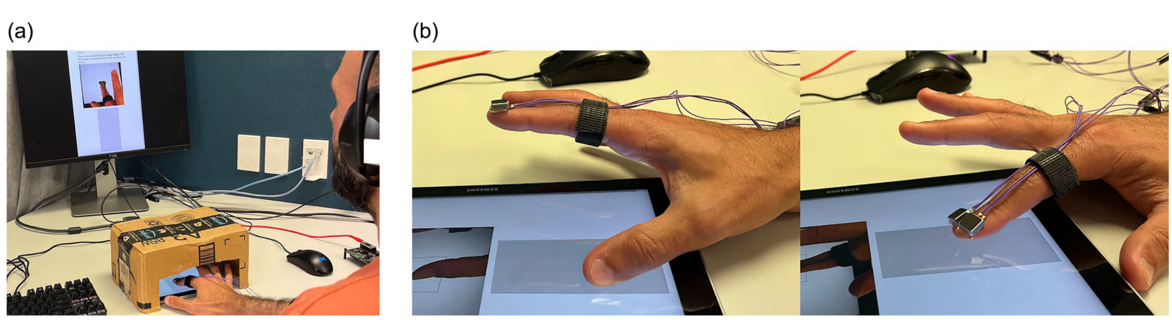

Figure 3. (a) Setup and Apparatus. (b) Two conditions. Study 1: (a) a cardboard box acted as a visual barrier to prevent the user from observing the LRAs. (b) There are two different INTERACTION_SPACE conditions: (1) IN-AIR: the participant touches the screen surface with the thumb while lifting the index finger up. (2) ON-SURFACE: the participant touches the screen surface with the index finger directly.

4.1. Hypotheses

The expectation was that PhantomFolds could not only render vibration feedback at the sides where the LRAs were mounted, but also produce single phantom sensations between the actuators by leveraging the funneling illusion (Alles, 1970). While Ando et al. suggested that surface contact increases the chances of users to feel sensations below the finger, the assumption here was that PhantomFolds renders phantom sensations between the actuators equally well for both in-air as well as on a surface interaction spaces. We expected that touching a surface would increase the perceived naturalness of sensations as it would provide additional passive haptic feedback complementary to the produced vibrations. Hence, we broke our assumptions down into 5 hypotheses to be tested within our first study:

H_1: When one LRA vibrates more powerful than the other, participants feel the sensation towards the side of the dominating vibration motor.

H_2: When both actuators are actuated at the same time participants feel a single phantom sensation between the actuators.

H_3: Phantom sensations can be produced at different locations between the actuators.

H_4: Phantom sensations can be produced equally well for in-air as well as for surface contact.

H_5: Perceived naturalness is increased for surface contact compared to in-air.

4.2. Participants

Eight participants aged $M = 25.63$ ($SD = 3.0$) years (4 male, 4 female) were recruited using convenience sampling while ensuring gender balance. The average nail size depicted $M = 129.03$ mm^2 $(SD = 21.61)$. All participants were right-handed. Three had experience with haptic feedback.

4.3. Design

The design was within-subjects and had the independent variables INTERACTION_SPACE {IN-AIR, ON-SURFACE}, LEFT_AMPLITUDE, and RIGHT_AMPLITUDE whereby each amplitude variable has 5 power levels {0, 25, 50, 75, 100%} of the maximum power of a vibration motor. Felt LOCATION_COUNT {0–2}, LOCATION {X-COORDINATE, Y-COORDINATE}, NOTICEABILITY {1–7}, NATURALNESS {1–7}, and CONFIDENCE {1–7} were measured, too. With the full design 2 INTERACTION_MODE × 5 LEFT_AMPLITUDE × 5 RIGHT_AMPLITUDE × 3 REPETITIONS × 8 PARTICIPANTS = 1200 samples were collected in total. 150 trials per participant. For the ON-SURFACE condition, finger-to-surface pressure was left uncontrolled and up to the participant. Each trial depicted a combination of the controlled independent variables. For every participant, all trials were fully randomized.

4.4. Task and procedure

Participants sat down in front of a computer wearing noise-canceling headphones playing white noise (Figure 3(a)). The stimuli were produced on the index finger of the participant's dominant hand. The two LRAs were mounted with their center at the lateral nail folds (Figure 3(b)) as described in Section 3. A cardboard box was used as a visual barrier to prevent the participant from observing the actuators with their eyes.

For the ON-SURFACE condition, the participant was instructed to touch the surface using their index finger. For the IN-AIR condition, the participant was instructed to touch the surface using their thumb while lifting their index finger up. Upon touching and holding the finger in a predefined area on the touchscreen surface of a *Samsung Galaxy Tablet*, the next trial was triggered. Each trial started with two auditory beeps, followed by replaying a combination of LEFT_AMPLITUDE and RIGHT_AMPLITUDE for one second using PhantomFolds. After each trial participants lifted their finger and answered several questions about the felt experience. First they were asked how many locations they felt

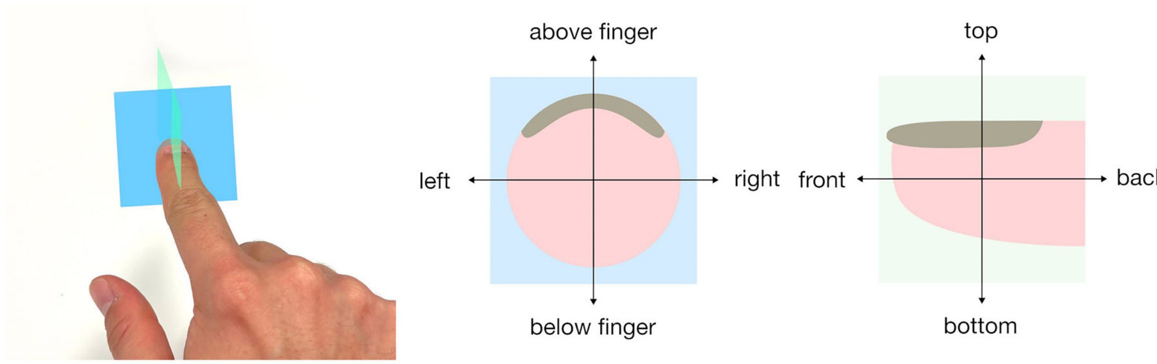

Figure 4. Participants indicated the perceived location of the stimuli on two distinct planes. The blue plane represents the intersection plane of the finger as viewed from the back, while the green plane represents the intersection plane of the finger as viewed from the side perspective.

(LOCATION_COUNT). For each distinct felt location, they were then asked to pin point the LOCATION on two 2D planes that intersect with the finger as depicted in Figure 4: A blue plane illustrating the intersection with the finger from the participants perspective behind the finger, and a green plane representing an intersection with the finger from the side. In addition, participants were asked to rate the corresponding NOTICEABILITY (1 – Not noticeable at all, 7 – Highly noticeable), the perceived NATURALNESS (i.e., how close the produced sensation is to a tactile sensation that may naturally occur in the real world; 1 – Not natural at all, 7 – Completely natural), and their COUNT_CONFIDENCE to clearly feel the reported number of locations as well as their CONFIDENCE to be able to pin point individual locations (1 – Not confident at all, 7 – Highly confident).

Participants were asked to take a break every 25 trials. They received a voucher worth ten dollars as compensation for their time following the user study.

4.5. Results

For the analysis AMPLITUDE_DELTA = RIGHT_AMPLITUDE – LEFT_AMPLITUDE which provided a measure at which side the vibration was dominating (–1 means left only, +1 means right only, 0 means balanced) and VIBRATION_INTENSITY = LEFT_AMPLITUDE + RIGHT_AMPLITUDE (the overall intensity of the vibration considering both actuators) were computed.

An entire session with one participant, including introduction and setup time, took about $M = 105.94$ ($SD = 25.2$) minutes on average. All perceived locations marked by the participants are plotted in Figure 5 on the finger-back-plane for IN-AIR (left) and ON-SURFACE condition (center), as well as on the finger-side-plane for both INTERACTION_SPACE conditions (right). We report the results based on the order of the hypotheses.

