Motion-Coupled Asymmetric Vibration for Pseudo Force Rendering in Virtual Reality

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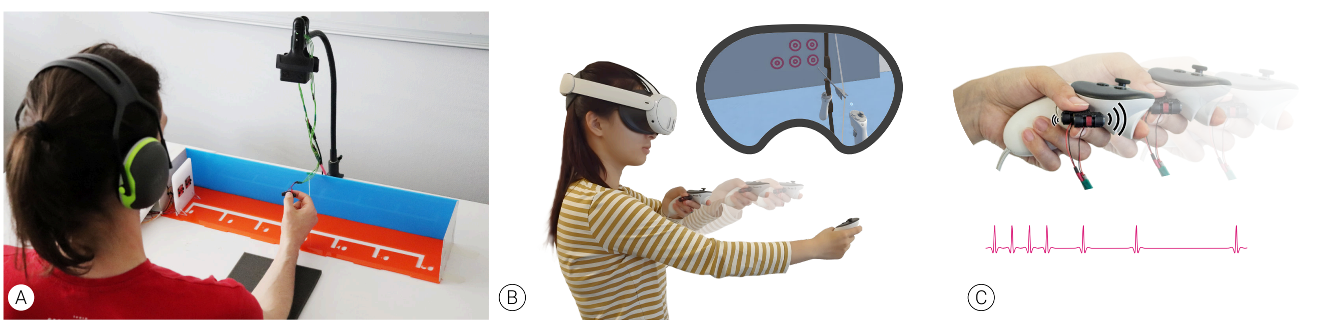

Figure 1: We investigate perceptual properties and potential applications of motion-coupled Asymmetric Vibration (AV) that elicit force sensations while minimizing vibration. Perceptual properties of force and vibration are examined in a psychophysics study in which participants move their hand along a line while pulses of AV are rendered (holding actuators in fingers) corresponding to their movement Ⓐ. We apply the same rendering approach in a bow-and-arrow VR game, where the AV pulses mimic the bow's string tension while stretching the bow Ⓑ. The higher tension is reflected by rending more AV pulses, as depicted in Ⓒ.

Abstract

In Virtual Reality (VR), rendering realistic forces is crucial for immersion, but traditional vibrotactile feedback fails to convey force sensations effectively. Studies of asymmetric vibrations that elicit pseudo forces show promise but are inherently tied to unwanted vibrations, reducing realism. Leveraging sensory attenuation to reduce the perceived intensity of self-generated vibrations during user movement, we present a novel algorithm that couples asymmetric vibrations with user motion, which mimics self-generated sensations. Our psychophysics study with 12 participants shows that motion-coupled asymmetric vibration attenuates the experience of vibration (equivalent to a ~30% reduction in vibration-amplitude) while preserving the experience of force, compared to continuous asymmetric vibrations (state-of-the-art). We demonstrate the effectiveness of our approach in VR through three scenarios: shooting arrows, lifting weights, and simulating haptic magnets. Results revealed that participants preferred forces elicited by motion-coupled

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asymmetric vibration for tasks like shooting arrows and lifting weights. This research highlights the potential of motion-coupled asymmetric vibrations, offers new insights into sensory attenuation, and advances force rendering in VR.

CCS Concepts

• **Human-centered computing → User studies**; *Haptic devices*; Virtual reality.

Keywords

virtual reality, haptic feedback, asymmetric vibration, pseudo forces, sensory attenuation

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1 Introduction

Virtual Reality (VR) enables us to create immersive experiences where the addition of haptic feedback enhances already compelling audio-visual stimuli. However, one crucial element remains challenging, namely creating force sensations. Due to the importance of force rendering [69], grounded force-feedback devices have been proposed [27, 65]. However, such haptic interfaces are bulky, mechanically complex, expensive, and have limited workspaces. Alternatively, VR haptics research has proposed custom hand-held controllers [8, 56], pneumatic systems [24, 34], or wearable interfaces [15, 29, 59]. While these methods can create immersive tactile experiences, they are difficult to scale, as they are either invasive (EMS), optimized for special use cases (custom hand controllers), or mechanically complex. Due to these constraints in implementation, vibrotactile feedback remains the dominant method.

