Motionless Movement: Towards Vibrotactile Kinesthetic Displays

Yuran Ding
Sensorimotor Interaction,
Max Planck Institute for Informatics,
Saarland Informatics Campus
Saarbrücken, Germany
Department of Computer Science,
University of Maryland,
College Park, Maryland, USA
yding@mpi-inf.mpg.de
yurand@umd.edu

Nihar Sabnis
Sensorimotor Interaction,
Max Planck Institute for Informatics,
Saarland Informatics Campus
Saarbrücken, Germany
nsabnis@mpi-inf.mpg.de

Paul Strohmeier
Sensorimotor Interaction,
Max Planck Institute for Informatics,
Saarland Informatics Campus
Saarbrücken, Germany
paul.strohmeier@mpi-inf.mpg.de

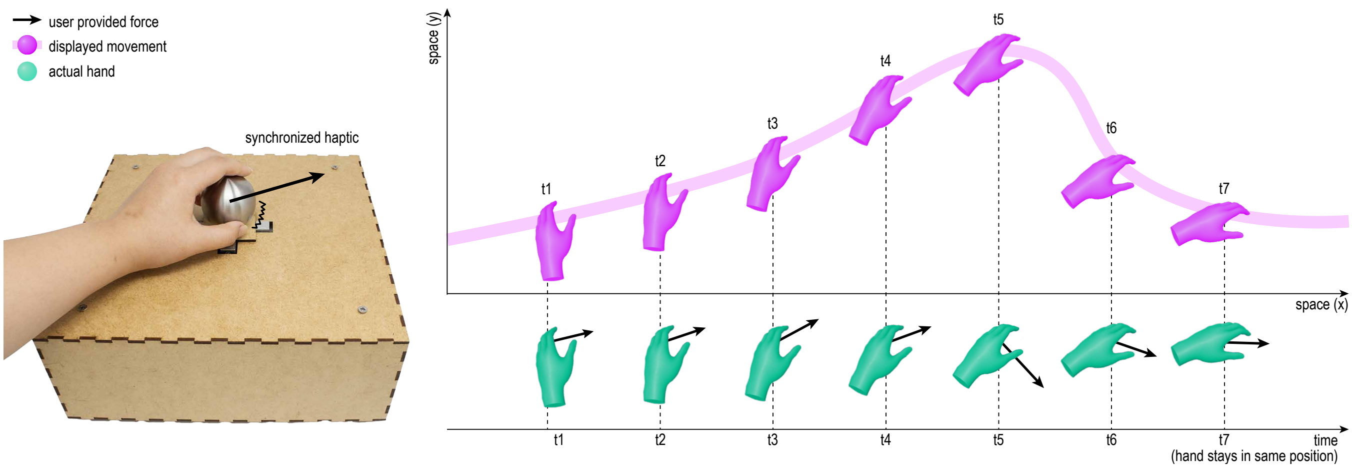

Figure 1: Motionless Movement, a vibrotactile kinesthetic display, offers users the experience of movement when there is none. On the left is our prototype: as the user pushes the handle, vibrotactile feedback corresponding to the force applied by the user synchronizes with the visual rendering of the virtual movement, providing an embodied movement experience. On the right, the graph shows the induced movement experience and actual movement. Note that the actual physical location of the handle and the user's hand stays stationary.

ABSTRACT

Beyond visual and auditory displays, tactile displays and grounded force feedback devices have become more common. Other sensory modalities are also catered to by a broad range of display devices, including temperature, taste, and olfaction. However, one sensory modality remains challenging to represent: kinesthesia – the sense of movement. Inspired by grain-based compliance illusions, we investigate how vibrotactile cues can evoke kinesthetic experiences, even when no movement is performed. We examine the effects of vibrotactile mappings and granularity on the magnitude of perceived motion; distance-based mappings provided the greatest sense of movement. Using an implementation that combines visual feedback and our prototype kinesthetic display, we demonstrate that action-coupled vibrotactile cues are significantly better at conveying an embodied sense of movement than the corresponding visual stimulus, and that combining vibrotactile and visual feedback is best. These results point towards a future where kinesthetic displays will be used in rehabilitation, sports, virtual-reality and beyond.

CHI '24, May 11–16, 2024, Honolulu, HI, USA

ACM ISBN 979-8-4007-0330-0/24/05
https://doi.org/10.1145/3613904.3642499

CCS CONCEPTS

• **Human-centered computing → Haptic devices**; **Empirical studies in HCI**.

KEYWORDS

kinesthetic display, kinesthesia, movement display, haptic rendering, tactile feedback, movement illusion, haptic illusion, human augmentation, embodiment

ACM Reference Format:
Yuran Ding, Nihar Sabnis, and Paul Strohmeier. 2024. Motionless Movement: Towards Vibrotactile Kinesthetic Displays. In *Proceedings of the CHI*

Conference on Human Factors in Computing Systems (CHI '24), May 11–16, 2024, Honolulu, HI, USA. ACM, New York, NY, USA, 16 pages. https://doi.org/10.1145/3613904.3642499

1 INTRODUCTION

We experience the world through a plethora of sensory modalities. Correspondingly, we have developed interfaces that provide humans with information on these diverse sensory channels. Displays for visual information and speakers for acoustics are common and well understood. While other sensory channels do not have interfaces that are as established, tactile displays and grounded force feedback devices are starting to become more common [46], and devices such as temperature [7, 47], gustatory [25, 33], or olfactory [8, 38] displays are being explored within HCI research. One sensory modality rarely discussed in the context of displays is kinesthesia — the sense that enables embodied perception of movement of body parts. The words kinesthesia and proprioception are often used interchangeably, in this paper, we refer *kinesthesia* to the awareness of body movement, and *proprioception* to the sense of the relative positioning of body parts[11].

Information mediated by kinesthesia is vital to us in numerous ways. When moving, kinesthesia helps us understand our movements. This both helps prevent us from injuring ourselves, by preventing overexertion of tendons and muscles, and also helps us better understand the arrangement and material qualities of the world around us. Therefore, kinesthesia is relevant in a broad range of domains, from virtual reality, where users might experience virtual embodied movement, and rehabilitation, where patients might be provided with a greater sense of movement to keep them motivated, to sports training, where athletes are provided with detailed embodied feedback to optimize their performance.

While not commonly referred to as *Kinesthetic Displays*, multiple instances of technologies exist that are able to manipulate the perceived configuration or movement of the body. One way of creating such altered kinesthetic experiences is by manipulating the acoustic feedback of the body. This has been used to change the perceived weight of users [63], provide people with an experience of reaching for far away objects with elongated arms [65], or provide people with an experience of growing fingers or noses [40, 64]. Past research showed that tendon vibrations can create a kinesthetic illusion of movement [17]. Another way of manipulating perceived kinesthesia that has found strong resonance within the HCI community is redirected pointing. By altering the spatial mapping of the visual feedback, researchers have manipulated the objects users grasp or surfaces they touch. Distorting the visually perceived movement allows dramatically manipulating the actually performed movement without creating an experience of mismatch in the user [1, 42].

We suggest a further mechanism: using action-coupled vibrotactile feedback for creating a kinesthetic experience. We base our assumption on literature of vibrotactile compliance illusions. For these compliance illusions, vibrotactile pulses are provided to users at fixed pressure levels [28, 52, 60]. The user then perceives the material they are interacting with as receding under their pressure. While most literature focuses on the perceived change in material, we believe there is a second phenomenon being overlooked: for the user to believe that the material they are pushing is deforming under the pressure of their finger, they must also believe that their finger is moving. In other words, *when experiencing a vibrotactile compliance illusion, users believe their finger is moving, even though it is not.* In this paper, we explore if and how this principle can be leveraged to intentionally induce the experience of movement where there is none.

We envision a general purpose kinesthetic display to have properties like augmenting and altering user actions with feedback, providing convincing movement perceptual experiences to stationary users, and directly actuating a user's body. One key attribute for all the aforementioned properties is that the augmented, altered, and induced movement experience should be embodied and not symbolic. Specifically, these movement experiences should feel natural, embodied, and not needing to be interpreted.

Our work provides a stationary user with an experience of movement, as a first step towards kinesthetic displays. Current efforts to alter body experience such as body distortions and redirected pointing have been relying on actual movement, which can be less favorable in contexts where movements are not so convenient or less cumbersome setups are needed.

We investigate the impact of vibrotactile mappings and granularity on perceived motion, finding that distance-based mappings yield the greatest sense of movement, while increasing granularity increase the magnitude of perceived movement, with diminishing returns after a certain point. We also integrate visual feedback with our vibrotactile kinesthetic display, showcasing that vibrotactile cues outperform visual stimuli in conveying an embodied sense of motion, with the combination of vibrotactile and visual feedback creating the most convincing embodied movement.

Our key contributions are the following:

(1) We investigate grain-based vibrotactile mappings and granularity on a perceived movement experience, and find that distance-based mappings provide the greatest sense of movement with a reasonably high naturalness, while increased haptic grains induces larger movement perception, with declining yields.
(2) Using an implementation that combines visual feedback and our kinesthetic display, we demonstrate that the vibrotactile cues alone are significantly better at conveying an embodied sense of movement than the corresponding visual stimulus, and that combining vibrotactile and visual feedback is best.
(3) We present a prototype vibrotactile kinesthetic display that induces a convincing movement experience when no actual movement is taking place. We use grain-based vibrations coupled with user action attempts to induce friction cues as movement illusions, creating more natural material experiences.

2 KINESTHETIC DISPLAYS

We use the term kinesthetic display to refer to a family of related display technologies. Here, we provide a brief overview of some of these to better position our specific design goal and describe the bigger research context within which we position it. This section will also help to establish a shared vocabulary to support future research in this direction and highlight how kinesthetic displays link to existing HCI research.

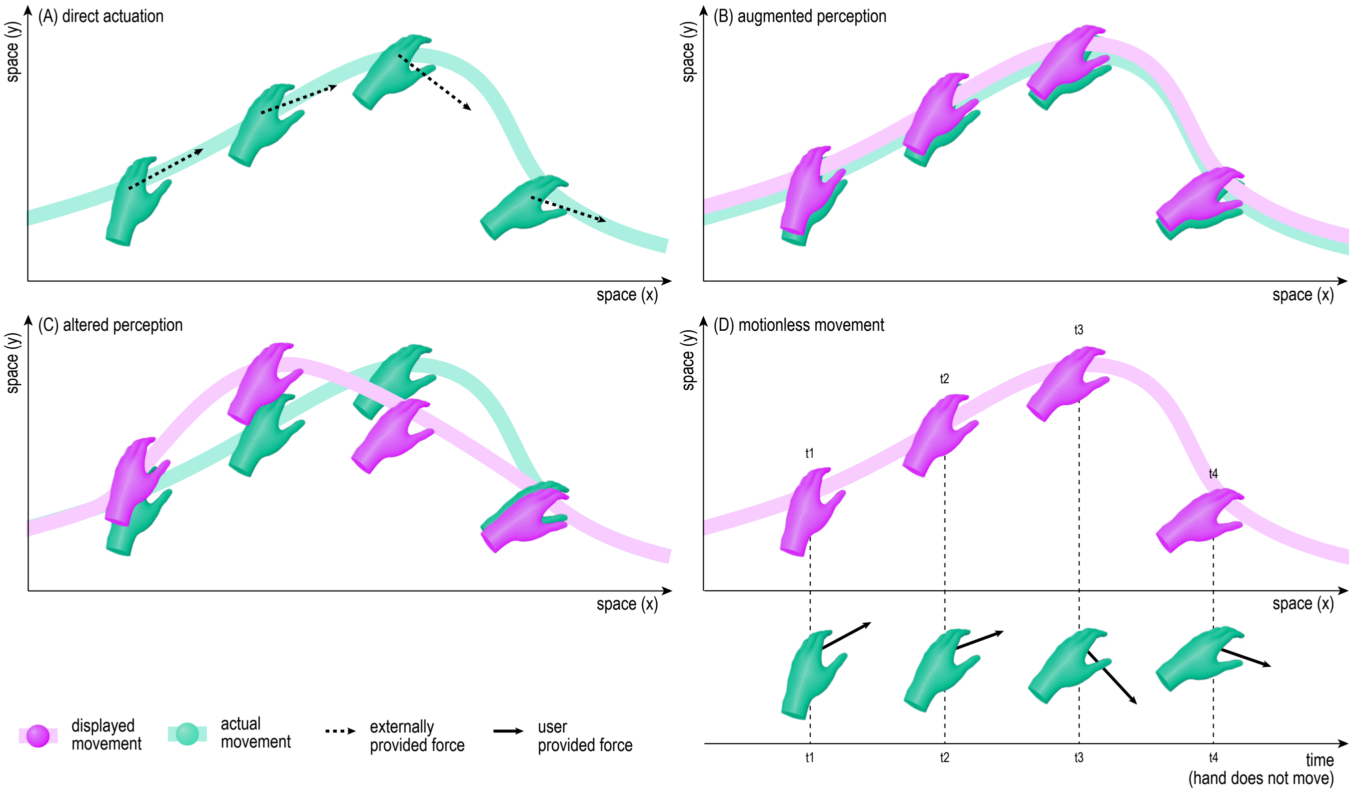

Figure 2: Possible kinesthetic displays. (A) Direct actuation: the kinesthetic display directly actuates a user's body. (B) Augmented perception: the kinesthetic display provides additional feedback on top of a user's actual experience. (C) Altered perception: changing body experience, performing movements the user otherwise could not. (D): Motionless movement: inducing motion when a user initiates action, while actually stationery.