4.5.1. Perceiving sensations at different sides

The perceived location X-COORDINATES on the finger-back-plane for the AMPLITUDE_DELTA are plotted in Figure 6(a) with 95% confidence intervals. For both INTERACTION_SPACE conditions two non-overlapping CIs can be observed for the AMPLITUDE_DELTA extremes $\{-1$ and $+1\}$. Additionally Spearman's rank correlation was computed to assess the relationship between the different continuous variables. For this assessment, samples for the ON-SURFACE condition and LOCATION_COUNT $= 1$ were considered. A Spearman's rank test indicated a large positive correlation between RIGHT_AMPLITUDE and X-COORDINATE, $r(573) = 0.52, p = 0.0$, as well as a medium negative correlation between LEFT_AMPLITUDE and X-COORDINATE, $r(573) = -0.49, p = 0.0$. In addition, a large positive correlation between AMPLITUDE_DELTA and X-COORDINATE was found, $r(573) = 0.7, p = 0.0$.

This shows that the proposed nail-mounted apparatus was able to shift the perceived location on the pad of the finger towards the dominant vibration amplitude. Therefore we accept $\boldsymbol{H_1}$.

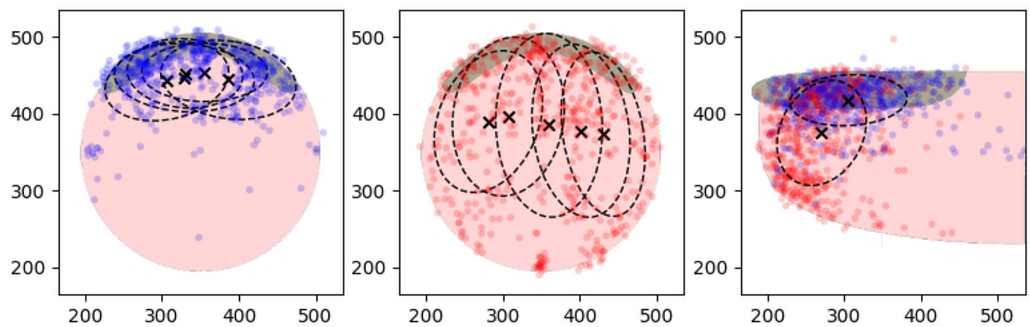

Figure 5. Perceived locations marked by participants on the finger-back-plane with 95% confidence ellipses for AMPLITUDE_DELTA {−1.0, −0.5, 0.0, +0.5, +1.0} (left and center), and on the finger-side-plane with 95% confidence ellipses for IN-AIR and ON-SURFACE. Marked locations for IN-AIR condition are displayed in blue and for ON-SURFACE in red. All points are plotted at 80% transparency in random order.

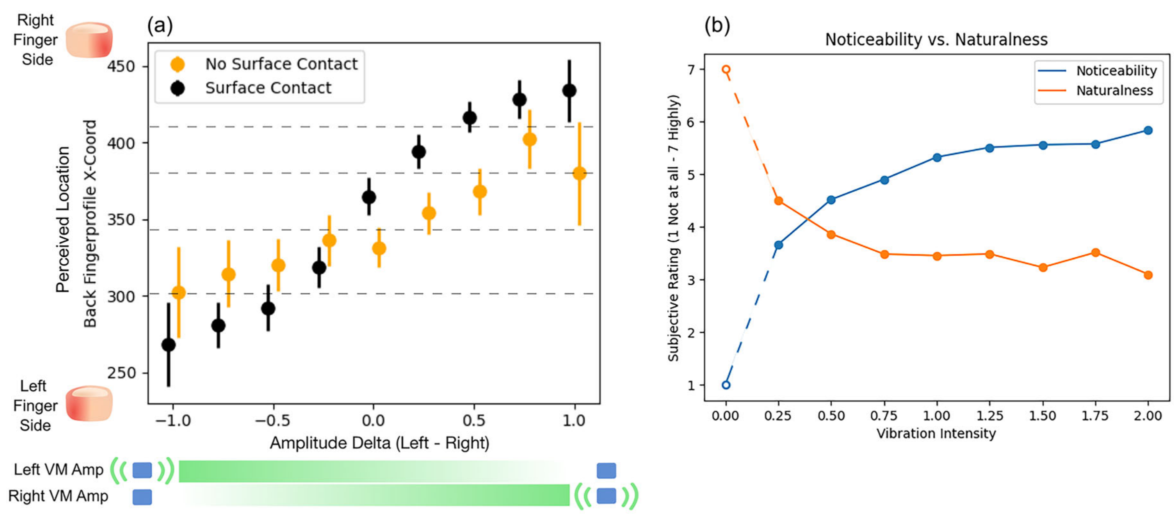

Figure 6. (a) The perceived location X-COORDINATE for ON-SURFACE and IN-AIR. (a) Mean values and 95% confidence intervals of the X-COORDINATES marked by participants on the blue finger intersection plane, displayed for different *amplitude delta* values under the no surface CONTACT (orange) and SURFACE CONTACT (black) conditions. Dashed lines suggest 5 sections users may potentially be able to discriminate. (b) The relationship of NOTICEABILITY and NATURALNESS WITH VIBTRATION_INTENSITY. (b) Mean subjective ratings for NOTICEABILITY and NATURALNESS plotted over different VIBRATION INTENSITY values. Mean values at intensity level zero were not recorded and merely represent expected values (dashed).

4.5.2. Producing single sensations (phantom sensations) between the actuators

Out of 768 trials at which both vibration motors were actuated simultaneously, participants felt a single sensation 649 times (84.51%), with a mean X-COORDINATE $M = 354.33(SD = 66.64)$ between the LRAs. In 118 trials (15.36%), two separate sensations were perceived, with 70 of these occurring under the ON-SURFACE condition. The mean confidence of participants to clearly perceive the reported number of sensations (COUNT_CONFIDENCE) was statistically significantly higher for ON-SURFACE $(M = 4.95, SD = 1.43)$ than for IN-AIR $(M = 4.84, SD = 1.41), T = 33619.5, p = 0.031$.

We conclude that participants perceive a single phantom sensations between the actuators when both actuators are actuated and also accept $\boldsymbol{H_2}$. The results furthermore suggest that participants were more confident in their ability to accurately perceive the number of sensations when the finger was in contact with a surface compared to when it was not, while maintaining a general level of confidence.

4.5.3. Producing phantom sensations at different locations

The respective mean X-COORDINATES with 95% Confidence Intervals that describe the location areas where participants reported to feel the sensations for each AMPLITUDE_DELTA are plotted in Figure 6(a). The non-overlapping confidence intervals indicate that participants could perceive sensations of individual amplitude deltas in different location areas. The plot furthermore reveals that participants could more reliably pin down the location of sensations perceived under the ON-SURFACE condition. While the means of the perceived locations for surface contact follow a strict monotonic behavior, they follow a non monotonic behavior for the IN-AIR condition with a higher dispersion around the means.

We therefore accept H_3 but have to reject H_4. Participants were able to perceive phantom sensations at different locations between the fingers. However, the findings show that phantom sensations were not produced equally well for ON-SURFACE and IN-AIR. Vibration stimuli were perceived more localized when participants were touching the surface.

4.5.4. The effect of surface contact on naturalness & noticeability

There was a small negative correlation between VIBRATION_INTENSITY and NATURALNESS, $r(573) = -0.12, p = 0.005$, indicating that weaker vibrations are perceived as more natural. Surface contact showed to influence naturalness as well. A one-sided Wilcoxon Signed-Ranks Test indicated that NATURALNESS was statistically significantly higher for ON-SURFACE $(M = 3.88, SD = 1.79)$ compared to IN-AIR $(M = 3.44, SD = 1.63), T = 62108.0, p = 0.0$.

When analyzing effects on the perceived NOTICEABILITY, a Spearman's rank test revealed a small positive correlation between LEFT_AMPLITUDE and NOTICEABILITY, $r(573) = 0.23, p = 0.0$, as well as a small positive correlation between RIGHT_AMPLITUDE and NOTICEABILITY, $r(573) = 0.27, p = 0.0$. Also a medium positive correlation between the overall VIBRATION_INTENSITY and NOTICEABILITY was found, $r(573) = 0.37, p = 0.0$, indicating that sensations produced with stronger vibrations were more noticeable. Furthermore, a one-sided paired t-Test showed that NOTICEABILITY was statistically significantly higher for ON-SURFACE $(M = 5.28, SD = 1.28)$ compared to IN-AIR $(M = 4.83, SD = 1.4), t(550) = 6.26, p = 0.0$.