Besides the ease of implementation and scalability, there are also strong reasons in perceptual theory to support the use of vibrotactile feedback. Research shows that a significant part of our tactile experience is mediated by cells sensitive to vibration [40]. This has led to sophisticated algorithms that simulate material properties of texture [86], movement [26, 37], and compliance [45, 96]. These material properties are induced by providing discrete, symmetric vibration pulses that are synchronized with user motion [74]. Beyond simulating textures, carefully designed vibrations have also been shown to convey force sensations [15, 21, 72, 91, 92]. These forces, known as "pseudo forces" can be elicited using asymmetric vibrations, typically generated by unequally accelerating a mass in opposite directions [1, 21]. Pseudo forces have been used to simulate weight, force, and inertia in VR [15, 50, 92]. However, one limitation remains: **force sensations elicited using asymmetric vibrations are inherently linked with the experience of vibration**. Therefore, it is not possible with current approaches to induce a force experience or increase its intensity without the user also experiencing an increased vibration, which has been shown to be distracting [95], annoying, and aggressive [49, 74, 76–78, 84].

We present **motion-coupled asymmetric vibration**, a novel algorithm that renders discrete asymmetric vibration pulses synchronized with user motion, generating pseudo forces that maximize the perceived force while minimizing the perceived vibration (Figure 1-C). Our algorithm leverages two mechanisms established in sensory attenuation literature: (a) the diminished perception of stimuli that correlate with our sensorimotor activity, i.e., self-generated stimuli are perceived to be less intense compared to externally generated stimuli [6, 44, 98], and (b) the reduced perception of vibration during movement [7, 10, 47]. To evaluate our algorithm, we perform two studies. First, in a controlled task, we explore the differences in the perceived intensity of vibration and force compared to traditional asymmetrical vibration [1]. Following a standard psychophysics magnitude estimation protocol [33], we identify the relative contributions of *continuity*, user *motion*, and *coupling* to movement on the resulting vibration and force experiences (Figure 1-A). Second, in a free-form exploration, we evaluate how our algorithm could be employed in VR. Compared to continuous asymmetric vibrations from previous work and symmetric vibrations in off-the-shelf VR controllers, our algorithm improves realism in action-dependent force scenarios, such as pulling a bow (Figure 1-B). The interviews revealed that continuous asymmetric vibrations obscure the perceived force, while motion-coupled asymmetric vibrations can enhance the user's experience in the absence of visual feedback.

> **Contribution Statement.** Our contribution is threefold: We contribute a novel algorithm based on sensory attenuation principles to render strong pseudo forces while reducing the perceived vibration. Next, empirical insights from our psychophysics study show that coupling asymmetric vibration to user motion attenuates vibration equivalent to a 30% reduction in amplitude. Finally, we demonstrate that our algorithm enhances the realism in VR applications.

2 Related Work

Research highlights several approaches to render forces, including the construction of novel haptic interfaces and vibrotactile rendering techniques. We contribute to the latter, building on algorithms established in the literature and adapting them based on established perceptual phenomena. We organize the related work into two parts: force rendering in VR with vibration design and perceptual mechanisms informing our algorithm design.

2.1 Force Rendering in VR and Beyond

2.1.1 Force Rendering Approaches for VR. Force rendering in VR was initially explored using grounded haptic interfaces, which provide accurate sensations [27, 65], but are bulky and expensive. An approach that avoids these limitations is augmenting commodity VR controllers to provide forces; for example, Stellmacher et al. [82] augmented a VR controller's trigger button. Dynamic and continuous resistance during interaction with virtual objects, generates counterforces that simulate different levels of virtual weights. This experience can be enhanced even further by introducing visual discrepancies when lifting virtual objects [83]. Such visual augmentations provide convincing impressions of counterforce or weight, even in the absence of physical feedback [54, 81].