Direct Actuation The most obvious way of conveying a body movement is through direct actuation (Figure 2, A). This is commonly done in many areas, for example, when teaching a sport or fine motor skill, it is common to take someone's hand and literally guide them through that movement [3, 67, 69]. In HCI, such systems often use EMS [35].

Augmented Perception While during *direct actuation*, a system or technology takes control over the user's body, *Augmented perception* is the polar opposite (Figure 2, B). Here, the goal is to provide the user with an augmented experience of their own, self-initiated movements [68]. The goal is, by presenting additional kinesthetic feedback, to provide the user with greater control over their actions. This is a phenomenon we encounter in our day-to-day activities, i.e., drawing with a pencil on a piece of paper provides richer feedback of our movements than drawing with a pencil on the glass surface of a tablet. Friction rendering devices [50, 61] could be considered examples of such perception augmenting kinesthetic displays.

Altered Perception While the purpose of *augmenting perception* is to provide users with more detailed information of the very action they are performing, we might instead *alter perception*, for example, to make people believe they can perform movements they actually cannot, or change how they experience their bodies (Figure 2, C). Jiménez et al. provide audio based methods that change how our bodies are experienced [63, 65], Nishida et al. blend the experience of two people using EMG and EMS [43], Shunichi et al. and Nishida et al. accelerate human reaction [27, 41], and Azmandian et al. change how we perform our movements [1].

Motionless Movement A further manifestation of the concept of kinesthetic displays are systems that enable experiencing motion even when the user remains motionless [39] (Figure 2, D). Here, we imagine transforming pressure cues or other movement-onset signals into feedback of movement. The user will experience tactile feedback of a movement that they do not perform. This can offer people opportunities to perform movements that they are otherwise not able to perform, be it due to physical limitations or space constraints.

An important distinction between these displays is the locus of control. For **direct actuation**, the control typically lies with the display, while for **augmented perception** it typically lies with the user. **Altered perception** and **motionless movement** come in two sorts: the movement experiences provided with such displays are initiated by the user, or they are provided to the user externally.

3 RELATED WORK

Kinesthesia enables mundane activities such as typing or lifting a glass to our lips, as well as feats like playing a piano concert or competing in an elite sport. Kinesthesia not only provides information about our body, but also helps form an embodied understanding of the world around us. In this section, we look at the literature on kinesthesia, how bodies can be moved by digital systems and how perception of movement can be created or altered using kinesthetic displays. Finally, we highlight how vibrotactile feedback coupled to human action can induce contingent material experiences, including sense of motion.

3.1 Kinesthesia

Kinesthesia can be defined as the perception of the position and movement of joints, body segments, and our body. Kinesthesia also plays a role in understanding our body shape and muscle forces [49]. Research has shown that it is possible to induce a sense of change in kinesthesia by providing audio, visual, and tactile cues [1, 63].

Tactile cues are fundamental to the sense of kinesthesia. It has been shown that in cases of emergency, tactile cues override other self-motion cues [22]. Schiller et al. further showed the role of muscled spindles as a source of feedback for proprioception [55]. Further, Hagert showed the importance of pacinian corpuscles for kinesthesia during wrist rehabilitation [21]. Tactile cues caused by skin stretch has also been shown to play an important role in kinesthasia [31]. In this paper, for the sake of simplicity, we use kinesthesia to refer to the introspective experience of relative *movement* between limbs of the body. Proprioception we refer to as the experience of the *position and orientation* of these limbs.

3.2 Technologies that Move the Body

In HCI, inducing body movements in a user is typically achieved by either grounded force feedback or electrical muscle stimulation (EMS) actuation.

3.2.1 Grounded Force Feedback. Grounded force feedback, which involves providing physical resistance or forces from a fixed stable base, has been explored, for instance, by providing a full six axis motion platform for each foot of the operator [51]. Furthermore, exoskeletons providing kinesthetic feedback have also been developed to assist in hand rehabilitation [19, 20, 57]. Exoskeletons with force feedback have also been used to physically assist elderly people [9]. Full-body suits with kinesthetic feedback have been used in VR gaming as well [1]. Additionally, grounded force feedback systems such as Hapseat [13], which use mobile armrests or headrests to apply forces to the user, have been used to alter kinesthetic experiences. However, kinesthetic feedback devices are grounded, thus restricting the users to a fixed location, and are bulky and expensive [46].

3.2.2 Electrical Muscle Stimulation. Another way of moving the body is by using electrical muscle stimulation (EMS). For instance, Lopes et al. used an interactive system with EMS that steers the user's wrist while drawing [34, 37]. EMS has also been used for controlling the direction of a user is walking [48]. Furthermore, Pose-IO is a wearable interface that offers input-output functionality based on the sense of proprioception [35]. EMS has also been used to show users how tools might be used, by electricaly inducing the required movements [36]. Nishida et al. also developed a wearable interface that measures electromyogram (EMG) signals and uses EMS simultaneously to share and augment kinesthetic feedback, which can be used for sports training and for hand tremor correction [44].

We extend upon this work by presenting an approach that conveys movement experiences without physically moving the user.

3.3 Isometric Input

In motor-control literature, human actions have been broadly classified into two types: isometric and isotonic [56]. Isometric actions involve muscle contractions devoid of joint movement, relying on force or torque, while isotonic movements entail joint movement alongside muscle contractions. These terms have been appropriated to describe different types of user input devices [72]. Isotonic devices can be moved effortlessly, most famously including the mouse. Isometric devices are less well known but also common, for example, the track-point of many laptops translates input force into mouse movement. When supplemented with compelling visual feedback, past explorations of isometric controls have been able to alter the proprioceptive sense of users, giving them an illusion of using nonisometric devices due to visual dominance [32, 39]. *By augmenting the user's isometric actions with action-coupled vibrotactile feedback, we aim to increase the extent to which users experience such isotonic movement illusions and the ease with which they can be induced.*

3.4 Sensorimotor Contingencies and Kinesthesia

The work presented in this paper is inspired by reflections on active perception by O'Regan and Noë [45], who show that our sensory modalities are active ways of exploring the world. These explorations are mediated by knowledge of *sensorimotor contingencies*, that is, by the *law-like correspondence between motor activity and resulting changes in sensory information* [45]. For example, in visual perception, we expect that stimuli in the visual field move left when the gaze shifts to the right.

There are diverse examples of systems that implicitly modify such sensorimotor contingencies to induce a sense of kinesthesia. For instance, haptic retargeting in VR is achieved by creating a mismatch between the physical and virtual positions of a user's hand. Here, the user subconsciously attributes the mismatch between performed action and expected outcome to an error in their kinesthetic experience and assumes the visual representation is correct. This enables guiding the user's physical hand, for example, to touch a proxy object that provides haptic feedback [1]. This method of steering the user's movements is the subject of ongoing investigation [15, 18]. Additionally, Nakamura has proposed a concept of providing visual feedback in the absence of actual user movement, facilitating a sense of movement in VR without physical motion [39]. Alterations in sensorimotor contingencies can also affect body perception. Manipulations of sensorimotor contingencies can also change how we experience our bodies. For instance, the sound of

[1]EXIT SUIT (https://github.com/willie-winkler/EXIT-SUIT)

footsteps can alter the self-perception of body weight [63], and the illusion of arm elongation can be created by shifting the origin of a tapping sound away from the actual tapping location [65].

The above examples are mediated through visual and acoustic stimuli, rather than our sense of touch. This is surprising, as mechanoreceptors of the skin play an important role in the perception of bodily movement [12, 21], and proprioceptors are also sensitive to mechanical stimuli; for example, vibrotactile stimulation of the tendons is experienced as an elongation of the muscle [70]. This is the basis of the well-known *"Pinocchio Illusion"* [29], in which a user who is touching their nose while their biceps is vibrated experiences their nose as being elongated [5]. There is a wide range of such illusions [54, 66]. However, these illusions are not easy to elicit consistently, and it is unclear how to systematically take advantage of them [66]. *With this paper, we present steps towards enabling consistent elicitation of such illusions, to enable technology designers to systematically use them in designs.*

3.5 Vibrotactile Rendering

Material properties are also experienced through sensorimotor contingencies. For instance, sliding one's hand over a material like wood creates vibration due to the friction between the wood's microstructure and the structure of one's finger. Bensmaïa and Hollins recorded the frequency spectra of such vibrations and showed that variations in vibration correlate with differences in experiences [4]. In other words, the feedback caused by our actions is what enables the experience to emerge. If a vibration is closely coupled to the dynamics of an action, it is not perceived as 'buzzing' but as a material property [52, 53]. Essentially, mapping the user input using mechanisms like sliders for linear motion, knobs for rotary motion, and buttons for pressure can be coupled with vibrotactile feedback to render material properties.

By preserving this close coupling, this sensorimotor contingency of material perception, a broad range of experiences can be created. Examples include virtual compliance while interacting with rigid materials [28], the alteration of perceived material properties [59], and experiencing deformations like twisting, bending, and torsion [23], or even feeling resistance in mid-air [58]. All these experiences can be implemented by the same general algorithm. Sabnis et al. presented a driving device, Haptic Servos, which provides a general-purpose approach to implementing material experiences using an input-output mapping algorithm [52]. This shows that the effectiveness of these systems lies in their ability to replicate the sensorimotor contingencies we naturally expect when interacting with materials.

The distinction between a material property and a movement may simply be a matter of one's frame of reference. For example, when Heo et al. [23] asked participants how much they could bend a rigid rod, the question framed responses in terms of changing material properties. Alternatively, asking participants how far they moved their hand would yield different responses; they would report greater movement if tactile stimulation was present and lesser movement if it was not. Similarly, while the haptic shoe presented by Strohmeier et al. [60] was described as changing the material of the ground, this also leads to a change in experienced movement, with participants reporting their foot moving into the ground more or less, depending on stimulation parameter choice. *In this paper, we assume that material and kinesthetic cues are equivalent to different sides of the same coin. We explore the use of action-coupled signals as used in material rendering for inducing kinesthetic experiences.*

3.6 Ways of Perceiving

In motor-control literature [56], a distinction is made between intrinsic and extrinsic feedback. Intrinsic feedback refers to the sensations athletes experience from their own movements, such as the vibration of a tennis racket due to air friction. In contrast, extrinsic feedback comes from external sources, such as a visual analysis of the racket's swing velocity [56].