As a consequence we also accept H_5. NATURALNESS is rated higher when participants touch the surface. While our original assumption was that surface contact adds additional passive feedback, we note that also the effect described by *Ando et al.* could have resulted in higher ratings. Participants may have felt vibrations originating from the surface, which would be expected to feel more natural. As more receptors are stimulated on the bottom of the finger when touching a surface, this could furthermore explain the increased noticeability ratings.

4.5.5. Distribution and recognizability of location areas

To assess how effective PhantomFolds can render spatial feedback between the actuators, the variance of the mean answer X-COORDINATES for individual AMPLITUDE_DELTAS provides an useful measure as it indicates how uniformly sensations could be rendered at different locations, maximzing the space between the actuators. We calculated an optimal variance of $s^2 = 0.329$ for nine evenly distributed location areas. For ON-SURFACE, the variance, $s^2 = 0.174$, is approximately 52.89% of the optimal variance $(s^2 = 0.329)$. The variance for IN-AIR, $s^2 = 0.043$, is about 13.1% of the optimal variance.

To assess how many location areas participants are most likely recognizable, we divided the finger into 3, 5, 7 and 9 equally sized bins and then calculated how many times participants marked the location within a bin compared to our predicted location (hit rate) for the corresponding AMPLITUDE_DELTA – assuming a linear relationship between AMPLITUDE_DELTA and X-COORDINATE of the perceived location. We display the individual hit rates in Figure 7. Based on the calculated hit rates, for a number of three bins, IN-AIR and ON-SURFACE perform similarly well. IN-AIR hit rates reveal two local maxima consistent across bin counts of 5, 7, and 9, whereas ON-SURFACE more equally distributed higher hit rates above random chance are observable. The dispersion (SD, displayed at the bottom of Figure 7) is lower for ON-SURFACE compared to IN-AIR.

4.5.6. Some sensations were felt below the finger

When plotting the perceived locations of participants on the finger-side-plane for the ON-SURFACE and IN-AIR condition independently, two major clusters at the nail and towards the pad could be observed (Figure 5), indicating that some participants felt sensations on the lower side of the finger similar as to the phenomenon explained by Ando et al. (2007). However, the 95% CI intervals in the figure overlap.

To investigate the vertical location distribution closer, the marked locations on the side plane were grouped into three REGIONS of the finger {ABOVE, BELOW, CENTER}. A Chi-Square Test of Independence

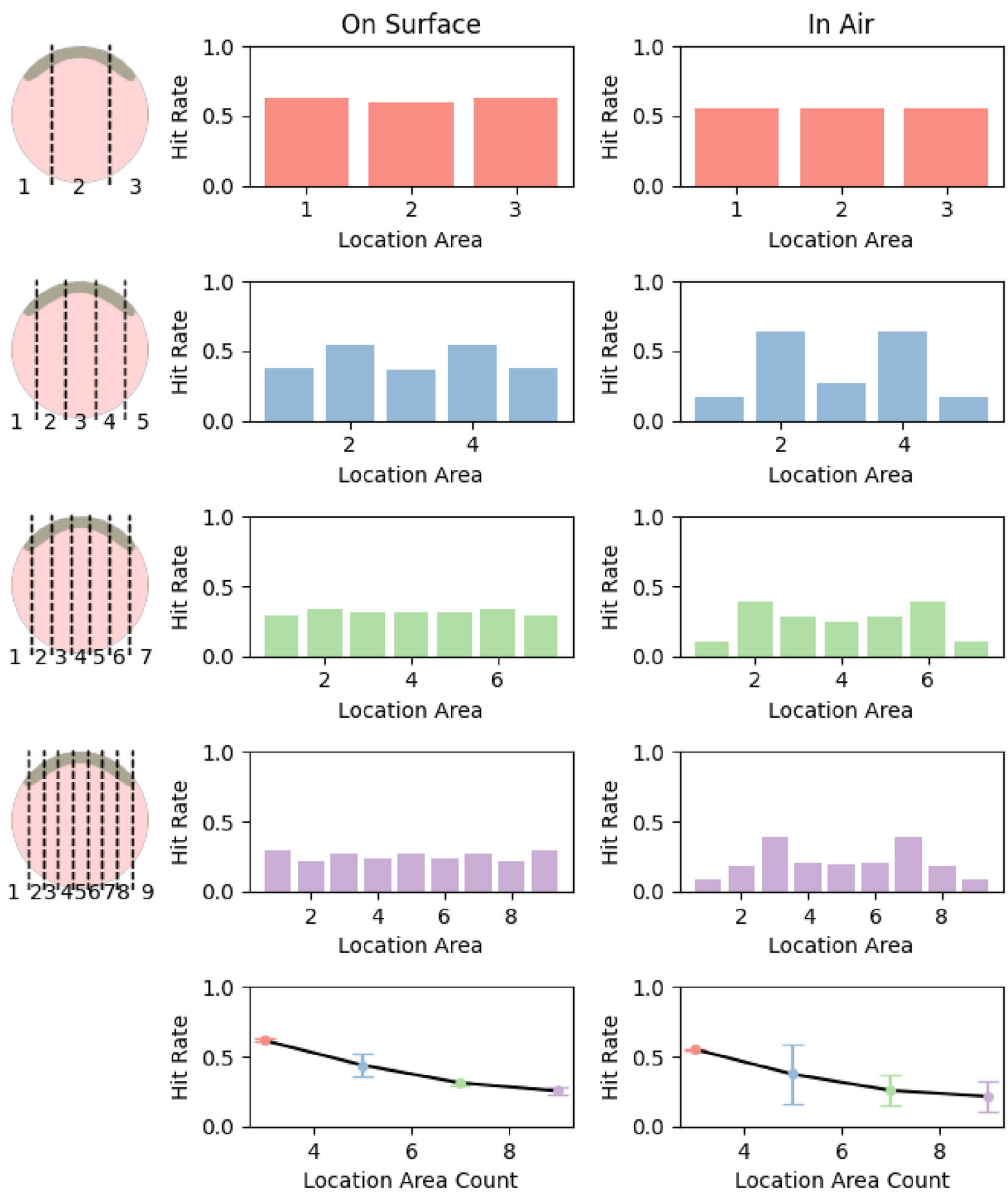

Figure 7. Estimated hit rates for different numbers (3, 5, 7, 9) of equally sized horizontal target location areas based on AMPLITUDE DELTA for ON-SURFACE and IN-AIR condition. Mean location area hit rates and standard deviation displayed for different bin numbers at bottom.

confirmed a significant relationship between INTERACTION_SPACE and REGION, $X^2(2, 1200) = 249.92, p < 0.001$, indicating that the perceived location shifted when touching the surface. Participants appeared to perceive the location of the sensation more often below the finger for the ON-SURFACE condition (ABOVE: 45.0%, BELOW: 40.17%, CENTER: 14.83%), compared to the IN-AIR condition (ABOVE: 82.83%, BELOW: 3.67%, CENTER: 13.5%). Despite this, there was still nearly an equal chance for participants to feel the location at the pad or at the nail for the ON-SURFACE condition.

We discuss the results in greater detail in Section 7.1.

5. Study 2: Producing spatial tactile feedback below the finger

In the second study we explored *RQ2: How reliably can PhantomFolds create the illusion of touch below the finger on surfaces and what factors lead to a higher success rate?* Compared to study 1, the focus relied on ON-SURFACE interaction only. The intention was to create an equal chance for participants to perceive a sensation at the finger PAD or finger NAIL by randomly playing vibrations from either side using different pairs of LRAs. To better understand factors influencing the success rate, different combinations of AMPLITUDE and FREQUENCY were played using the vibration motors.

5.1. Hypotheses

The assumption was that while vibrations are equally often played from both sides, participants would more consistently state to perceive the sensation at the finger PAD instead of the finger NAIL if the illusion can be successfully produced – similar to Ando et al. (2007). Based on pilot tests, a further assumption was that the effect would work best at a high amplitude and a lower FREQUENCY. The idea that a higher amplitude would work better, could be supported through the theory that through more intense vibrations at the finger NAIL, receptors on the finger PAD are more easily stimulated. Our pilot tests also indicated that in some cases it appeared impossible to locate the vibration stimuli. It was, therefore, decided to provide participants with three distinct answer options for the perceived location: PAD, NAIL and UNSURE.

Consequently, we formulated the following three hypotheses to be tested:

H_6: Participants perceive vibrations at the finger pad significantly more often than at the finger nail.

H_7: Participants perceive vibrations significantly more often at the finger pad for high amplitudes.