Then there are custom-built hand-held haptic devices; for example, *Thor's Hammer* generates force feedback through six propeller motors integrated into an ungrounded device [36]. Similarly, *Air-Racket* provides directional force feedback using pneumatic actuators to simulate virtual racket sports [94]. Moreover, ungrounded graspable interfaces directly stimulate the user's fingertips or palm during grasping interactions, for example, *NormalTouch*, where an extruded and tiltable platform provides force feedback [8]. The *CLAW* device uses a force impedance approach to provide force feedback with actuated movement to the user's index finger to simulate grasping, touching, and triggering actions [16], while the *CapstanCrunch* device provides adjustable friction to render haptic compliance in response to grasping [79]. Alternatively, dynamic passive haptic feedback uses repositioning or reconfiguration of the controller to generate weights and forces through physical properties [103, 104]. However, to provide sufficient forces, body-grounded haptic interfaces use kinesthetic links affixed to the user's body [68]. Here, braking mechanisms render spring-like forces [12]. Wearable solutions using EMS can also simulate forces by directly stimulating the user's muscles [59, 61, 62] to simulate virtual weights [28] or physical boundaries [60], but user acceptance remains low [53]. Furthermore, recent skin stretch devices like *QuadStretcher* [51] and *ArmDeformation* [58] provide directional force cues and have been shown to enhance body ownership and realism in VR. *Springlets* are epidermal skin stretch devices that provide directional cues among other tactile primitives [35]. Despite their potential, such methods rarely find their way into commodity VR, mainly due to a lack in generalizability beyond the envisioned use case, which might be due to the limited expressive range they are able to apply [105].

2.1.2 Vibration Algorithms to Render Material and Force Experiences. The potential of vibration in shaping tactile experiences is shown by how our tactile receptors respond to different vibration frequencies [40] and how vibration can help us distinguish between materials [9]. Providing discrete vibration pulses coupled with user motion elicits material experiences of stretching, bending, and twisting on a rigid rod [37]. Similarly, providing vibration pulses at fixed intervals of user movement successfully simulates texture experiences in air and on smooth sliders [74, 84, 86]. Vibrotactile cues, coupled to changes in exerted pressure by the user, are sufficient for compliance (and deformation) experiences to emerge [45, 96, 100]. Furthermore, Ding et al. [26] showed that discrete vibration pulses coupled to user force can create an illusion of movement for the user, even when there is no motion. Sabnis et al. [73] showed that motion-coupled vibrations give users the feeling of being in control, despite their objective performance remaining the same.

On the other hand, asymmetric vibrations are used to create a sensation of force [4, 21, 72]. This is achieved by accelerating a mass unequally in two opposite directions such that the user perceives a pulling sensation in the direction of the higher acceleration. Early implementations used a slider-crank mechanism to induce a "virtual force vector" [1, 2]. Amemiya and Maeda [4] showed that weight perception can be altered by aligning the device in the direction of gravity. Recently, researchers have used vibrotactile actuators such as voice coils [19, 21] and linear resonant actuators [70] to produce asymmetric vibration with compact devices. Research on actuator modeling and finger pad interaction identified an optimal signal frequency of 40Hz to elicit compelling pseudo forces [20, 70].

In VR, Choi et al. [15] developed *Grabity*, a haptic device designed to simulate grip contact forces, weight and inertia in pinch grasp configuration using pseudo forces. Further, they demonstrated that the magnitude of the generated pseudo forces can be adjusted by changing the amplitude of the asymmetric input signal. Kim et al. [50] developed *HapCube*, a miniaturized device to provide pseudo forces using asymmetric vibrations. Asymmetric vibrations have also been used in VR to demonstrate a fishing experience [88] and kinesthetic forces arising from moving masses [92]. Research into the perception of pseudo force sensation shows that the perceived strength of the pulling sensation increases with the motion of the hand holding the actuator [3], which might be due to the phenomenon of tactile suppression, where the vibration is suppressed when the user moves. Recently, Tanabe et al. [91] have shown a method of generating stronger pseudo forces using vibrations asymmetric in time rather than in amplitude. Tanabe and Kaneko [90] has also shown that providing pseudo forces in the direction of movement can decrease the user's sense of agency, indicating that the illusion contributes to the sensation of the hand being moved.