This concept aligns with distinctions made in discussions about technological mediation [71]. Don Ihde talks about embodied and hermeneutic mediation [24]. For example, an augmented shoe might provide informaiton about surface compliance in two different ways. Embodied mediation would allow the wearer to feel the compliance directly through their actions. Hermeneutic mediation, on the other hand, might involve an indicator showing how deep the foot has sunk into the ground. In the embodied scenario, the experience is *pre-reflective*; the user intuitively perceives the softness of the ground without the need to consciously focus on it. Conversely, in the hermeneutic scenario, the user must actively observe and interpret the indicator to understand the ground's softness. This understanding emerges through *reflection. In this exploration, we aim to provide users with an experience as close as possible to intrinsic feedback, enabling an embodied pre-reflective understanding of kinesthesia.*

4 DESIGN RATIONALE

Kinesthesia, our sense of movement, underlies the experience of all human activities. From typing on a keyboard to riding a bicycle, these actions are experienced and enabled through kinesthesia. Introducing a display that provides kinesthetic experiences would transform our interaction *with* and understanding *of* the body. It would make the personal experience of kinesthesia shareable and communicable. Traditionally, understanding movement often requires performing it, evident in scenarios where teachers or therapists manually guide their students' or patients' movements. A kinesthetic display would allow the sharing or transferring of movement experiences. In music, sports, physiotherapy, and rehabilitation, students or patients could directly experience their instructors' movements, even without prior knowledge of performing them. Furthermore, kinesthetic displays would enable users to experience movements in virtual reality that might be impossible in the physical world. This would enable us to work with movement similarly to how we work with other media, such as images or sounds.

In this paper, we explore the type of kinesthetic display we call *motionless movement*. We choose this oxymoron intentionally, because when interacting with this interface users do not perform any motion, yet they experience movement. Our prototype kinesthetic display is *motionless*, but not *actionless*. It requires users to actively apply pressure to the object. For the sake of simplicity, we focus on a single end effector, a hand of a user. The user interacts with the system by applying pressure to a rigid object. The rigid object

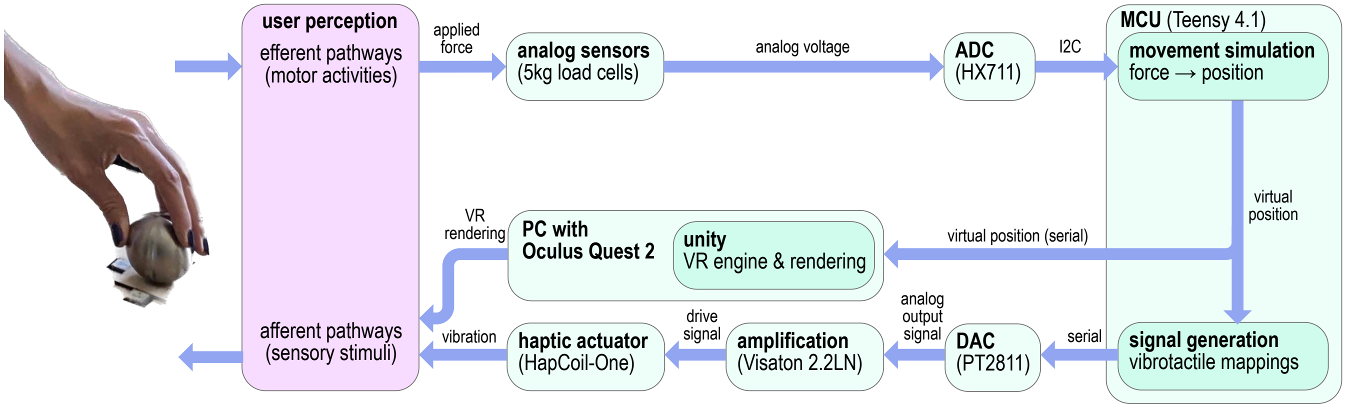

Figure 3: System flowchart for the prototype vibrotactile kinesthetic display.

then provides tactile feedback simulating movement to the user. Again, for sake of simplicity, the current prototype is a desktop-mounted device. One might, however, imagine integrated these devices in the armrest of a chair, enabling users to perform virtual arm movements in VR.

The current system explored in this paper does not yet meet all the ambitions we have for kinesthetic displays. However, it allows us to explore if our theoretical considerations for the design of such displays hold. The insights from designing this type of kinesthetic display will be transferable to other non-grounded kinesthetic displays.

4.1 What is a *good* kinesthetic display?

There are many ways in which we can provide movement cues. For example, we could vibrate the right hand side of a limb to indicate movement to the right and the left hand side of a limb to indicate movement to the left. As long as the user keeps track of the tactile signals, they can form a mental model of their movement. This way of understanding movement, however, remains symbolic and requires constant attention from the user. According to Ihde the movement information would be *hermeneutically mediated* [24]. One might also say that the feedback is *extrinsic* [56]. We do not believe such a device to provide especially compelling user experience.

We believe a good kinesthetic display should provide movement cues in an *embodied* manner [24]. The user should be able to understand the movement pre-refletively, even without consciously attending to it. The goal of a *good* kinesthetic display should be to provide feedback indistinguishable from *intrinsic feedback* [56].

4.2 Theoretical Grounding

Visual and auditory perception are both distal senses corresponding to a clearly defined physical phenomenon. Both senses enable us to perceive stimuli external to our body. Seeing allows us to perceive a distinct physical phenomenon – electromagnetic radiation between 350 and 750 nm. Hearing allows us to perceive a distinct physical phenomenon – pressure fluctuations between 20 and 20,000 Hz. These two properties make it comparatively easy to build displays. All which is required is an object, external to the body, which produces the required physical phenomena.

Kinesthesia, on the other hand, is significantly more complex. For one, it is an internal, proximal sense. The phenomenon we perceive through kinesthesia originates from our person, rather than an external object. Additionally, there is no single, clearly bounded corresponding physical effect, rather kinesthesia relies on a combination of visual, haptic, acoustic and interoceptive cues. The combination of these properties make it appear prohibitively difficult to build a display for the sense of kinesthesia.

Looking towards perceptual theories which emphasis the role of human action in perception, however, provides a way forward. O'regean and Noë [45] suggest that the defining characteristics of different sensory modalities are not the physical phenomena they reveal to us; after all, any stimulus simply results in firing of nervous cells. There is no qualitative difference from on cell firing to another cell firing. Instead, O'Regean and Noë suggest that it is the learned patterns between motor activity and sensory information which form the basis of the different senses and enable us to make sense of the world. For example, when we move our eyes to the right, this allways goes hand in hand with firing caused by the visual field shifting to the left. O'Regean and Noë call these patterns of action and feedback *sensorimotor contingencies* [45].

This suggests that, when creating a display for kinesthesia, we need not identify the physical phenomenon to recreate, but instead identify sensorimotor contingencies which acompany kinesthetic perception. One such contingency is that when moving, tactile feedback occurs at frequencies proportional to movement. For example, when moving our finger over a grid, tactile impulses occur at slow rate, when we move our finger slowly and at a fast rate, when we move our finger fast. This work explores if this sensorimotor contingency alone can be used to convey a sense of movement, even when the user is not moving.

4.3 Research Approach

We explore the use of sensorimotor contingencies for the design *Motionless Movement* displays by means of four studies. These studies explore how design choices influence user perception and each study builds upon the previous. In Study 1, we investigate how

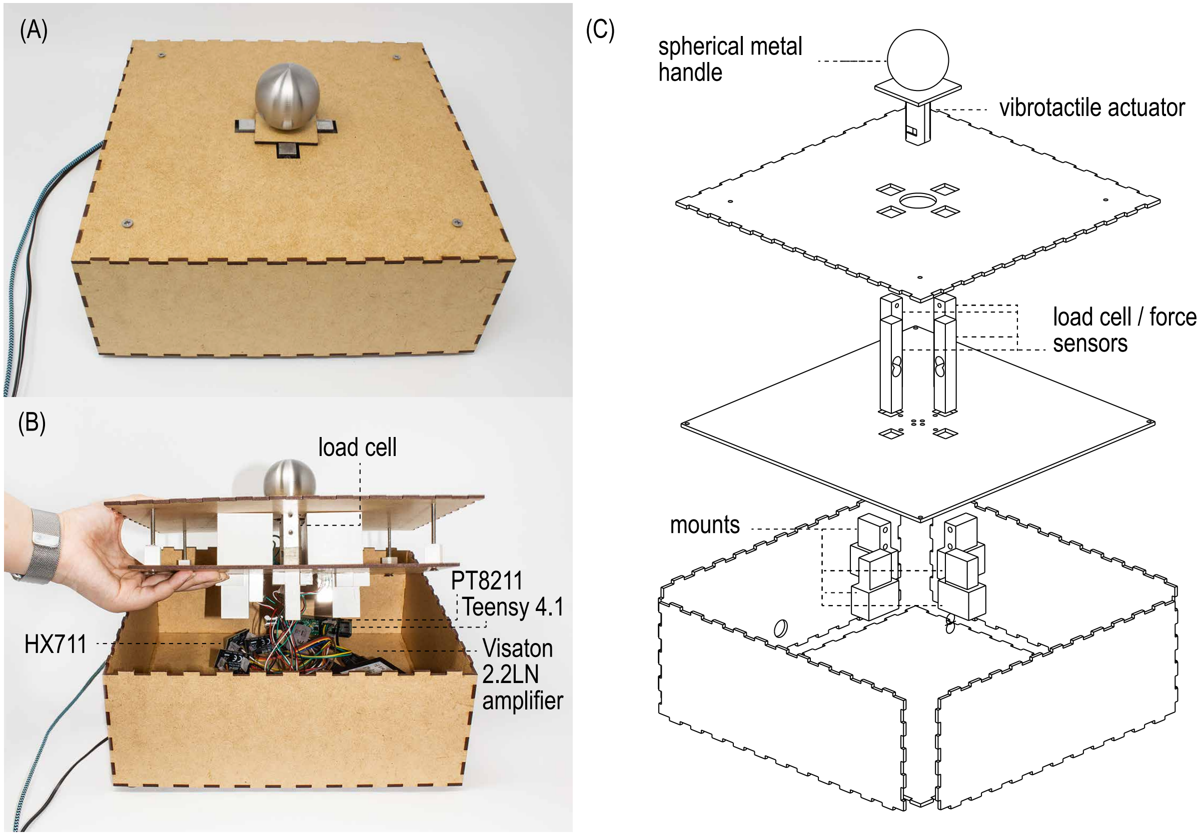

Figure 4: Prototype vibrotactile kinesthetic display. (A) Image of the prototype vibrotactile kinesthetic display. (B) Interior of the vibrotactile kinesthetic display, with hardware components labeled. The display is connected to the computer through cables. (C) shows the mechanical design for the prototype vibrotactile kinesthetic display in the explosion view.

grain-based haptic mapping methods might affect perceived magnitude and naturalness of the movement experience. This is to identify a desirable mapping that induces embodied movement experiences. The purpose of Study 2 is to understand how granularity of the desirable haptic mapping might affect the magnitude of perceived movement experience using the desirable haptic mapping method in Study 1. In Study 3, we add visual feedback in virtual reality to the experience, to identify if and how haptic granularity would be mapped to the magnitude (gain) of visual movement. In particular, what visual mappings would seem "just right" for the corresponding haptic granularity. Taking the visual-haptic match that users reckon "just right", that fits their mental model of the movement experience, Study 4 further examines the interplay of visual and haptic stimuli on the experience of movement. This information is of interest in estimating the relative strength of tactile and visual cues on the movement experience. Beyond the current motionless movement context, the findings of these studies can be applied to the design of future vibrotactile kinesthetic display types, such as augmented or altered movement.