H_8: Participants perceive vibrations significantly more often at the finger pad for low frequencies.

5.2. Participants

24 Healthy participants aged $M = 25.16$ ($SD = 5.39$) years (12 male, 12 female) were recruited using convenience sampling while ensuring gender balance. The average measured nail width depicted $M = 10.14 (SD = 1.05)$. All participants were right-handed.

5.3. Design

Every participant performed the same task under all conditions (within-subjects design). Independent variables depicted FREQUENCY, AMPLITUDE and PLAYED_LOCATION. FREQUENCY comprised 10 values from 20 to 200 Hz, with step size 20. AMPLITUDE comprised three power values {33, 66, 100%}. Both actuators were always actuated simultaneously with the same AMPLITUDE. PLAYED LOCATION comprised two levels {PAD, NAIL}. In total 10 FREQUENCY × 3 AMPLITUDE × 2 PLAYED LOCATION × 2 REPETITIONS × 24 PARTICIPANTS = 2.880 samples were collected. The key dependent value measured in the experiment was ANSWER_LOCATION with three possible options {PAD, NAIL, UNSURE}. Finger pressure was controlled with the help the pressure sensor below the finger. Participants were asked to apply slight pressure of 30 g with a tolerance of $\pm 10g$ to limit cognitive load and distraction from the actual task. Each trial comprised a combination of the independent variables. Trials were fully randomized.

5.4. Task and procedure

Next to the two LRAs mounted at the lateral nail folds (like in study 1) two additional vibration motors were embedded in the surface that allowed to play vibrations at the finger pad. A force sensing resistor (FSR) below the finger furthermore allowed to measure the pressure level during each trial. The pressure level was controlled by asking the participant to maintain a constant pressure level as indicated by a visual scale that indicated a green color while the user stayed within the allowed range. At the beginning of each trial, a vibration comprising a combination of FREQUENCY and AMPLITUDE was played at the participants NAIL or PAD for one second. After the vibration the participant clicked one of three buttons. They could answer that they perceived the sensation on the NAIL, PAD, or in cases where they would find it impossible to identify the location they could answer UNSURE. After clicking one of the answer buttons the next trial began. Each experiment session had two additional test trials at the beginning to familiarize the participant with the task. One test trial vibrated once at the finger NAIL and once at the finger PAD, at 100 *Hz* FREQUENCY and 50% AMPLITUDE.

5.5. Results

For the analysis the individual answer rates of NAIL, PAD and UNSURE as well as the confusion rate – how often the participants were unable to recognize the actual vibration origin – were taken into account. Figure 8 displays the confusion matrix as well as the individual answer rates for the NAIL condition over the different FREQUENCY levels.

5.5.1. Perceiving tactile feedback below the finger

Participants answered PAD in 46.23% of all cases, followed by NAIL in 41.01% of all cases, and UNSURE in 12.75% of all cases. For vibrations played at the NAIL, the confusion rate was 37.97% (CI = [31, 36*]*), with answer rates $pad = 25.94\%$ and $unsure = 12.03\%$. In 62.03% of all NAIL-cases, participants could correctly identify the origin of the vibration. For vibrations played at the PAD, the confusion rate was 33.48% ($CI = [35, 41]$) with answer rates $nail = 20.00\%$ and $unsure = 13.48\%$. In 66.52% of all PAD-cases, participants could correctly identify the origin of the vibration.

A Wilcoxon signed-rank test revealed a significantly larger ($Z = 69844.50, p = 0.009$) confusion rate for vibrations played at the NAIL (37.97%) compared to PAD (33.48%). In addition, an one-sided binomial test revealed that the proportion of PAD answers (1276 out of 2408) was statistically significantly greater from the proportion of nail answers (1132 out of 2408), $p = 0.00$.

Based on these results we accept $\boldsymbol{H_6}$. Participants perceived vibrations at the finger pad statistically significantly more often than on the finger nail. While this shows that in some cases sensations appear to come from below the finger even though they are rendered using *PhantomFolds* from above the finger, our results indicate a low effect size, i.e., low robustness across participants considering all trials.

5.5.2. Influence of amplitude on the perceived location

To investigate the influence of amplitude on the creation of the illusion at the finger pad, only trials where vibrations were played at the finger nail are considered in the following. Here, the highest answer rate for PAD was 26.96% at 66% AMPLITUDE, followed by 25.65% at 100% AMPLITUDE and 25.22% at 0.33% AMPLITUDE.

A Friedman test did not show a significant effect of AMPLITUDE on the PAD answer rate ($X^2(2) = 0.48, p = 0.787$). However, a significant effect of AMPLITUDE on the answer rates of NAIL

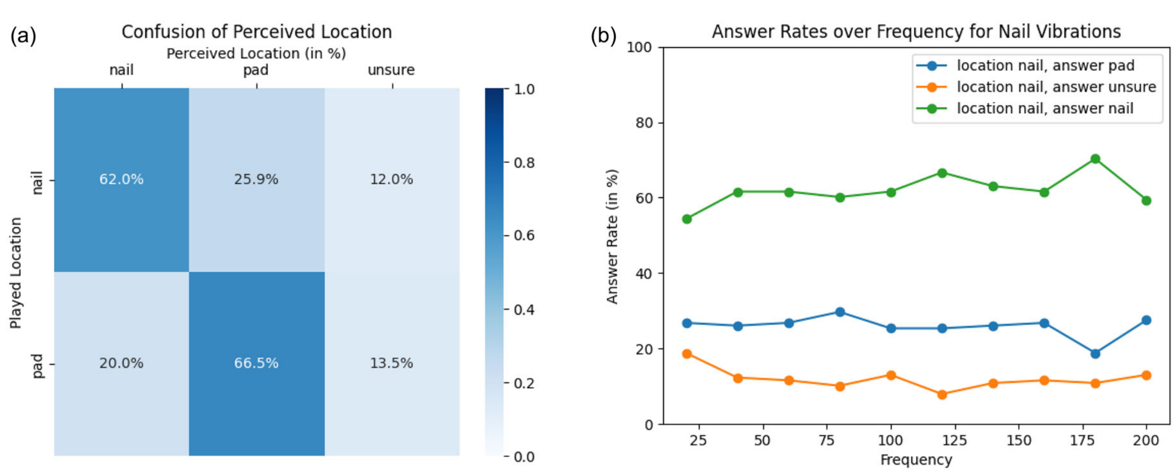

Figure 8. (a) Confusion of Perceived Location. (b) Answers over Frequency for Nail Condition. (a) In $62 - 66.5\%$ Of all cases, the participant was able to identify the origin of the vibration. In $38 - 33.5\%$ of the cases, the participant was confused, and either UNSURE ($12 - 13.5\%$) or stated to perceive the vibration on the other side ($20 - 25.9\%$). (b) The spectrum of answers for each FREQUENCY for the fingernail condition. Green = correctly identified origin at NAIL. Blue = phantom sensation perceived at PAD. Orange = participant was unsure.

($X^2(2) = 15.91, p = 0.0$) and UNSURE ($X^2(2) = 34.44, p = 0.0$) were found. Pairwise Wilxocon tests with Benferroni correction revealed a significant higher answer rate of NAIL for 100% AMPLITUDE ($M = 67\%, CI = [62, 71]$) and 66% AMPLITUDE ($M = 64\%, CI = [60, 68]$) compared to 33% AMPLITUDE ($M = 56\%, CI = [51, 60]$). In contrast, the answer rate of UNSURE was significantly lower for 100% AMPLITUDE ($M = 8\%, CI = [5, 10]$) and 66% AMPLITUDE ($M = 9\%, CI = [6, 12]$) compared to 33% AMPLITUDE ($M = 19\%, CI = [16, 23]$).

Participants could more accurately identify the true origin of the vibration stimuli at higher AMPLITUDE levels and had a harder time to identify the origin at the 33% AMPLITUDE level. The confusion rate for location at NAIL and AMPLITUDE at 33% was highest with 44.35%, followed by the confusion rate of 36.09% at 66% AMPLITUDE, and a lowest confusion rate of 33.48% at 100% AMPLITUDE.

Based on these results, we reject $\boldsymbol{H_7}$. Higher AMPLITUDE levels do not result in a greater chance to produce the illusion.