The drawback of pseudo forces induced by continuous asymmetric vibrations is that the pseudo forces and vibrations are intricately linked. Thus, to increase the pseudo force, one needs to increase the vibration intensity. However, strong vibrations are perceived as distracting, annoying, and aggressive [49, 74, 77, 84, 95]. Also, continuous vibration is perceived by the user as being external [76], which might distract the user from the intended pseudo force sensation. Our contribution focuses on asymmetric vibration, typically perceived as external, coupled with user movements, which elicits a self-generated sensation of force and thereby attenuates the perceived vibration.

2.2 Perceptual Phenomena

Habituation is a form of learning that allows organisms to gradually reduce their response to repeated inconsequential stimuli [93]. This process helps conserve cognitive resources by diminishing the attention to stimuli that lack biological significance. According to the Sokolov model [80], the nervous system builds a stimulus model after repeated exposure. As this model becomes more accurate, the response diminishes, leading to habituation.

2.2.1 Sensory Attenuation (SA) through Prediction. SA is a form of Habituation where self-generated sensory signals are perceived less intensely compared to externally generated signals of similar intensity, particularly during voluntary movements [44]. The attenuation is believed to stem from the brain's predictive mechanisms, where an efference copy of the motor command generates a prediction of the sensory consequences, which is then compared against the actual sensory feedback [47]. If the prediction matches the feedback, the sensory signal is attenuated [101]. For example, tickling yourself is almost impossible as the predicted sensation closely matches the actual sensory feedback, leading to a cancellation of the tickling sensation. In contrast, when someone else tickles you, there is no efference copy to predict the incoming sensory signal, and, thus, the tickling is perceived more intensely [10].

One of the primary functions of SA is to differentiate between self-generated and externally generated stimuli that are less predictable [101]. For example, the brain attenuates sensory feedback from self-induced touch while remaining sensitive to similar external stimuli [47]. This selective filtering is essential not only for efficient sensory processing, but also for the attribution of agency, whereby movements perceived as self-generated are subject to attenuation while externally caused movements are not [10, 25]. Thus, SA is closely linked with the sense of agency – the feeling of being in control of one's actions [32]. When there is a match between the predicted and actual sensory outcomes of a movement, sensory attenuation occurs, reinforcing the sense of agency and making the user feel that the observed movement has been internally generated [46, 66] and vice versa.

We speculate that vibrotactile texture rendering approaches [74, 86] inducing texture experiences despite providing vibrations is partly due to such attenuation processes. In this research, our focus is to understand whether sensory attenuation can attenuate the perceived vibration while preserving the pseudo force when the asymmetric vibration pulses are coupled to user motion.

2.2.2 Sensory Attenuation through Movement. We look at two neural processes that contribute to sensory attenuation of stimuli during movement. The first, called tactile suppression, refers to the reduction in sensitivity to touch stimuli during self-generated movements [7, 10, 46]. This phenomenon is thought to arise from the brain's predictive mechanisms, which estimate the sensory consequences of one's own movements. Research has shown that when these predictions are precise, the reliance on tactile feedback decreases, leading to reduced tactile sensitivity [6, 13]. For example, during activities like typing on a keyboard, tactile suppression minimizes the perception of key presses generated by one's own fingers, allowing the user to focus on the outcome of the typing, such as the words on the screen. This reduction in tactile sensitivity helps prevent sensory overload, which could otherwise result from the continuous processing of self-generated tactile feedback. Tactile suppression has been extensively studied in the context of sensory attenuation, where externally generated stimuli are perceived as less intense during voluntary movement compared to when the individual is stationary [14, 31, 99].