5 IMPLEMENTATION

To conduct the studies discussed in the previous section, we have designed a haptic feedback device which translates pressure input into vibrotactile signals. The purpose of this device is to induce a sense of movement in users, even though their hand remains motionless (Figure 1). Users provide pressure on a spherical metal handle, which is detected by load cells. This pressure input is then transformed into vibrotactile signals and visual rendering data through a microcontroller. Finally, users experience this integrated feedback through haptic sensations and virtual reality renderings. If one considers the user part of this system, what we have built is a closed loop perception augmentation device. A system overview can be found in Figure 3.

In this section, we document the hardware setup, movement simulation, action coupled feedback algorithm, and virtual reality renderings for our prototype vibrotactile kinesthetic display. All the design files and codes will be openly accessible post acceptance.

5.1 Hardware Setup

For the physical construction of the prototype, we laser-cut a 3mm MDF board to create an enclosure for the force sensors and the vibrotactile actuator. This enclosure includes a center hole on top to accommodate a spherical metal handle (55mm in diameter) and four holes to accommodate the four mounted 5kg straight bar load cells. For convenience of mechanical design and to avoid unwanted coupling, we vertically mount the four load cells to detect the force

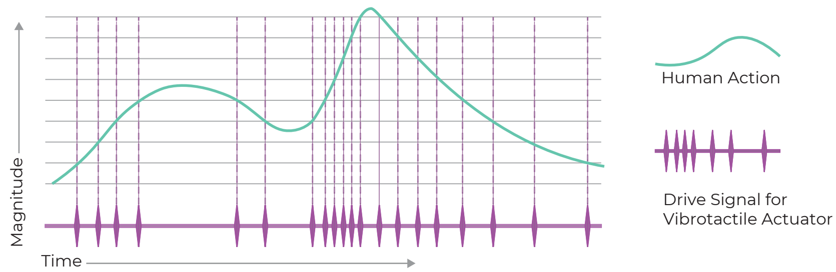

Figure 5: Generic visualization of tactile mapping algorithm. The y axis shows the measured magnitude of some aspect of human action, while the x axis shows how the signal unfolds in time. We describe the resulting signal as *action-coupled.*

applied to the sphere handle in four directions within the horizontal plane when users initiate movement. We fix the handle to avoid wobbling, which might hamper the perception of movement.

A washer is fitted between the four load cells to prevent any additional force on the load cells in the resting state. We connect a HapCoil-One vibrotactile actuator from Actonika (frequency range 10Hz-1000Hz) using a 3D-printed PLA casing to directly vibrate the metal handle. The casing is designed to mount the actuator vertically and constrain the vibration propagation along the screw into the metal handle (Figure 4).

5kg load cells (strain gauges) are each connected to an HX711 load cell amplifier board (modified to have its maximum sampling frequency of 80Hz) that sends data to the Teensy 4.1 development board using I2C communication protocol (Figure 4, Figure 3). While, in theory, the user's pressure actions can be fully captured using two strain gauges, we find it convenient to use four sensors, which reduces the mechanical complexity of the device. We measure force in four directions, forward, backward, left, and right. The left and right signals are then combined in software to form the x dimension, while the forward and backward signals are combined to form the y dimension. Signals from the load cells are sampled by 80Hz, which is the maximum sampling frequency of HX711 Analog to Digital Converter.

Vibrotactile signals are produced by customizing Haptic Servos [52] which uses the Teensy Audio Library capable of running at the highest rate of 44.1KHz [2]. The HX711 is polled at 80Hz, while the haptic signal is updated at >200 Hz. The output from the microcontroller is then converted to analog signals using a PT8211 DAC shield. The analog signal is amplified using a Visaton 2.2LN amplifier and rendered into vibrations with the Hapcoil-One [3] (Figure 4, B and C; Figure 3). We provide more details about the haptic mappings coupled to a user's movement intention in Subsection 5.3.

5.2 Action-Coupled Feedback Algorithm

To render vibrotactile feedback based on the applied force by the user, we divide the sensor range between the resting value of force into a number of discrete bins. When a sampled sensor value changes and enters a new bin, an AC pulse (i.e., audio signal) with a designed waveform, duration, amplitude, and frequency is generated. When the signal changes fast, pulses are generated rapidly. When the signal changes slowly, pulses are generated proportionally slowly. The relevant variables required for generating the signal are the number of bins, which corresponds to the overall density of pulses (in the sensor range), a.k.a. granularity. The vibration specification of each pulse is determined by the type of waveform used as well as the duration, amplitude, and frequency of that waveform.

5.3 Haptic Signal Mappings

We have designed four types of vibrotactile signal to explore in our experiments. Taking inspiration from the material compliance illusion Kildal [28]. Our first mapping is **pressure-based**. Here we take the magnitude of instantaneous force in the direction of movement and map it against a maximum of 10N with 300 grains (Figure 6, A). This results in a clear experience of movement, however, in our experience, the movement feels small.

To enable bigger movements, we introduce a **distance-based** mapping (Figure 6, B). Using a simple movement simulation, we transform the force signal used in the first mapping to a position. We couple grains to this virtual position, creating an experience similar to a grain-based friction illusion (cf. the implementation by Strohmeier et al. [61]) along the simulated movement path. The output of the movement simulation model is mapped against a maximum instantaneous displacement value of 0.01m with 400 grains.

An issue we experienced with this distance-based mapping is that movement onset and the endings of movements did not feel compelling. To address this, we created a **hybrid** mapping (Figure 6, C). This uses a pressure-based mapping up to when the force in the direction of movement reaches 1.2N (this value is selected to roughly match the force needed to overcome the static friction for moving a 0.5kg object on a desk). When forces exceed 1.2N, the mappings become distance based. Finally, for reference, we also created a mapping which simply displays **continuous vibration** when force is exerted (Figure 6, D). For generic visualization of tactile mapping algorithm, see Figure 5.

5.4 Movement Simulation

To implement the distance-based and hybrid mappings, we have built a movement simulation model in Arduino IDE and uploaded it to Teensy 4.1; it takes in the force sensed by load cells when users

[2]Teensy Audio Library (https://www.pjrc.com/teensy/td_libs_Audio.html)
[3]Hapcoil-One by Actronika Data Sheet (https://uploads-ssl.webflow.com/5eb037130a8b570a78e002a0/600946155d92f4663545dbfa_HapCoil_One_HC121238O_datasheet.pdf)

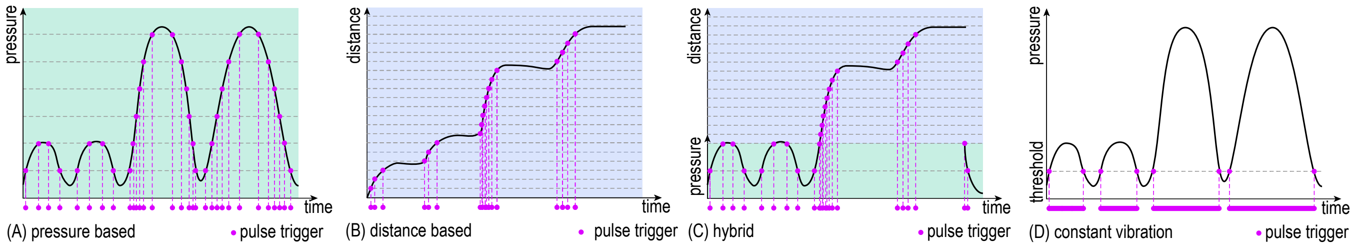

Figure 6: Visualization of the four types of vibrotactile signals with respect to the same user action. The bin sizes are arbitrary, intended to provide a general idea of generating action-coupled vibrations. When the black line (corresponding to measures of user action) crosses the horizontal dotted lines (representing the bins), a vibrotactile pulse is triggered. (A) illustrates the pressure based mapping as known from compliance illusions; (B) illustrates distance based mapping, where the bins are mapped against the instantaneous distance travelled, computed based on pressure input; (C) illustrates the hybrid mapping, which combines pressure based mapping with distance based mapping. (D) illustrates continuous vibration triggered upon reaching a threshold.

initiate movements and outputs variables for haptic and visual renderings. The model assumes a constant mass ($m = 0.5kg$) of the spherical handle and no friction. We take readings of the four load cells and compute the force (F) applied by the user. We calculate the acceleration (a), velocity (u) and displacement (s) of the ball based on Newton's laws of motion ($a = F/m$, $s = ut + \frac{1}{2}at^2$, where t = the time of each system loop and $m = 0.5kg$). Specifically, the velocity (u) is initially 0 and is updated for each loop, which is computed by adding initial velocity of the previous loop to the product of acceleration (a) of the previous loop and time ($u_{current} = u_{previous} + a_{previous}t_{previous}$). The acceleration ($a$) is also updated every loop, computed by the force (F) sensed by the load cells in the direction of movement divided by the constant mass. The sampling frequency of force is 80Hz (at the maximum of HX711 load cell amplifier). The system loop takes around 12ms. To communicate to Unity, the position information of the sphere computed by the movement simulation model is printed to the serial port.

5.5 Signal Modulation

All mappings are additionally modulated based on user applied pressure (see also a similar approach by Strohmeier et al. [59]). Frequency starts from 60Hz and logarithmically increases to 100Hz when the force reaches 10N, while amplitude started at 0.1 and logarithmically increases to 0.6 when the force reaches 10N. Both amplitude and frequency follow logarithmic mappings.

5.6 Virtual Reality Renderings

Although our prototype vibrotactile kinesthetic display does not require visual renderings, we add a VR scenario to increase the realism of the experience. This VR scenario features a hand avatar pushing the sphere on a pebbled plane in Unity3D (Figure 7, B). Note that the pebbled texture is just a placeholder texture for experiment purposes and is not related to vibrotactile mappings and renderings in any sense. Hand tracking is enabled by the Oculus Hand Tracking Library and the Oculus Integration package in Unity. The hand avatar and the sphere in VR represent the user's way of grabbing or pushing the spherical handle in the real world. We use the Aridity library in Arduino, allowing bidirectional communication over COM ports from Unity. Unity takes in the position information of the sphere from Arduino and renders the moving sphere. We connect an Oculus Quest 2 to display the embodied movement in VR, synchronizing it with the user's actions initiated on the metal sphere handle and the coupled haptic feedback.

The prototype vibrotactile kinesthetic display was used for all studies. We also used the same motion simulation model Arduino Code for signal generation and virtual position calculation. However, we only integrated the VR renderings in our last 2 studies that investigated the matching and interplay of visuals and haptics.

6 EVALUATION

As explained in **Design Rationale** (Subsection 4.3), we conducted four comprehensive studies to investigate the effectiveness and implication of the prototype vibrotactile kinesthetic display. We first investigated the impact of vibrotactile mappings on perceived movement in terms of naturalness and magnitude. Additionally, we explored the influence of the granularity of vibrotactile mappings on the magnitude of the perceived movement and examined potential correlations between haptic granularity and visual gains. Finally, we assessed the effectiveness of virtual reality (VR) and haptic renderings in shaping beliefs about movement. For all studies, we obtained consent from participants and compensated them at the standard rate of 12 €/hour for their time and effort.