5.5.3. Influence of frequency on the perceived location

The three highest PAD answer rates for vibrations played at the finger nail were 80 Hz ($29.71\%, SD = 45.86$), followed by 200 Hz ($27.54\%, SD = 44.83$), and 20 Hz (26.81%, $SD = 45.86$) shared with 60 Hz and 160 Hz. 180 Hz scored lowest for both, the confusion rate ($29.71\%, SD = 49.28$) as well as the PAD answer rate ($27.53\%, SD = 44.83$) (Figure 8(b)).

A Pearson correlation test did not show any significant correlation between FREQUENCY and confusion rate ($r = -0.52, p = 0.122$), PAD answering rate ($r = -0.36, p = 0.304$) NAIL answering rate ($r = 0.52, p = 0.122$) or UNSURE answering rate ($r = -0.42, p = 0.222$). The three highest confusion rates for vibrations considering all AMPLITUDE levels and played at the NAIL were at 20 Hz ($45.66\%, SD = 45.00$), followed by 200 Hz ($40.58\%, SD = 50.28$), and 80 Hz (39.86%, $SD = 49.14$). Friedman tests did not show statistical significance ($X^2(9) = 12.03$) for neither NAIL ($p = 0.21$), PAD ($p = 0.69$), nor UNSURE ($p = 0.36$).

As no statistically significant effect was found between the FREQUENCY and the answer rate of PAD, we reject $\boldsymbol{H_8}$. Our assumption that lower frequency levels would increase the chance to create the illusion of touch below the finger using PhantomFolds when touching a surface appears wrong.

We discuss the results in greater detail in Section 7.2.

6. Study 3: Use case validation

In a third study, we investigated *RQ3: How well can PhantomFolds increase realism in MR applications in an unobtrusive way?* To explore this question we developed three distinct MR use case scenarios in which we measured the perceived realism and the degree PhantomPholds impedes the interaction (Figure 9):

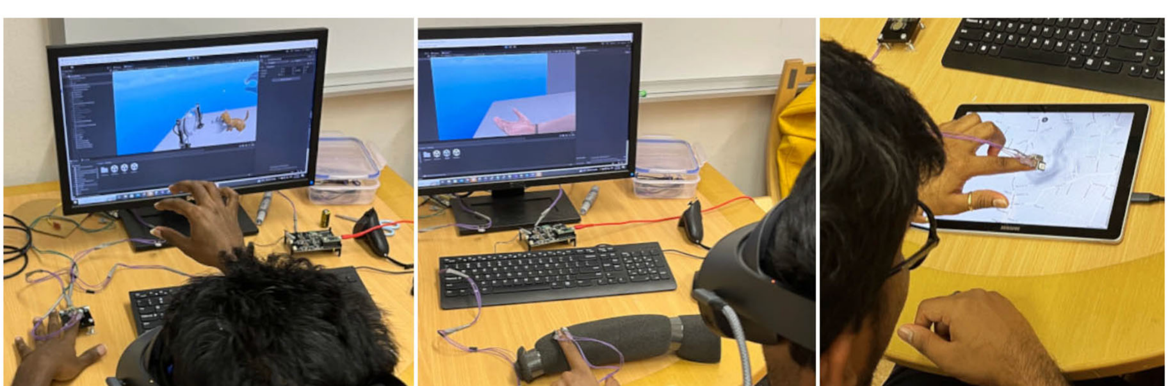

Figure 9. A virtual cat is walking from right to left and the user can feel it touching their index finger with its head (left). The user can feel the pulse of a virtual arm the closer they get to the wrist (center). The user can feel the elevation on a 2D map (right).

- In Use Case Scenario 1 PhantomFolds provides tactile feedback that allows the user to feel a virtual cat walking below the finger from one side to the other. Here PhantomFolds renders spatial tactile feedback that simulates the directional stroking sensation at the finger when the cat strokes along the finger with its head from below.
- In Use Case Scenario 2 the user can locate the tactile pulse on the arm of a virtual patient in a medical context. PhantomFolds renders feedback towards the finger side closest to the pulse location and with an intensity dependent on the distance to the pulse location. This gives the user cues about how far and on which side of the finger the pulse is located. The feedback is only played when the user touches the virtual arm.
- In Use Case Scenario 3 PhantomFolds enhances a two-dimensional map (a Google Maps section) by rendering the height profile. When the user touches and moves their finger on the map, they can feel different elevations and slopes below the finger.

In Use Case Scenario 1 we additionally aimed to compare matching vs. non-matching visio-tactile feedback (i.e., when visual directional cues and tactile directional cues align vs. mismatch) and investigate the difference of playing vibrations at the nail vs. pad.

6.1. Hypotheses

The assumption was that PhantomFolds is able to increase realism in the use case scenarios while participants rate PhantomFolds as unobtrusive, i.e., not impeding the interaction. As tactile feedback is known to be able to enhance realism, we also expected that playing tactile feedback with PhantomFolds will increase realism compared to playing no tactile feedback in Use Case Scenario 1. Naturally a similar increase was expected when visual directional cues and tactile directional cues match. In addition, we assumed that the increased realism for feedback played using pad mounted actuators would be higher than feedback played using nail mounted actuators, because our prior studies indicated that PhantomFolds can produce sensations below the finger better with pad mounted actuators. Finally, we expected that in conditions where the visual stimuli and the tactile feedback matched, feedback matching and perceived realism would be rated higher.

Hence, the following six hypotheses were to be tested through the study:

H_9: When playing tactile feedback using nail mounted actuators, perceived realism is rated higher compared to no feedback.

H_{10}: When playing tactile feedback using nail mounted actuators, feedback matching is rated higher compared to no feedback.

H_{11}: When playing tactile feedback using nail mounted actuators, feedback matching is rated higher when visual and tactile feedback are matching.

H_{12}: When playing tactile feedback using nail mounted actuators, increased realism is rated lower than when using pad mounted actuators.

H_{13}: Perceived realism is rated higher than neutral (4) across the different application scenarios.

H_{14}: PhantomFolds is rated to be less impeding than neutral (4) across the different use case scenarios.

6.2. Participants

12 Participants aged $M = 28.08 (SD = 4.98)$ years (6 male, 6 female) were recruited using convenience sampling. All participants were familiar with VR applications, and 3 had advanced experience with VR. Five participants stated to have had basic experience with touch feedback in VR (e.g., force feedback controllers for games). All participants were right-handed.

6.3. Design

The study had a between-subjects design. Six participants experienced vibrations played at the finger nail only (NAIL_GROUP), the other six participants experienced vibrations played at the finger pad only (PAD_GROUP). NAIL_GROUP performed Use Case Scenario 1-3, whereas PAD_GROUP only performed Use Case Scenario 1 as pad actuators were not applicable to scenario 2 and 3.

Independent variables for Use Case Scenario 1 comprised CAT_WALK {LEFT-TO-RIGHT, RIGHT-TO-LEFT}, TACTILE_FEEDBACK {SWIPE_LEFT, SWIPE_RIGHT, NO_FEEDBACK}, and VIBRATION_LOCATION {PAD, NAIL}. The finger was positioned like in *Study 2* so that vibrations could be played from above or below without the participant knowing the active actuator location. Visual feedback was played at any tactile feedback condition.

For Use Case Scenario 2 and 3 tactile feedback was always active, and vibrations were always played from the nail. For all use case scenarios AMPLITUDE was modulated between 0% and a maximum of 100% power level. FREQUENCY was fixed at 200 *Hz* (best performing frequency over different amplitude levels, see Study 2).

On a 7 point scale we measured for all use case scenarios PERCEIVED_REALISM (1 Not realistic at all – 7 Completely realistic), FEEDBACK_MATCHING (1 Visual and touch feedback do not match at all – 7 Visual and touch feedback match perfectly), and OBTRUSIVENESS (1 Did not impede me at all – 7 Completely prevented me from performing the task). For both participant groups NO_FEEDBACK formed the shared baseline condition. Pressure was not controlled to allow participants to focus on exploring the application scenario. 2 CAT_WALK $\times$ 3 TACTILE_FEEDBACK $\times$ 1 VIBRATION_LOCATION (per group) $\times$ 3 REPETITIONS $\times$ 12 PARTICIPANTS = 216 samples were collected in total. All trials were randomized.