The second process, known as tactile gating, prioritizes certain tactile inputs over others based on factors such as attention, intention, and relevance, effectively filtering sensory information to ensure that the most relevant touch sensations reach conscious awareness or are processed more efficiently [17]. This goes beyond merely reducing sensation during movement (tactile suppression) by selectively processing specific tactile information. For example, in a VR scenario where a user interacts with virtual objects, tactile gating can help amplify the perception of the object's surface texture while attenuating the sensation of the user's own hand movements, making the virtual environment feel more tangible and believable. The difference between tactile suppression and tactile gating is as follows: tactile suppression specifically involves the reduction of sensitivity to self-generated touches during voluntary movement, while tactile gating refers to the selective filtering of external tactile inputs during those same movements [47].

Our algorithm uses these two principles by coupling user motion to asymmetric vibration, such that it provides a stimulus only when the user moves. Thus, we expect tactile suppression of the vibration to take place while the tactile gating process allows the user to focus their attention on the elicited pseudo force.

3 Motion-Coupled Asymmetric Vibration

Careful consideration of our somatosensory experiences shows that the same physical stimulus can lead to different perceptual experiences depending on the context. For example, the same sound at 60 decibels seems loud in a library, while it might go unnoticed in a bustling café. Similarly, when you sit, you initially feel the pressure of the chair against your body, but shortly after, you stop noticing the pressure, unless you move or shift your position. In the same way, we investigated whether it is possible to render asymmetric vibration stimuli in a way that elicits levels of pseudo forces similar to traditional methods while reducing the perceived asymmetric vibration. Symmetrical vibrations, whether motion-coupled or continuous, do not elicit pseudo-forces [72, 84]. This was further informed by preliminary tests we conducted, which showed that neither motion-coupled nor continuous symmetric vibrations induce a force sensation.

Focusing on asymmetric vibrations, this research addresses the drawback of rendering forces using continuous asymmetric vibration: increasing the pseudo force is linked with an increase in the amount of vibration. This is not ideal, as research has shown vibration is often described as aggressive [49, 74, 84], annoying [76, 77], agitating, or a combination of all of them [78]. People often have negative associations with continuous vibrations [76], and these can be perceptually misleading, such that the desired effects are not communicated. The ability to render perceptually pure forces, that is, forces that are not accompanied by an experience of vibration, is crucial for a general purpose tactile display.

3.1 Designing Motion-Coupled Asymmetric Vibration based on Sensory Attenuation

Motion-Coupled Asymmetric Vibration (MCAV) is a novel approach that aims to minimize the perceived intensity of asymmetric vibrations while preserving the perceived pseudo forces elicited by those vibrations. This design leverages two sensory attenuation mechanisms. The first mechanism is based on sensory attenuation through prediction, where self-generated stimuli are perceived weaker than the same stimuli generated externally [44]. The second mechanism is the reduction in sensitivity to touch stimuli during active self-generated movement [46].

In applying these principles, we designed vibrations that are generated in direct response to user motion, known as motion-coupled vibrations [74] or grain-based vibrations [37]. Since the vibrations are generated based on the signal measured from human motion, they are caused by the user, enabling the user to develop a predictive model. In consequence, they are perceived as self-generated, reducing the intensity with which the vibrations are perceived [76]. This coupling of vibration pulses with user action takes advantage of the body's natural ability to filter out self-induced stimuli, reducing discomfort usually associated with external vibrations [78]. Thus, we expect that MCAV would attenuate the vibration aspect, in turn increasing the pseudo force.

3.2 Implementation of Motion-coupled asymmetric vibration

Rendering Motion-Coupled Asymmetric Vibration requires: (a) a method for sensing human movement (b) a controller for transforming human movement to a control signal and (c) an actuator for rendering vibrations. Moreover, sensory attenuation is highly sensitive to the timing and contingency between the action and the sensory feedback, so even a slight delay between the action and the resulting feedback significantly weakens the attenuation effect [10, 48, 71]. Thus, good quality rendering of MCAV requires tracking precision during sensing, latency considerations and broadband vibrotactile actuation [20, 102].