6.0.1 A Note on Methods. We present all our results as interval estimates [30], as these provide a better intuition of the underlying phenomena of interest than p-values [14]. However, though we prefer to avoid null hypothesis significance testing [2, 6, 10], these interval estimates can also be used to find equivalent information: To establish whether differences between levels are significant, we calculate the 95% confidence interval of the difference of adjacent estimates. The confidence intervals for the differences of means provide a range of likely values for $\mu_1 - \mu_2$. If there is no difference between the population means, then the difference will be zero (i.e., $\mu_1 - \mu_2 = 0$). If a 95% confidence interval includes the null value, then there is no statistically meaningful or statistically significant difference between the groups. If the confidence interval does not include the null value, then we conclude that there is a statistically significant difference between the groups [62]. For all results we

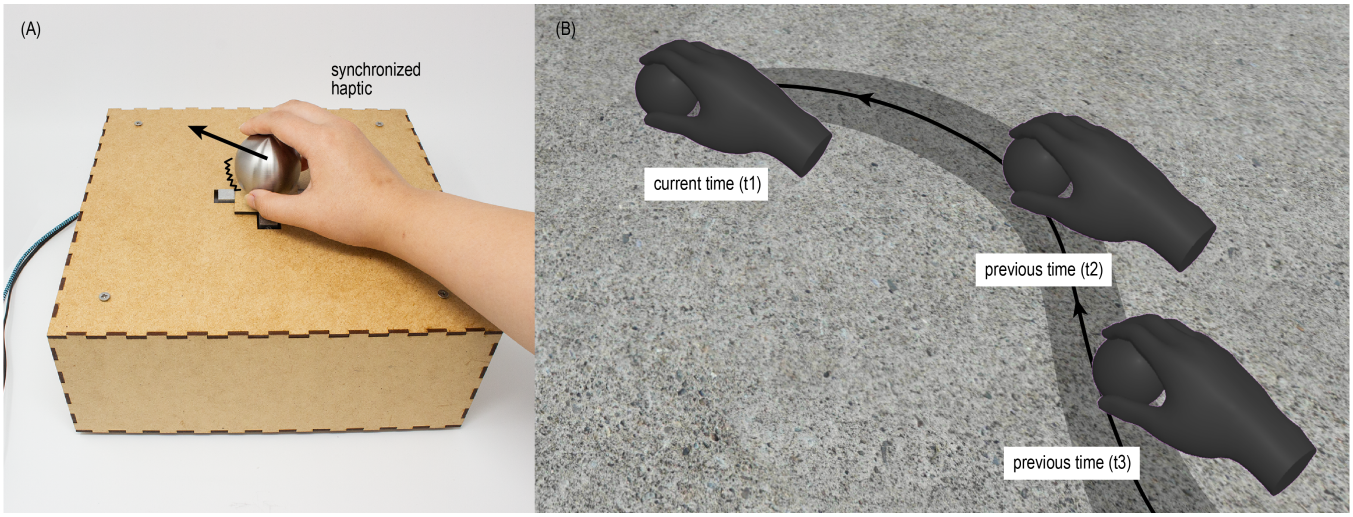

Figure 7: Setup when a user intents to push the sphere forward. (A) shows the physical setup of the display. The display provides synchronized haptic feedback together with the VR visual renderings. (B) shows the VR renderings of the path of movement.

will report confidence intervals and, where relevant, confidence intervals of the differences of means.

6.1 Study 1: Movement Perception of Haptic Mappings

To understand how haptic feedback mapping methods affect the magnitude of perceived movement, and to understand whether this experience was induced in an embodied manner, we performed a magnitude estimation study. In this study we compared three methods of mapping user action to haptic feedback (distance-based, hybrid, pressure-based) and two control conditions (constant vibration, no vibration). For all vibrating conditions, amplitude and frequency of vibrations were also modulated the same way so that they increase logarithmically with acceleration.

6.1.1 Stimuli. We used the four haptic stimuli described in Section 4.3, hybrid, distance-based, pressure-based, and continuous. We also added a fifth stimulus as a reference, which was a condition with no vibration at all.

6.1.2 Procedure. The study was conducted with 10 participants, 9 right-handed and 1 left-handed, all of whom have normal haptic perception. The study lasted approximately 30 minutes. The vibrotactile kinesthetic display with the spherical metal handle on top was placed on the desk. Participants remained standing so that their arm rested naturally when pushing the sphere. Participants were asked to imagine pushing a ball on a horizontal plane. They were then instructed to freely push the spherical metal handle in any direction. Participants were blindfolded and wore earphones that played white noise to mask the audiovisual cues. They were then instructed to rate the haptic experience based on the two following aspects:

(1) How large is the **movement** perception? Compared to other conditions, how much do you feel you can move the object? Note that it is not about estimating the distance you move, but about the movability of the object. Assign large numbers if the experience suggests that the ball can be moved far, and small numbers if the movement is very subtle. (Do not worry about whether you feel the experience is realistic or not.)
(2) How **natural** does the experience feel? Does it feel like something you are familiar with from interacting with physical materials, or does it feel more like a vibration created by a machine or device? Assign large numbers when the experience feels like something you might experience when interacting with physical materials and small numbers when it feels artificial, like vibrations you might be familiar with from your phone or a machine. Do not worry about movement in this case, for example, even if you do not feel movement, but it feels natural like physical materials, you should give it a high score.

We adopted the same procedure for magnitude estimation in psychophysics studies [16]. Participants were told when a set started and were asked to assign any integer rating they wanted for the first stimuli of the set and base their rating for the rest of the stimuli in this set on the difference between the previous stimuli. They were told that there was no limit on the range of ratings they could give, but they had to keep the scale in the same set (5 stimuli) consistent. They were also encouraged to share their experience out loud as they explored the stimuli. Throughout the study, their comments were recorded.

The 5 conditions were presented in a balanced Latin square method, with 4 repetitions per participant, to avoid order effects. Before the actual study began, participants were asked to perform a practice set with 5 conditions to familiarize themselves with the rules.

6.1.3 Result. Data was standardized for each participant by first removing the participant's average response from each estimate and then dividing each estimate by the standard deviation. Resulting data is in standardized units. An estimate of one indicates that

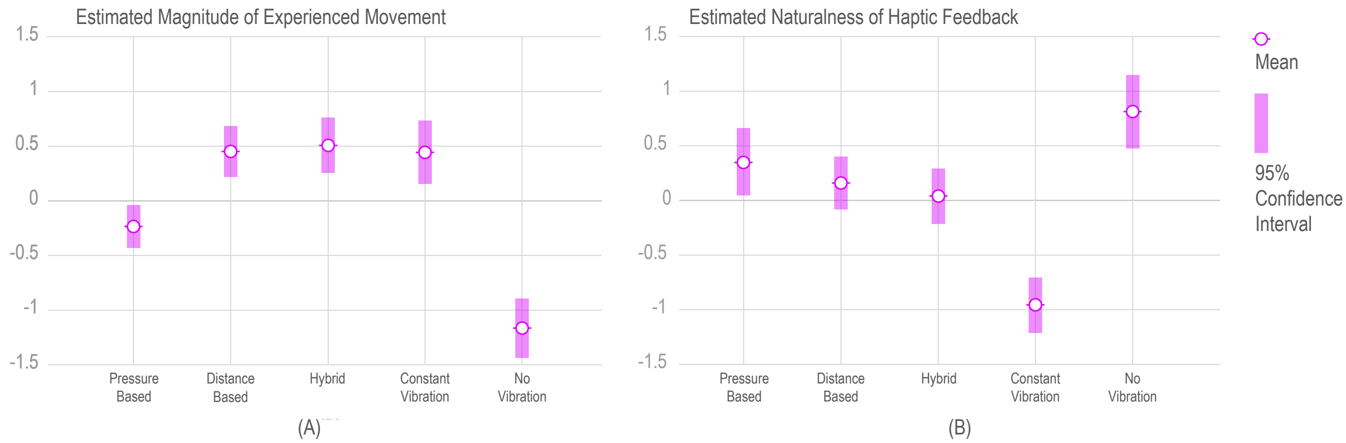

Figure 8: (A) Estimated magnitude of experienced movement by haptic mappings and (B) estimated naturalness of haptic feedback. Y axis shows standardized estimates, the unit is standard deviation with respect to the per user average estimate.

this estimate is one standard deviation above the average estimate for that user. This highlights differences between conditions while removing individual differences between participants. We then computed the mean and the 95% confidence interval for all levels, for both magnitude of experienced movement and naturalness of haptic feedback (Figure 8).

To identify whether there were significant effects, we calculated the confidence interval of the mean differences between conditions. For naturalness, we found that both constant vibration and no vibration were different from all others, while hybrid, distance-based, and pressure-based were similar. For magnitude of the Experienced Movement, we found that pressure-based, and no vibration was significantly different from all other conditions, while hybrid, distance-based, and constant vibration were similar. (Please refer to our supplement for visualizations of the confidence intervals of the differences of means.)

The **no vibration** condition does not provide any feedback on user action, and thus it is rated the lowest with movement, and, because it felt like a natural object that was stationary, participants rated it with the highest natural score.

The **pressure-based** condition was rated the most natural apart from the no vibration control condition. However, the experienced movement, while natural, was felt to be very small. From participants' comments, they were all able to feel a certain compliance, as in the ball moved and returned. P1 felt like "not moving ... the ball is like stress ball material ... pushing into something ... there is resistance." P4 liked this mapping and felt that the "boundary ... felt natural ... like something is resisting my motion ... like a bigger version of xBox joystick." P6 found it "felt quite like pushing something with stretches ... when I push it more and back... it felt like whoooosh joystick kind of feeling... something squeaky or stiff... moves and come back... ." P7 remarked that "this one it is very natural, it has the bounce." P8 commented, "I'm feeling the ball is moving very slow, with friction ... I'm pushing and the ball is returning to its original position, it's bouncing." P9 found it "feels like a spring, like it gets stuck after pushing a bit more."

Distance-based and hybrid mappings have similar ratings in terms of naturalness and movement. They had relatively high movement scores but were rated relatively natural. We found that distance-based and hybrid mappings are often associated with embodied moving experiences in the physical world, such as textures and frictions. P1 felt like they were "moving along something with rifles, like moving across a fence." P6 felt like "going over a bumpy surface very fast." P8 felt "friction here ... the ball is moving really fast ... could be accelerating." P9 felt "something that is rolling over an uneven terrain," and P10 remarked "this one has a little bit of a friction in the beginning and starts sliding."

Interestingly, while **constant vibration** scored very low in terms of naturalness, it received similarly strong ratings for experienced movement as the hybrid and distance-based did. We believe this is mainly due to the amplitude and frequency modulation. P2 mentioned that the constant vibration "feels like frequency increment is very apparent ... instantly with my movement, and stronger intensity or higher amplitude feels like I'm moving more." P10 commented that "I can move very far, but it doesn't feel natural at all. The vibration is way too regular to associate it with any surface... it starts to feel like a machine, when I push it, it vibrates." Not all participants agreed in their interpretation, though. P8 mentioned that the constant vibration "(felt) more like vibration than movement. I don't feel any friction here, and I'm not feeling any movement ... it doesn't feel natural." P6 interpreted the symbolic meaning oppositely, with the increased amplitude and frequency of constant vibration signifying more resistance: "it didn't feel very natural, felt just like a buzz. It felt more like as I move it, the buzz become stronger ... feels like it is resisting."

The way we interpret the evaluation of constant vibration in comparison with the other mappings is that the amplitude and frequency modulation was able to provide users with symbolic cues they could associate with distance, which Ihde would refer to as *hermeneutic mediation* [24]. While we believe that pressure-based, distance-based, and hybrid provided an *embodied mediation* of distance. Based on this data, both the distance-based and hybrid mapping can be selected. However, we opt to use the distance-based from here on, as the added complexity of the hybrid algorithm does not appear to have any measurable benefit.

6.2 Study 2: Movement Perception with Haptic Grain Levels in Distance-Based Mappings

Knowing which mapping has desirable traits for conveying strong movement naturally, we performed this study to understand how different number of grains would impact the magnitude of experienced movement. We carried out a magnitude estimation study. In this study we compared three different haptic grain levels (200, 400, 800) using the distance-based mapping.

6.2.1 Stimuli. We created a set of three haptic stimuli with the distance-based mapping. Everything remained constant except for varying their grain levels (200, 400, and 800, respectively, mapping over a maximum instantaneous change of 0.01m in the motion simulation model). Vibration grains are composed of sine wave pulses, the amplitude and frequency increasing logarithmically with the acceleration of virtual motion calculated in the movement simulation model.