6.4. Task and procedure

All participants (NAIL_GROUP and PAD_GROUP) started with Use Case Scenario 1. They sat down at a table wearing a Meta Quest Pro VR headset with hand tracking enabled. Their non-dominant hand's index finger was placed at the apparatus as in *Study 2* with the capability to play vibrations at the finger nail or pad. They could operate and provide input through a 2D interface displayed in VR using their other hand. Participants were able to see virtual hands based on the tracking of their real hands. For each trial in Use Case Scenario 1, the virtual cat walked from one side of the table to the other side while stroking with its head along the participants' left index finger from below. The visual and tactile feedback were played corresponding to the combination of CAT_WALK, TACTILE_FEEDBACK, and VIBRATION_LOCATION for each trial. The NAIL_GROUP only experienced feedback played from the nail. The PAD_GROUP only experienced feedback played from the pad. When TACTILE_FEEDBACK was NO_FEEDBACK, the visual feedback would be played without any tactile feedback. At the end of each trial (when the cat reached the other side of the table), the participants rated the PERCEIVED_REALISM and FEEDBACK_MATCHING. This was repeated until all trials were completed. Participants underwent three test trials at the beginning. In the first test trial, visual feedback was played without tactile feedback. In the second, visual feedback and tactile feedback were played with mismatching direction. In the third, the visual and tactile feedback matched.

The NAIL_GROUP furthermore experienced Use Case Scenario 2 and Use Case Scenario 3. In the second use case scenario, participants were instructed to touch the virtual arm at different locations and try to locate the location where they feel the pulse strongest. In the third use case scenario, their task was to navigate and explore the two-dimensional map using their index finger. They were asked to use the tactile feedback to locate the hill and identify the highest elevation. After each of the three use case scenarios, each participant was asked to rate the respective use case regarding the overall PERCEIVED_REALISM, FEEDBACK_MATCHING, and OBTRUSIVENESS. After completing all use case scenarios, participants were furthermore asked to comment about their experience.

6.5. Results

For analysis, the TACTILE_FEEDBACK and CAT_WALK combinations were grouped into NONE, MATCHING, and NOT_MATCHING tactile feedback. The mean ratings for NONE, MATCHING, and NOT_MATCHING are displayed in Figure 10(a,b).

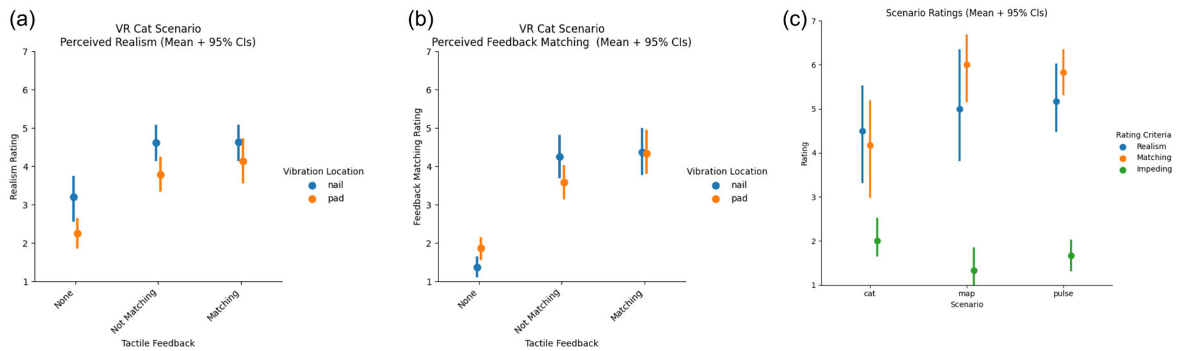

Figure 10. (a) VR Cat scenario conditions realism rating. (b) VR cat scenario conditions feedback matching rating. (c) Use case scenario rating.

6.5.1. Tactile feedback on perceived realism and feedback matching in use case scenario 1

Participants who perceived vibrations at the finger nail rated PERCEIVED_REALISM $M = 3.18; CI = [2.97, 3.38]$ and FEEDBACK_MATCHING $M = 1.35; CI = [1.27, 1.44]$ for the NO_FEEDBACK condition. When TACTILE_FEEDBACK was played, they rated PERCEIVED_REALISM $M = 4.62; CI = [4.32, 4.91]$ and FEEDBACK_MATCHING $M = 4.29; CI = [4.02, 4.56]$.

Friedman tests revealed a significant effect of TACTILE_FEEDBACK on PERCEIVED_REALISM $X^2(2) = 19.72, p = 0.0$ and on FEEDBACK_MATCHING $X^2(2) = 44.69, p = 0.0$ for the NAIL_GROUP. *Post-hoc* analysis using pairwise Wilxocon tests with Benferroni correction revealed a significant higher rating of PERCEIVED_REALISM when tactile feedback was both MATCHING $(M = 4.64, CI = [4.19, 5.09], p = 0.001)$ and NOT_MATCHING $(M = 4.61, CI = [4.15, 5.07], p = 0.0)$ compared to when NONE tactile feedback was played $(M = 3.19, CI = [2.61, 3.78])$. Similarly, significantly higher ratings were found for FEEDBACK_MATCHING when tactile feedback was both MATCHING $(M = 4.36, CI = [3.75, 4.97], p = 0.0)$ and NOT_MATCHING $(M = 4.25, CI = [3.68, 4.82], p = 0.0)$ compared to when NONE tactile feedback was played $(M = 1.36, CI = [1.12, 1.61])$. There was no significant difference between PERCEIVED_REALISM ratings of MATCHING and NOT_MATCHING $(p = 1.0)$, as well as no significant difference between FEEDBACK_MATCHING ratings of MATCHING and NOT_MATCHING $(p = 1.0)$.

Hence, we accept $\boldsymbol{H_9}$ and $\boldsymbol{H_{10}}$, but have to reject $\boldsymbol{H_{11}}$. Participants perceived an increase in realism and feedback matching through tactile feedback played using PhantomFolds. However, our study did not show that feedback matching is rated higher when the visual feedback is matched by tactile feedback played using PhantomFolds. There was also no significant difference between PERCEIVED_REALISM ratings of MATCHING and NOT_MATCHING $(p = 0.296)$, as well as no significant difference between perceived FEEDBACK_MATCHING ratings of MATCHING and NOT_MATCHING $(p = 0.108)$ for the PAD_GROUP.

6.5.2. Vibration location on increased realism and feedback matching in use case scenario 1

To compare the INCREASED_REALISM added through tactile feedback between PAD_GROUP and NAIL_GROUP, the mean rating for NONE tactile feedback (baseline) was first calculated for each participant and subtracted from their corresponding ratings for the MATCHING and NOT_MATCHING conditions. This way, values for both the INCREASED_REALISM as well as the INCREASED_FEEDBACK_MATCHING ratings relative to the baseline condition were obtained.

Between groups comparisons using Mann-Whitney U tests revealed no significant difference of the INCREASED_REALISM ratings for MATCHING tactile feedback, between PAD_GROUP $(M = 1.87; CI = [1.75, 1.99])$ and NAIL_GROUP $(M = 1.43; CI = [1.33, 1.52])$ $U = 544.50, p = 0.245$, as well as for INCREASED_REALISM ratings for NOT_MATCHING tactile feedback between PAD_GROUP $(M = 1.51; CI = [1.41, 1.61])$ and NAIL_GROUP $(M = 1.40; CI = [1.31, 1.49])$ $U = 582.50, p = 0.463$. Also no significant difference in the increased FEEDBACK_MATCHING ratings could be found for MATCHING tactile feedback, between PAD_GROUP $(M = 2.45; CI = [2.29, 2.61])$ and NAIL_GROUP $(M = 2.98; CI = [2.79, 3.17])$ $U = 737.50, p = 0.314$. However, a Mann-Whitney U test revealed a significantly lower FEEDBACK_MATCHING rating for PAD_GROUP $(M = 1.71; CI = [1.60, 1.82])$ compared to the NAIL_GROUP $(M = 2.87; CI = [2.69, 3.05])$ when NOT_MATCHING tactile feedback was played $U = 872.50, p = 0.011$.

As a consequence, $\boldsymbol{H_{12}}$ is rejected. When playing the vibration patterns using nail-mounted LRAs the increase in realism was not significantly lower compared to when using pad-mounted LRAs.

6.5.3. Overall perceived realism, feedback matching, and obtrusiveness ratings across all use case scenarios

Overall, PERCEIVED_REALISM and FEEDBACK_MATCHING was rated high. On average PERCEIVED_REALISM was rated $M = 4.87, CI = [4.56, 5.18]$ for the different scenarios, FEEDBACK_MATCHING was rated $M = 5.31, CI = [4.97, 5.65]$. Participants did not think that PhantomFolds impeded their task in the different scenarios, with a low OBTRUSIVENESS rating of $M = 1.66, CI = [1.55, 1.76]$. Hence, we accept $\boldsymbol{H_{13}}$ as well as $\boldsymbol{H_{14}}$. The mean ratings are displayed in Figure 10(c).