6.2.2 Procedure. The study was conducted with 12 participants, 11 right-handed and 1 left-handed, all of whom have normal haptic perception. The study lasted approximately 15 minutes. We adopted the same procedure as Study 1, only this time, we asked the participants to rate only how large the movement perception was (for detailed prompt, see the first question in Study 1). We encouraged participants to speak out loud as they explored and recorded their remarks.

We adopted the same magnitude estimation procedure as in Study 1 and present all conditions in a balanced Latin square to minimize order effects. There were 4 repetitions per condition per participant, and participants were asked to keep the scale consistent for all 6 stimuli presented (2 repetitions of 3 different conditions).

6.2.3 Result. As before, we standardized the estimates and plotted their mean and 95% confidence intervals (Figure 9, A). We found that increasing grains leads to a large estimate of experienced movement, however, with apparently diminishing returns above 400 grains. We calculate the 95% confidence interval of the difference of adjacent estimates to identify any significant differences. If this interval does not contain zero, then the difference is significant at $p == 0.05$. We found a significant difference between 200 and 400 grains *(95% CI [-0.61 to -1.07]* but not between 400 and 800 *(95% CI [0.06 to -0.36])* .

Participants had mixed responses to the 800 grain condition. For instance, P9 found it intuitively coupled to strong movement sensation, and mentioned that "it felt so easy, it felt like i was touching it, and immediately it started moving ... for a second I have to hold this (table) with another hand cuz I felt like otherwise I would just fall back. It felt like I was trying to hold something that would move away." For participants who found the other way, it seems that the lower threshold of pulses made them less conscious of how the haptic signal is mapped to the user's action. P8 mentioned, "there is lower threshold before continuous vibration ... something telling me something that I should not do ... felt like continuous vibration really fast ... as a warning sign not as movement." P10 explained, "this one feels a bit more like sluggish ... a bit like sensitive, it wants to move itself ... less connected to the way it moves ... less sensitive to my input."

6.3 Study 3: Understanding Haptic Grains and Visual Gains

Following Study 2, we had the same participants perform a design task to understand how visual rendering in VR can match with the haptic granularities. Participants were asked to tune the visual gain in VR until it matched the corresponding haptic feedback. We recorded the visual gain that participants thought most closely matched the haptic feedback.

6.3.1 Stimuli. We continued to use the same distance-based haptic mappings of 200, 400, and 800 grains as our independent variable, as in Study 2. Another variable is visual gain, which is the number that is multiplied to the instantaneous change in distance when computing the position coordinates of the sphere in the movement simulation model.

6.3.2 Procedure. The study was performed with the same 12 participants from Study 2, with 11 right-handed, and 1 left-handed. The study lasted approximately 5 minutes. We use a balanced Latin square to determine the order of stimuli. Stimuli were presented sequentially, with no repetition (3 stimuli per participant). Participants wore a pair of headphones playing white noise with an Oculus Quest 2. Visual renderings of a sphere resting on a pebbled ground and a tracked hand avatar of the participant was shown in Virtual Reality. Participants went through the standard calibration of the Oculus Quest 2. They were then asked to move the sphere in VR using the spherical handle until the sphere in VR matched the metal sphere in the real world. We adjusted the vertical height of the sphere and plane in VR if it did not match the real-world counterpart. We then coupled the hand avatar to the sphere in VR, still allowing the change in hand gestures to be reflected in the VR hand avatar when participants pushed the metal sphere around in the real world. For every stimulus presented, we started the visual gain from 1. Participants were asked to push the sphere around in VR and were instructed to tell the experimenter to either increase or decrease the visual gain iteratively until the visual rendering of the sphere matched the current haptic rendering perfectly. The experimenter then recorded the selected visual gain and repeated the same procedure for the next haptic stimulus. We recorded the participants' comments as they performed the visual and haptic matching design task.

6.3.3 Result. As before, we standardized the estimates and calculated their mean and 95% confidence intervals; however, no clear pattern emerged (see Figure 9, B). We assume this is because the connection between visual and haptic is mediated by a mental model of the materiality of the interaction, which we did not control because we had a context-free implementation. Future studies should explore this question in the context of real-world interactions, where it is reasonable to assume shared mental models between users.

Users did, however, each individually, voice preferences for certain combinations, which were used for the final study where we looked at the effectiveness of the haptic feedback in creating a belief in movement.

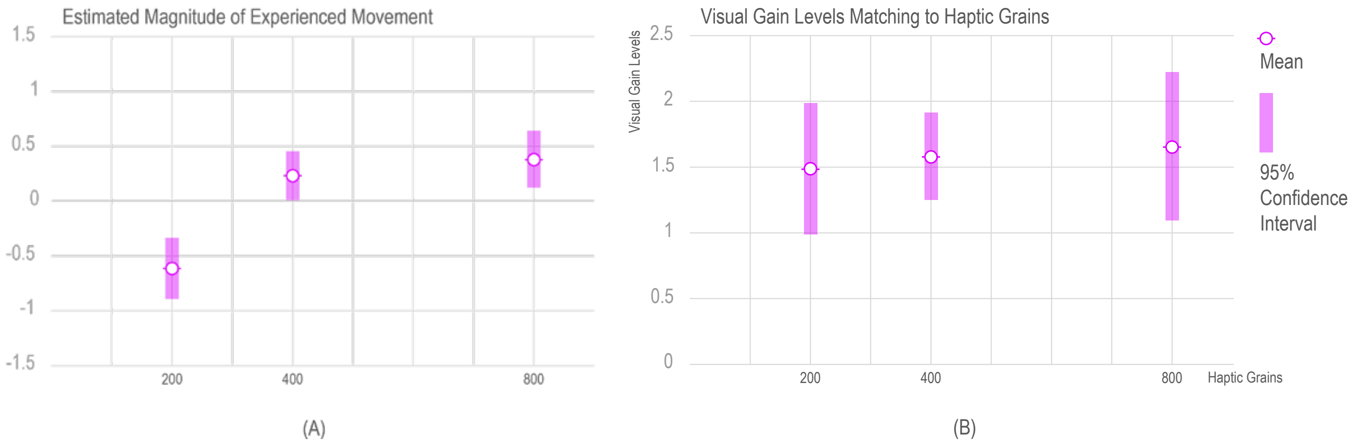

Figure 9: (A) Estimated magnitude of experienced movement from Study 2. (B) Visual gain levels that match the respective haptic grains. Y axis shows standardized estimates, the unit is standard deviation with respect to the per user average estimate.

6.4 Study 4: Effect of VR Renderings on Belief in Movement

Following Studies 2 and 3, with the same participants, we investigated the effect of visual renderings on the belief in embodied movement, using distance-based haptic mapping and the visual-haptic match setting that the participants selected in Study 3. We performed a magnitude estimation on the belief in movement with experiences using both haptics and visual, haptics only, visual only, and none.

6.4.1 Stimuli. We asked participants to choose one of the visual-haptic matches they designed in Study 3. We proceeded to Study 4 with that pairing the participants selected. All the haptic mappings were distance-based and sine wave. Our four conditions were: 1) both haptics and visual, which is the visual-haptic pairing the participants selected, with the same visual as in Study 3 (sphere on a pebbled plane with hand avatar pushing it); 2) haptics only, which is the distance-based haptic mapping with the same grain level as the first condition but without rendering any visual feedback in VR; 3) visual only, which renders the movement in VR using the same visual renderings and visual gain as in the first condition without any haptic feedback; 4) none, where there is no visual feedback in VR and no haptics feedback at all.

6.4.2 Procedure. We performed this study on the same 12 participants from Studies 2 and 3. Participants wore a pair of earphones playing white noise and an Oculus Quest 2 displaying VR renderings. We went through the same calibration and VR real-world mapping procedure as in Study 3. They were asked to push the ball around just as they would push any ball around in the real world. Participants were given the same instructions on performing magnitude estimation as in Studies 1 and 2, only this time, they were asked to rate their belief in movement with the following prompt: How strongly do you **believe in** the embodied movement? Think about how much you feel your hand / the sphere moving compared to what you would experience in the real world. Assign large numbers if the experience suggests that you are moving and small numbers if not. We encouraged participants to speak out loud as they explored and recorded their remarks. We used balanced Latin square to determine the order of stimuli, with 3 repetitions of the 4 conditions per participant. Participants were asked to keep the scale consistent for every repetition (4 stimuli).

6.4.3 Result. Again, we standardized the estimates and calculated their mean and 95% confidence interval as seen in (Figure 9, B). The belief in movement is highest in the both haptics and visual condition, followed by haptic only, and then visual only. The none condition was rated the least convincing movement condition. As the confidence intervals are relatively small in relation to the size of the difference in estimates, and because none of the confidence intervals overlap, statistical significance is apparent for all differences based on visual inspection.

Although the haptic only condition induced more belief in movement than the visual only condition on average, some participants found it more convincing to see the visual rendering whereas some did not. We looked at participants' comment to see what the reason could be. Participants who found haptic only condition to be more

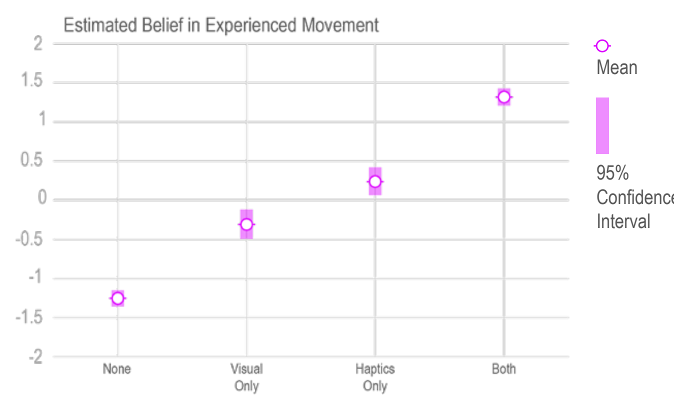

Figure 10: Estimated belief in experienced movement from Study 4. Y axis shows standardized estimates, the unit is standard deviation with respect to the per user average estimate.

convincing commented on the visual only condition as follows: "didn't feel like I was moving in my hand [...] the more I'm doing the less I believe" (P9), and "it's this similar feeling to when you use a computer mouse, you know, like, Okay, I feel like I'm moving it. But it's not like it's my hand. Like I'm very obviously like translating my movements into something else...Yeah. Not convinced," (P11). For those participants that rated visual only to induce higher belief in movement mentioned that "actually, that felt really movable. If I picture it, it's like, a smooth surface... Somehow it feels really responsive just from the visuals," (P7). In general, participants felt embodied movement experience when haptic was present; in particular, they felt friction. P3 mentioned that "the vibration that I can feel would indicate that I'm actually ... scratching my hand across like rough surface." P11 mentioned that with VR, "the combination of (visual and haptics feels) like ... oh wow I must be doing that in a bit more profound way." In fact, the contrast between the haptics and no haptics conditions was so large that they commented, "when you (the experimenter) suddenly take away the vibration it feels really really very strange ... I (P11) was like oh no, this is absolute crap."

7 DISCUSSION

We started this exploration based on the assumption that tactile movement cues alone are sufficient for conveying a believable experience of movement. Considering that visual cues alone are able to redirect movement [18] and acoustic cues alone can change how far we believe we can reach [65], this assumption appears reasonable. Looking at material illusions such as those presented in Pseudobend [23] or created with Haptic Servos [52] and focusing on the user provides a strong clue on how to use haptics: If the user believes that the material they are interacting with has been deformed, the user has also implicitly assumed that the body part that created this deformation must have moved as well.

In our first experiment, we explored whether the style of action-coupled grain-based feedback used by Heo [23] and Sabnis [52] can be used to not only implicitly but also explicitly convey a sense of motion. The result was positive, but complex. We found that the magnitude of perceived motion and the realism of that motion need not correlate. This is reminiscent of findings by Strohmeier et al. [60], who distinguished between the qualia of a haptic illusion and its salience. We did, however, find that vibration coupled to virtual motion – so, essentially, compliance – provided a natural experience, which was estimated to lead to a strong experience of motion by our participants. We also show that, up to a point, the perceived magnitude of the movement can be manipulated by the granularity of the texture.