We discuss the results in greater detail in Section 7.3.

7. Discussion

In this work, we conducted three studies exploring the perception of spatial tactile feedback at the finger using two nail mounted actuators (PhantomFolds). First we investigated the perception of touch illusions created between the actuators for in-air and on-surface MR interaction spaces. Then we investigated the ability to create touch illusions below the finger. Finally, we investigated perceived realism and obtrusiveness of PhantomFolds in three different use case scenarios. In this section, we discuss the findings from our three studies with respect to our initial research questions. We end our discussion with a comparison to contemporary alternative approaches to produce tactile feedback at the finger for MR applications and highlight several limitations as well as starting points for future work.

7.1. RQ1: How well can PhantomFolds produce spatial feedback between the actuators for in-air and on-surface interactions by leveraging the funneling illusion?

Our initial study confirmed $\boldsymbol{H_{1-3}}$ and showed: PhantomFolds can not only produce tactile sensations at the sides where the LRAs were attached. PhantomFolds can produce spatial feedback at location areas between the actuators and at different perceivable intensity levels for ON-SURFACE as well as IN-AIR interactions. However, $\boldsymbol{H_4}$ had to be rejected. The spatial perception of tactile feedback rendered using PhantomFolds is not equal for ON-SURFACE and IN-AIR interaction spaces. Surface contact had a statistically significant positive effect on several measurements, including the perceived NATURALNESS, NOTICEABILITY, and acuity of the perceived locations. Figures 5 and 6(a) display clear differences in the distributions of marked location areas for ON-SURFACE and IN-AIR condition with respect to individual AMPLITUDE_DELTAS.

Spatial tactile feedback locations rendered between the actuators for SURFACE-CONTACT showed to be four times wider and more evenly distributed across the finger compared to the IN-AIR condition ($s^2 = 0.329$ vs. $s^2 = 0.174$). We note that there is still considerable room for optimizing the rendering of different location areas for both interaction spaces, to approach an optimal variance of the perceived mean locations $s^2 = 0.329$. Our findings show that two nail-mounted actuators are likely being able to render 3 location areas robustly for IN-AIR interactions and at least 5 location areas for ON-SURFACE interactions.

We can observe a similar drop in our hit rates (the number of times participants felt the sensation at a predicted location area) for an increasing number of bins (target location areas) compared to prior work (Barghout et al., 2009; Luo et al., 2023). However, our overall hit rates are significantly lower (~ 62.5 vs. $\sim 97\%$ for three targets) (Luo et al., 2023). The latter can be partially attributed to the difference of our exploratory approach, allowing participants to answer any location, in contrast to Luo et al. (2023) who provided a fixed set of answer possibilities. While recognizing more than 5 distinct locations between the actuators appears challenging with PhantomFolds, we still believe continuous interpolation between the actuators could be possible and beneficial to render realistic continuous feedback patterns.

One way to make spatial feedback rendered through PhantomFolds more effective, could be achieved by improving the rendering algorithm. Prior work has been debating on what relationship the rendering location and AMPLITUDE_DELTA of the vibration motors play in context of the funneling illusion. While several work indicates that a linear interpolation works best for their approach (Barghout et al., 2009; Luo et al., 2023), our results indicate that a non-linear relationship, an s-curve (Figure 6(a)), could describe the relationship best when exploiting the funneling illusion using two nail-mounted actuators. We explain this non-linear behavior through the finger shape and the limited finger size. Since the data exhibits an s-shaped curve pattern, it suits to be fit to a Sigmoid function. In doing so we can yield a function L_x, that describes the relationship between the perceived location's x-coordinate and the amplitudes of the left and right vibration motors, A_r and A_l.

$$L_x = \frac{170.633}{1 + e^{-3.757 * (A_r - A_l + 0.063)}} + 265.388 \tag{2}$$

7.2. RQ2: How reliably can PhantomFolds create the illusion of touch below the finger on surfaces and what factors lead to a higher success rate?

Despite a statistically significant increase in the answer rate for pad was found, the overall effect size was small ($Cohen's\ d = 0.11 < 0.20$) with a PAD answer rate of 46.23% and a NAIL answer rate of 41.01%. We conclude that even though our results indicate the possibility of creating sensations below the finger in some cases, spatial tactile feedback below the finger for ON-SURFACE interactions can not be reliably produced using the PhantomFolds apparatus.

While our results appear less promising as the findings from Ando et al. it should be noted that the presented studies slightly differ from Ando et al. (2002)'s method. Most importantly, in our work a static finger condition is investigated opposed to dynamic movement of the finger in Ando et al.'s work. While using multiple actuators could have had an adverse effect on evoking the illusion, our results could hint that the effect is more easily evoked for a dynamic finger setting. However, since we provided participants in our study with the option to answer "unsure" we believe it could be possible to convince the user to feel sensations below the finger, particularly for those cases where they were uncertain, through providing additional stimuli such as visual feedback.

A significant effect for AMPLITUDE or FREQUENCY on the ability to create the illusion below the finger could not be found. However, lower AMPLITUDE levels resulted in a higher CONFUSION_RATE. While the high CONFUSION_RATE at the lowest AMPLITUDE (33%) could be explained through the stimulus not being noticeable enough to locate it anymore, we note that this explanation is unlikely to hold true for the increased CONFUSION_RATE at the condition with an amplitude level of 66%. When looking at the plot from *Study 1* (Figure 6(b)) the NOTICEABILITY stays at a similar level for 66 and 100%. Hence, there could be a sweet-spot between 33 and 66% AMPLITUDE to produce the illusion more reliably.

Our first analysis indicated no direct effects between FREQUENCY levels and the ability to produce an illusion below the finger. This was counter intuitive to our initial assumption that FREQUENCY would effect the ability to produce an illusion below the finger and prior psycho-physiological research indicating receptors responding to different FREQUENCY ranges better (Abraira & Ginty, 2013b; Löfvenberg & Johansson, 1984; McGlone & Reilly, 2010). After investigating and observing local maxima for the PAD answer rates at different FREQUENCY levels for individual participants, a deeper analysis was performed, which tested if individual characteristics such as GENDER, AGE and NAIL_WIDTH effect the number of PAD answers for different frequency levels. Pearson chi-square tests did not show a significant effect of GENDER on the ANSWER_LOCATION ($X^2(2, 1320) = 4.08, p = 0.130$). Also a Pearson correlation test did not show a significant correlation between FREQUENCY and AGE for PAD answers when playing vibrations from the NAIL ($r = 0.59, p = 0.070$). However, a Pearson correlation test revealed a significant large negative correlation between FREQUENCY and mean NAIL_WIDTH for PAD answers ($r = -0.73, p = 0.017$), indicating that for high FREQUENCY levels most participants confused vibrations from the NAIL with vibrations at the PAD when they had a smaller NAIL_WIDTH, and for lower frequency levels more participants confused vibrations from the NAIL with vibrations at the PAD when they had a larger NAIL_WIDTH (Figure 11). This correlation could indicate that a calibration phase to adjust the FREQUENCY per user could potentially increase the success rate, which we suggest to investigate in future.

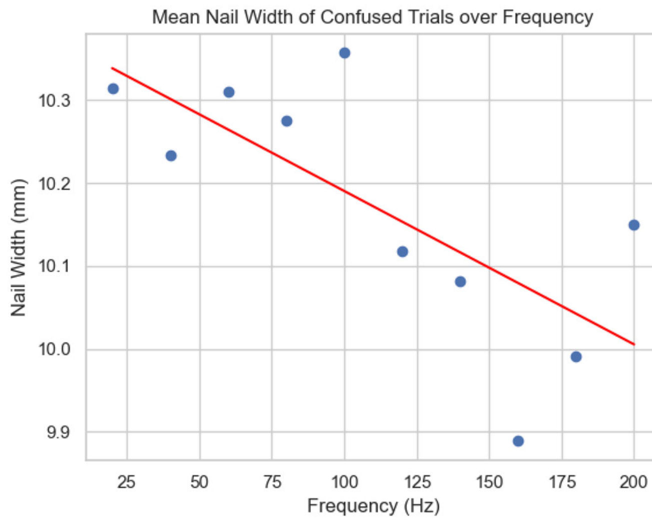

Figure 11. Mean nail width of confused trials plotted over frequency.