Finally, knowing that visual feedback alone is able to create powerful movement illusions, we were interested to see how our haptic feedback designed compared. We created two conflicting stimuli, one where the user's visual hand moves, but no haptic feedback is provided, and the other where haptic feedback is provided, but the visual hand does not move. We find it very interesting that, on average, the condition where haptic feedback of movement is provided and visual feedback indicates no movement is rated higher than the inverse, where the users receive visual feedback without tactile feedback. This essentially means that, on average, people focus on tactile feedback over visual feedback when reflecting on how convincing the embodied movement experience is. This is quite astounding, as in most situations the visual feedback is given priority. It was also a pleasant surprise to see how combining visual and haptic feedback creates a best-of-both-worlds type of situation. These results also suggest that our method is able to induce a stronger illusion than previous work that relied on visual feedback only [32, 39].

Our prototype kinesthetic display conveys a reasonably strong and natural sense of movement by recreating the sensorimotor contingencies of body movement. We consider kinesthetic experiences and material experiences to be akin to two sides of the same coin. Knowing how we are moving, tactile cues coupled to our motion, reveals properties of the material we are interacting with. If we understand the materials we are touching, tactile cues reveal properties of our movements. The tactile cues we provide might also be framed as friction. However, we assume that the user will create a mental model of the material world around them and use the cues to infer information of movement. The tactile signal is not designed to recreate any particular material, but to optimally integrate into the users movement experience.

8 LIMITATIONS & FUTURE WORK

A limitation of our experiments is that we did not specify the way users should manipulate the object beyond pushing the object in the horizontal plane – that they should hold and push the object in the palm or push it with several fingerpads or fingers. Therefore, we do not know if there were any effects caused by certain hand positions or by the skin-deformation as the users applied pressure. Moreover, the number of vibrotactile pulses received by the user is dependent on the amount of force applied by the user, thus affecting how the illusion is experienced. Moreover, there might be individual differences between a user's perceptual sensitivity to vibrotactile pulses and how their mental model associates the applied force-based vibrotactile pulses to elicit an experience.

Our current implementation has a number of technical limitations. Due to the sampling rate of 80Hz, a strain value is sent only every 12.5 milliseconds. As our sensory system is highly sensitive to signal onset [26], in our experience, a lower sampling rate results in decreasing the fidelity of the illusion to some extent, as also reported on by Sabnis et al [52]. While we optimized the parameters according to this constraint, we hope to improve this in future iterations by choosing an analog amplifier. Also, our current prototype can only render movement experience on a two-dimensional plane. Rotations or rolling is also not possible. To achieve a more generic display, future iterations will require a sensing system with a greater degree of freedom.

While we imagine it might be integrated in the armrest of a gaming chair, our current form-factor is not optimal. Finding better ways of implementing such systems will be a major challenge going forward.

Another important step we have not yet explored is combining this style of kinesthetic cue with illusions that use agonist-antagonist muscle stimulation [17, 55]. These are able to induce an experience of movement without requiring an action-coupled signal. They are, however, experienced as vibration and are difficult to consistantly induce. A prospect that excites us is to create a motion-coupled version of the agonist-antagonist illusion. We expect such an illusion to be more consistent than the existing approaches, and we assume that our approach will overcome the accompanying experience of vibration.

9 CONCLUSION

What is a Kinesthetic Display? What does it look like? What is it made of? We still do not know. The goal of the research presented in this paper was not to present a final definitive prototype or product. Rather, we hope to — by explicitly naming them — draw attention to their existence. Because they do already exist in many isolated instances, they are not commonly recognized as belonging to the same category. Furthermore, we hope to — by providing definitions of the different styles of kinesthetic displays that might one day exist — bring structure to a potential debate and future design work on the broad range of possible implementations. And lastly, with the experiments we have presented, we have formed an empirical basis for future work in this direction.

We have designed a prototype of a vibrotactile kinesthetic display to investigate how action-coupled vibrotactile cues evoke kinesthetic experiences without any physical movement being performed. Our work highlights that action-coupled signals can be used for inducing a sense of movement. Specifically, we have found that position-based vibrotactile mappings work well. However, somewhat to our surprise, we did not find any clear link between the number of grains used and the magnitude of the experience of movement. The utility of vibrotactile cues also exceeds our expectations. We found that the vibrotactile cues alone are significantly better at conveying an embodied sense of movement than the corresponding visual stimulus. Combining vibrotactile and visual cues outperformed either modality alone.

REFERENCES

[1] Mahdi Azmandian, Mark Hancock, Hrvoje Benko, Eyal Ofek, and Andrew D Wilson. 2016. Haptic retargeting: Dynamic repurposing of passive haptics for enhanced virtual reality experiences. In *Proceedings of the 2016 chi conference on human factors in computing systems*. 1968–1979.

[2] Monya Baker. 2016. Statisticians issue warning over misuse of P values. *Nature* 531, 7593 (March 2016), 151–151. https://doi.org/10.1038/nature.2016.19503

[3] Ekin Basalp, Peter Wolf, and Laura Marchal-Crespo. 2021. Haptic training: which types facilitate (re) learning of which motor task and for whom? Answers by a review. *IEEE transactions on haptics* 14, 4 (2021), 722–739.

[4] Sliman Bensmaïa and Mark Hollins. 2005. Pacinian representations of fine surface texture. *Perception & Psychophysics* 67, 5 (July 2005), 842–854. https://doi.org/10.3758/bf03193537

[5] Christopher C. Berger, Baihan Lin, Bigna Lenggenhager, Jaron Lanier, and Mar Gonzalez-Franco. 2022. Follow Your Nose: Extended Arm Reach After Pinocchio Illusion in Virtual Reality. *Frontiers in Virtual Reality* 3 (2022). https://www.frontiersin.org/articles/10.3389/frvir.2022.712375

[6] Lonni Besançon and Pierre Dragicevic. 2019. The Continued Prevalence of Dichotomous Inferences at CHI. In *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI EA '19)*. Association for Computing Machinery, New York, NY, USA, 1–11. https://doi.org/10.1145/3290607.3310432

[7] Jas Brooks, Steven Nagels, and Pedro Lopes. 2020. Trigeminal-based temperature illusions. In *Proceedings of the 2020 CHI conference on human factors in computing systems*. 1–12.

[8] Michelle Carr, Adam Haar, Judith Amores, Pedro Lopes, Guillermo Bernal, Tomás Vega, Oscar Rosello, Abhinandan Jain, and Pattie Maes. 2020. Dream engineering: Simulating worlds through sensory stimulation. *Consciousness and cognition* 83 (2020), 102955.

[9] Simon Christensen, Sajid Rafique, and Shaoping Bai. 2021. Design of a powered full-body exoskeleton for physical assistance of elderly people. *International Journal of Advanced Robotic Systems* 18, 6 (2021), 17298814211053534.

[10] Geoff Cumming. 2013. The New Statistics: Why and How. *Psychological Science* 25, 1 (Nov. 2013), 7–29. https://doi.org/10.1177/0956797613504966

[11] R. Barry Dale. 2012. 4 - Principles of Rehabilitation. In *Physical Rehabilitation of the Injured Athlete (Fourth Edition)* (fourth edition ed.), James R. Andrews, Gary L. Harrelson, and Kevin E. Wilk (Eds.). W.B. Saunders, Philadelphia, 41–66. https://doi.org/10.1016/B978-1-4377-2411-0.00004-6

[12] Chris J. Dallmann, Marc O. Ernst, and Alessandro Moscatelli. 2015. The role of vibration in tactile speed perception. *Journal of Neurophysiology* 114, 6 (2015), 3131–3139. https://doi.org/10.1152/jn.00621.2015 arXiv:https://doi.org/10.1152/jn.00621.2015 PMID: 26424580.

[13] Fabien Danieau, Julien Fleureau, Philippe Guillotel, Nicolas Mollet, Anatole Lécuyer, and Marc Christie. 2012. HapSeat: producing motion sensation with multiple force-feedback devices embedded in a seat. In *Proceedings of the 18th ACM symposium on Virtual reality software and technology (VRST '12)*. Association for Computing Machinery, New York, NY, USA, 69–76. https://doi.org/10.1145/2407336.2407350

[14] Pierre Dragicevic. 2016. Fair Statistical Communication in HCI. https://api.semanticscholar.org/CorpusID:64470036

[15] Cathy Mengying Fang and Chris Harrison. 2021. Retargeted Self-Haptics for Increased Immersion in VR without Instrumentation. In *The 34th Annual ACM Symposium on User Interface Software and Technology (UIST '21)*. Association for Computing Machinery, New York, NY, USA, 1109–1121. https://doi.org/10.1145/3472749.3474810

[16] George A Gescheider. 1988. Psychophysical scaling. *Annual review of psychology* 39, 1 (1988), 169–200.

[17] JC Gilhodes, JP Roll, and MF Tardy-Gervet. 1986. Perceptual and motor effects of agonist-antagonist muscle vibration in man. *Experimental brain research* 61 (1986), 395–402.

[18] Eric J Gonzalez and Sean Follmer. 2023. Sensorimotor Simulation of Redirected Reaching using Stochastic Optimal Feedback Control. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23)*. Association for Computing Machinery, New York, NY, USA, 1–17. https://doi.org/10.1145/3544548.3580767

[19] Abhishek Gupta and Marcia K O'Malley. 2006. Design of a haptic arm exoskeleton for training and rehabilitation. *IEEE/ASME Transactions on mechatronics* 11, 3 (2006), 280–289.

[20] Abhishek Gupta, Marcia K O'Malley, Volkan Patoglu, and Charles Burgar. 2008. Design, control and performance of RiceWrist: A force feedback wrist exoskeleton for rehabilitation and training. *The International Journal of Robotics Research* 27, 2 (2008), 233–251.

[21] Elisabet Hagert. 2010. Proprioception of the wrist joint: a review of current concepts and possible implications on the rehabilitation of the wrist. *Journal of Hand Therapy* 23, 1 (2010), 2–17.

[22] Laurence R. Harris, Kenzo Sakurai, and William H. A. Beaudot. 2017. Tactile Flow Overrides Other Cues To Self Motion. *Scientific Reports* 7, 1 (April 2017), 1059. https://doi.org/10.1038/s41598-017-01111-w

[23] Seongkook Heo, Jaeyeon Lee, and Daniel Wigdor. 2019. PseudoBend: Producing Haptic Illusions of Stretching, Bending, and Twisting Using Grain Vibrations. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology (UIST '19)*. Association for Computing Machinery, New York, NY, USA, 803–813. https://doi.org/10.1145/3332165.3347941

[24] Don Ihde. 1990. *Technology and the lifeworld*. Indiana University Press, Bloomington, MN.

[25] Hiroo Iwata, Hiroaki Yano, Takahiro Uemura, and Tetsuro Moriya. 2004. Food simulator: A haptic interface for biting. In *IEEE virtual reality 2004*. IEEE, 51–57.

[26] Roland S. Johansson and J. Randall Flanagan. 2009. Coding and use of tactile signals from the fingertips in object manipulation tasks. *Nature Reviews Neuroscience* 10, 5 (April 2009), 345–359. https://doi.org/10.1038/nrn2621

[27] Shunichi Kasahara, Jun Nishida, and Pedro Lopes. 2019. Preemptive action: Accelerating human reaction using electrical muscle stimulation without compromising agency. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 1–15.

[28] Johan Kildal. 2010. 3d-press: haptic illusion of compliance when pressing on a rigid surface. In *International Conference on Multimodal Interfaces and the Workshop on Machine Learning for Multimodal Interaction*. 1–8.

[29] Konstantina Kilteni, Antonella Maselli, Konrad P. Kording, and Mel Slater. 2015. Over my fake body: body ownership illusions for studying the multisensory basis of own-body perception. *Frontiers in Human Neuroscience* 9 (2015). https://doi.org/10.3389/fnhum.2015.00141

[30] Martin Krzywinski and Naomi Altman. 2013. Error bars. *Nature Methods* 10, 10 (Sept. 2013), 921–922. https://doi.org/10.1038/nmeth.2659

[31] Irene A Kuling, Eli Brenner, and Jeroen BJ Smeets. 2016. Proprioceptive localization of the hand changes when skin stretch around the elbow is manipulated. *Frontiers in psychology* 7 (2016), 1620. https://doi.org/10.3389/fpsyg.2016.01620

[32] A. Lecuyer, S. Coquillart, A. Kheddar, P. Richard, and P. Coiffet. 2000. Pseudo-haptic feedback: can isometric input devices simulate force feedback?. In *Proceedings IEEE Virtual Reality 2000 (Cat. No.00CB37048)*. 83–90. https://doi.org/10.1109/VR.2000.840369

[33] Ying-Ju Lin, Parinya Punpongsanon, Xin Wen, Daisuke Iwai, Kosuke Sato, Marianna Obrist, and Stefanie Mueller. 2020. FoodFab: creating food perception illusions using food 3D printing. In *Proceedings of the 2020 CHI conference on human factors in computing systems*. 1–13.

[34] Pedro Lopes and Patrick Baudisch. 2017. Interactive systems based on electrical muscle stimulation. In *ACM SIGGRAPH 2017 Studio*. 1–2.

[35] Pedro Lopes, Alexandra Ion, Willi Mueller, Daniel Hoffmann, Patrik Jonell, and Patrick Baudisch. 2015. Proprioceptive interaction. In *Proceedings of the 33rd annual acm conference on human factors in computing systems*. 939–948.

[36] Pedro Lopes, Patrik Jonell, and Patrick Baudisch. 2015. Affordance++ allowing objects to communicate dynamic use. In *Proceedings of the 33rd annual acm conference on human factors in computing systems*. 2515–2524.

[37] Pedro Lopes, Doăa Yüksel, François Guimbretière, and Patrick Baudisch. 2016. Muscle-plotter: An interactive system based on electrical muscle stimulation that produces spatial output. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. 207–217.

[38] Haruka Matsukura, Hironori Hashiguchi, and Hiroshi Ishida. 2017. Tracking of a gas plume with the aid of olfactory assist mask. *IEEE Sensors Journal* 17, 16 (2017), 5332–5340.

[39] Sousuke Nakamura. 2021. Challenges for Immersive Virtual Reality and Initiatives in the Motion-Less VR. *Journal of Japan Society for Fuzzy Theory and Intelligent Informatics* 33, 3 (2021), 89–96. https://doi.org/10.3156/jsoft.33.3_89

[40] Elena Nava and Ana Tajadura-Jiménez. 2020. Auditory-induced body distortions in children and adults. *Scientific Reports* 10, 1 (Feb. 2020), 3024. https://doi.org/10.1038/s41598-020-59979-0

[41] Jun Nishida, Shunichi Kasahara, and Kenji Suzuki. 2017. Wired muscle: generating faster kinesthetic reaction by inter-personally connecting muscles. In *ACM SIGGRAPH 2017 Emerging Technologies*. 1–2.

[42] Jun Nishida, Soichiro Matsuda, Mika Oki, Hikaru Takatori, Kosuke Sato, and Kenji Suzuki. 2019. Egocentric smaller-person experience through a change in visual perspective. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 1–12.

[43] Jun Nishida and Kenji Suzuki. 2017. BioSync: A Paired Wearable Device for Blending Kinesthetic Experience. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 3316–3327. https://doi.org/10.1145/3025453.3025829

[44] Jun Nishida, Kanako Takahashi, and Kenji Suzuki. 2015. A wearable stimulation device for sharing and augmenting kinesthetic feedback. In *Proceedings of the 6th Augmented Human International Conference*. 211–212.

[45] J. Kevin O'Regan and Alva Noë. 2001. A sensorimotor account of vision and visual consciousness. *Behavioral and Brain Sciences* 24, 5 (Oct. 2001), 939–973. https://doi.org/10.1017/s0140525x01000115

[46] Claudio Pacchierotti, Stephen Sinclair, Massimiliano Solazzi, Antonio Frisoli, Vincent Hayward, and Domenico Prattichizzo. 2017. Wearable haptic systems for the fingertip and the hand: taxonomy, review, and perspectives. *IEEE transactions on haptics* 10, 4 (2017), 580–600.

[47] Roshan Lalitha Peiris, Yuan-Ling Feng, Liwei Chan, and Kouta Minamizawa. 2019. Thermalbracelet: Exploring thermal haptic feedback around the wrist. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 1–11.

[48] Max Pfeiffer, Tim Dünte, Stefan Schneegass, Florian Alt, and Michael Rohs. 2015. Cruise control for pedestrians: Controlling walking direction using electrical muscle stimulation. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. 2505–2514.

[49] Uwe Proske and Simon C. Gandevia. 2012. The proprioceptive senses: their roles in signaling body shape, body position and movement, and muscle force. *Physiological Reviews* 92, 4 (Oct. 2012), 1651–1697. https://doi.org/10.1152/physrev.00048.2011

[50] Joseph M Romano and Katherine J Kuchenbecker. 2011. Creating realistic virtual textures from contact acceleration data. *IEEE Transactions on haptics* 5, 2 (2011), 109–119.

[51] Gerald P Roston and Thomas Peurach. 1997. A whole body kinesthetic display device for virtual reality applications. In *Proceedings of International Conference on Robotics and Automation*, Vol. 4. IEEE, 3006–3011.

[52] Nihar Sabnis, Dennis Wittchen, Courtney N Reed, Narjes Pourjafarian, Jürgen Steimle, and Paul Strohmeier. 2023. Haptic Servos: Self-Contained Vibrotactile Rendering System for Creating or Augmenting Material Experiences. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. 1–17.

[53] Nihar Sabnis, Dennis Wittchen, Gabriela Vega, Courtney N Reed, and Paul Strohmeier. 2023. Tactile Symbols with Continuous and Motion-Coupled Vibration: An Exploration of using Embodied Experiences for Hermeneutic Design. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. 1–19.

[54] Bethany Schiller, 3rd Colgan, Wes, Brandon Calderon, and Bruce R. Johnson. 2018. Muscle Spindles and Our Sense of Physical Self: Kinesthetic Illusions of Limb Position and Posture. *Journal of undergraduate neuroscience education : JUNE : a publication of FUN, Faculty for Undergraduate Neuroscience* 16, 3 (15 Sep 2018), A282–A288. https://pubmed.ncbi.nlm.nih.gov/30254545 30254545[pmid].

[55] Bethany Schiller, Wes Colgan III, Brandon Calderon, and Bruce R Johnson. 2018. Muscle Spindles and Our Sense of Physical Self: Kinesthetic Illusions of Limb Position and Posture. *Journal of Undergraduate Neuroscience Education* 16, 3 (2018), A282.

[56] Richard Schmidt. 2018. *Motor control and learning 6th edition with web resource* (6 ed.). Human Kinetics, Champaign, IL.

[57] Emanuele Lindo Secco and Andualem Maereg Tadesse. 2020. A wearable exoskeleton for hand kinesthetic feedback in virtual reality. In *Wireless Mobile Communication and Healthcare: 8th EAI International Conference, MobiHealth 2019, Dublin, Ireland, November 14-15, 2019, Proceedings 8*. Springer, 186–200.

[58] Paul Strohmeier, Sebastian Boring, and Kasper Hornbæk. 2018. From Pulse Trains to "Coloring with Vibrations": Motion Mappings for Mid-Air Haptic Textures. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3173574.3173639

[59] Paul Strohmeier, Jesse Burstyn, Juan Pablo Carrascal, Vincent Levesque, and Roel Vertegaal. 2016. Reflex: A flexible smartphone with active haptic feedback for bend input. In *Proceedings of the TEI'16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction*. 185–192.

[60] Paul Strohmeier, Seref Güngör, Luis Herres, Dennis Gudea, Bruno Fruchard, and Jürgen Steimle. 2020. bARefoot: Generating Virtual Materials using Motion Coupled Vibration in Shoes. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*. ACM, Virtual Event USA, 579–593. https://doi.org/10.1145/3379337.3415828

[61] Paul Strohmeier and Kasper Hornbæk. 2017. Generating haptic textures with a vibrotactile actuator. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. 4994–5005.

[62] Lisa Sullivan. 2017. Confidence Interval for Two Independent Samples, Continuous Outcome. https://sphweb.bumc.bu.edu/otlt/mph-modules/bs/bs704_confidence_intervals/bs704_confidence_intervals5.html Accessed: 2023-12-05.

[63] Ana Tajadura-Jiménez, Maria Basia, Ophelia Deroy, Merle Fairhurst, Nicolai Marquardt, and Nadia Bianchi-Berthouze. 2015. As light as your footsteps: altering walking sounds to change perceived body weight, emotional state and gait. In *Proceedings of the 33rd annual ACM conference on human factors in computing systems*. 2943–2952.

[64] Ana Tajadura-Jiménez, Maria Vakali, Merle T Fairhurst, Alisa Mandrigin, Nadia Bianchi-Berthouze, and Ophelia Deroy. 2017. Contingent sounds change the mental representation of one's finger length. *Scientific reports* 7, 1 (2017), 5748.

[65] Ana Tajadura-Jiménez, Torsten Marquardt, David Swapp, Norimichi Kitagawa, and Nadia Bianchi-Berthouze. 2016. Action Sounds Modulate Arm Reaching Movements. *Frontiers in Psychology* 7 (2016). https://www.frontiersin.org/articles/10.3389/fpsyg.2016.01391

[66] Mitchell W. Taylor, Janet L. Taylor, and Tatjana Seizova-Cajic. 2017. Muscle Vibration-Induced Illusions: Review of Contributing Factors, Taxonomy of Illusions and User's Guide. *Multisensory Research* 30, 1 (2017), 25 – 63. https://doi.org/10.1163/22134808-00002544

[67] Laia Turmo Vidal, Elena Marquez Segura, and Annika Waern. 2018. Movement Correction in Instructed Fitness Training: Design Recommendations and Opportunities. In *Proceedings of the 2018 Designing Interactive Systems Conference (DIS '18)*. Association for Computing Machinery, New York, NY, USA, 1041–1054. https://doi.org/10.1145/3196709.3196789

[68] Laia Turmo Vidal, Ana Tajadura-Jiménez, José Manuel Vega-Cebrián, Judith Ley-Flores, Joaquin R. Díaz-Durán, and Elena Márquez Segura. 2024. Body Transformation: An Experiential Quality of Sensory Feedback Wearables for Altering Body Perception. In *Proceedings of the Eighteenth International Conference on Tangible, Embedded, and Embodied Interaction* (<conf-loc>, <city>Cork</city>, <country>Ireland</country>, </conf-loc>) *(TEI '24)*. Association for Computing Machinery, New York, NY, USA, Article 25, 19 pages. https://doi.org/10.1145/3623509.3633373

[69] Laia Turmo Vidal, Hui Zhu, and Abraham Riego-Delgado. 2020. Bodylights: Open-ended augmented feedback to support training towards a correct exercise execution. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–14.

[70] Keigo Ushiyama, Satoshi Tanaka, Akifumi Takahashi, and Hiroyuki Kajimoto. 2019. Reinforcement of Kinesthetic Illusion by Simultaneous Multi-Point Vibratory Stimulation. In *SIGGRAPH Asia Posters* (Brisbane, QLD, Australia) *(SA '19)*. ACM, New York, Article 17, 2 pages. https://doi.org/10.1145/3355056.3364576

[71] Peter-Paul Verbeek. 2005. *What things do*. Pennsylvania State University Press, University Park, FL.

[72] Shumin Zhai. 1996. *Human performance in six degree of freedom input control*. University of Toronto.