7.3. RQ3: How well can PhantomFolds increase realism in MR applications in an unobtrusive way?

Participants confirmed with their feedback in our last study that PhantomFolds does not significantly impede user interaction of the different use case scenarios. The mean OBTRUSIVNESS rating for all use case scenarios was very low ($M = 1.66$ on a 7 point scale). Most participants commented that they could feel the device, but did not feel a disturbed by it in the scenarios, "You feel that the device is there but that's okay." (P6). Furthermore, PhantomFolds significantly increased realism in Use Case Scenario 1 when playing vibration feedback complementary to visual feedback ($M = 4.62$ vs. $M = 3.18$). In our use case evaluation realism was rated to be similarly increased when playing vibration feedback from the finger nail as to when playing it from the finger pad. This motivates future work on haptic feedback devices to increase realism in MR applications through nail mounted instead of pad mounted vibration motors. Nevertheless, *Study 3* did not reveal an effect of tactile and visual feedback matching on the perceived realism. This means that even though PhantomFolds is capable to produce spatial feedback, the directional spatial patterns played using PhantomFolds did not significantly contribute to the increased realism in our first use case scenario. In context of this it should be noted that in Use Case Scenario 1 the participant's finger was fixed on the apparatus, as described in *Study 2*, to create more controlled conditions and establish surface contact. Furthermore, the visual and touch feedback sometimes had a small offset in time: "In some cases the timing is off."(P1, P9). Use Case Scenario 1 was rated lowest regarding all criteria compared to the other scenarios. Overall, we conclude that PhantomFolds can significantly increase the realism in different MR scenarios by rendering tactile feedback for surface interactions from the top of the finger nail in an unobtrusive way. While the realism was increased in our scenarios, they also show that there is still room to improve realism through tactile feedback further. We suggest additional investigations particularly with respect to the influence of spatial tactile patterns using PhantomFolds on perceived realism and other measures such as user performance in the future. In the following section, we discuss another factor that likely influenced perceived realism ratings.

7.4. Trade-off between naturalness and noticeability

The results of *Study 1* show that with increasing VIBRATION_INTENSITY, the NOTICEABILITY increases, but at the same time the NATURALNESS decreases. This suggests that there is a trade-off between NATURALNESS and NOTICEABILITY. By looking at the graph in Figure 6(b), two observations can be made: (1) At a combined VIBRATION_INTENSITY level of 0.38, the subjective NATURALNESS and NOTICEABILITY ratings appear to balance each other out at a neutral rating level. (2) The subjective ratings do not vary greatly for VIBRATION_INTENSITY levels ≥ 1.25. For applications where subtle feedback is required focusing on lower vibration intensities around $0 - 0.38$ may be desirable, and for applications where noticeability is more important than NATURALNESS focusing on VIBRATION_INTENSITY around $0.38 - 1.25$ could be desirable.

7.5. Comparing PhantomFolds to alternative approaches rendering tactile feedback for MR surface interactions

PhantomFolds depicts one of the first approaches with the potential to project spatial feedback below the finger using vibro-tactile illusions for on-surface interactions in MR. Nevertheless, there are several recent alternative approaches that do not use vibro-tactile feedback and should be compared to PhantomFolds in greater detail in the future (Kourtesis et al., 2022). Most notably, Tanaka et al. (2023) proposed using electro-tactile feedback at the back of the hand to provide touch sensations at the palmar side of the hand without impeding user interaction (Tanaka et al., 2023). The researchers report "93.3% of the points where the strongest sensation was felt occured on the palmar side" which hints that this approach could be good alternative to using nail-mounted actuators (with PhantomFolds at 46.23%). However, a current side-effect of most electro-tactile feedback devices is that it can produce unwanted weaker sensations at other locations. *SkinHaptics* used an array of ultrasound transducers at the palm of the hand to induce sensations on the back of the hand. The reported findings are hard to compare as the authors report mainly stimulation within the hand palm. A drawback of this approach could be the energy attenuation and sensitivity to the arrangement and the requirement of a careful calibration to focus the ultrasound to a specific point or region (Spelmezan et al., 2016). While being a more intrusive approach, it would be interesting to explore if this apparatus could also produce sensations at the finger pad similarly to Tanaka et al., 2023) and PhantomFolds. The authors of Tacttoo propose rendering tactile feedback directly at the pad in an unobtrusive way by using a very thin layer of electrodes (Withana et al., 2018). It is yet unknown how the different approaches perform in comparison for different MR interaction spaces. While the reliability of PhantomFolds to render feedback at different locations could be improved for real world applications, we argue that it independently of that depicts a simple, cheap, safe and compact solution to project feedback through the body in an unintrusive and unobtrusive way compared to the other approaches. We find that a direct comparison regarding noticeability, perceived location, spatial resolution, comfort, perceived realism, safety, compactness, energy consumption, obtrusiveness, and feel-through capabilities would be valuable to judge the approaches regarding their relative performance in MR interaction scenarios in the future.

7.6. Influence of different surface-to-finger conditions and individual differences

Many factors such as finger orientation, pressure, and different surface properties (convex, concave, hard, or soft) could influence the perception of tactile sensations at the finger produced by PhantomFolds. In addition, our work mostly focused on the perception of spatial tactile feedback when the finger is stationary and does not move. However, the perception of spatial tactile feedback may change for dynamic finger movements along a surface, especially at different speeds. While these investigations are not focus of the presented work, we believe a better understanding of the influence of these different factors could further help to judge the applicability of spatial tactile feedback rendered at the finger through devices like PhantomFolds and help to develop more effective tactile feedback devices for MR. In the context of potential factors influencing perception, we further note that our studies did not control for individual differences in tactile sensitivity, which could potentially affect the results.

7.7. Improving form factor and multi-finger extension for real-world applications

While PhantomFolds showed to be unobtrusive enough in its current form to allow the participants to interact within different application scenarios with their raw hands, the setup could be further miniaturized to support more seamless long-term operation for real-world applications. E.g., in some cases, the actuators at the back of the finger may still interfere with physical props and hand-held controllers in MR/VR. Furthermore, the electronics, including the driver board, were stationary and not body-worn. In future a device could be designed with similar capabilities, but mounted on the back of the user's finger like *Haplets* (Preechayasomboon & Rombokas, 2021). Alternatively, an artificial fingernail as proposed by Vega and Fuks (2014) using piezo-electric actuators could aim to address those issues. In the future, PhantomFolds could be extended from augmenting a single finger to multiple fingers. This way shapes of objects and textures of augmented surfaces could be rendered more realistically. Similar to the physical keys of an analogue keyboard, the user could more easily feel the edges of a virtual keyboard on a surface to align their fingers better. The tactile cues rendered with such a device could hence improve not only user experience but also text input performance.

8. Conclusion

In this paper, we introduced PhantomFolds, an unobtrusive nail-mounted device consisting of two linear resonant actuators (LRAs) located at the lateral nail folds to generate spatial tactile feedback for in-air as well as on-surface interactions in MR. In a series of three studies, we investigated the perception of spatio-tactile feedback produced by PhantomFolds under various conditions. In study 1, we found that participants perceived phantom sensations at different locations between the actuators and they could more consistently localize the sensations when their finger touched a surface. Study 2 focused on the ability of creating the illusion of sensations below the finger despite rendering stimuli from the top. Our results revealed that participants perceived feedback at the finger pad (i.e., below the fingertip) in approximately 46% of trials and at the finger nail in approximately 40% (they were unsure for the remaining cases). We could show that the overall tendency of perceiving sensations below the finger was statistically significant, indicating that the illusion can occur, but it did not have a large robust effect across all users. Notably, variations in vibration amplitude and frequency did not significantly enhance the effect. We suggest that individual factors, such as fingernail size, may influence perception and propose that personalized calibration could improve the reliability of this tactile illusion in future implementations. In Study 3 we found that PhantomFolds significantly enhanced perceived realism in mixed reality applications while remaining unobtrusive to user interaction. Our findings encourage more work leveraging nail-mounted LRAs to produce tactile feedback in MR applications.

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Ethical approval

The studies of this work have been carried out in accordance with approved guidelines and regulations. Ethics approval for the research was obtained from the University of Auckland Human Participants Ethics Committee, The University of Auckland (Ref. UAHPEC1470).

Disclosure statement

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