Different sensing methods can be used to sample user action. For distance sensing, the entire sensor range in which the user moves is divided into a discrete number of bins, Figure 3-Ⓐ. The bin distribution over the sensor range can be any desired function. If the user movement changes the sensor value and enters a new bin, an asymmetric vibration pulse is generated, as shown in Figure 3-Ⓑ. When the user moves fast, bins change fast, and the asymmetric vibration pulses are generated rapidly. When the bins change slowly, the pulses are generated proportionally more slowly, thus creating a dynamic effect of force: assisting or resisting the user based on the direction of the asymmetric vibration. Any suitable haptic actuator can be used to generate vibrations from the audio signal.

Referring to Figure 2, asymmetric vibrations are generated by accelerating a mass with unequal velocities in two opposite directions. One cycle of an asymmetric vibration consists of a large acceleration peak for a short duration (green) in one direction, followed by a small acceleration peak for a long duration in the opposite direction (red). Humans only perceive the larger acceleration, and if such asymmetric vibrations are provided in succession, they create a sensation of force in the direction of the larger acceleration. The asymmetric vibrations are generated by double differentiating the displacement x of the moving mass described in [5] with an amplitude factor A as a pre-multiplier:

$$x = A \cdot [(r\cos\omega t + \mu(d - r\cos\omega t) + \sqrt{l_2^2 - \{r(\mu-1)\sin\omega t\}^2})] \tag{1}$$

where

$$\mu = \frac{l_1}{\sqrt{r^2 + d^2 - 2rd\cos\omega t}}, \quad \omega = 2\pi f \tag{2}$$

To render MCAV, one pulse of asymmetric vibration was triggered for every bin change, Figure 3-Ⓒ. We used the frequency of 40Hz for the best experience of pseudo force [20, 70, 72]. This fixed the duration of a single pulse to 25 milliseconds to have a full period, thus minimizing clipping artifacts. In the current implementation, if the bin is changed, i.e. the next pulse is triggered while the current pulse is being played, the algorithm stops the current pulse and plays the next one. Triggering two or more pulses was experimented with, but having a pulse of 50 milliseconds or more

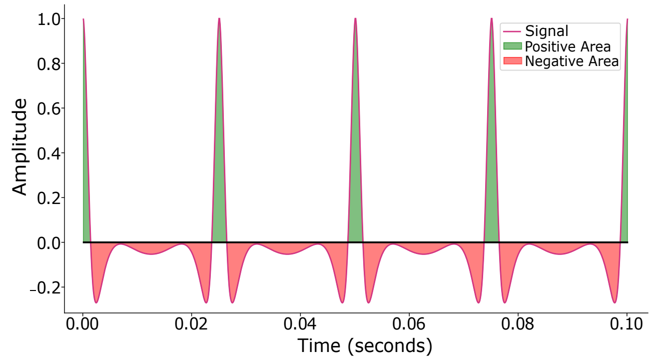

Figure 2: Asymmetric vibration signal at 40Hz (cf. [5]). The positive and negative area of each cycle is equal (i.e., net force is zero).

goes beyond the perceptual threshold [97], compromising the experience of self-generated vibrations. Thus, the variables required for generating the signal are the number of bins, which corresponds to the overall density of pulses (in the sensor range) and to how the bins are distributed in the sensor range. We have adapted an established system in research, Haptic Servos [74], which is able to produce the desired signal in under *5ms*. Like Haptic Servos, we use a Teensy 4.1 microcontroller with a PT8211 DAC. However, we use the Visaton 2.2 voltage amplifier rather than the D-class amplifier (PAM8403) that is integrated in Haptic Servos. This is because the D-class amplifier removes the high-frequency components while amplifying the audio signal, and, hence, it filters the short-duration-high-peak of the asymmetric vibration responsible for inducing force sensations. The technical evaluation shows that the driving signal and the measured acceleration of the actuators match the desired asymmetric waveform. Details of the technical evaluation can be found in Appendix A.

Ergonomic Gripping. We explored multiple configurations for integrating the actuators to render high quality pseudo forces. These include attaching the actuators to a handle like Tanabe et al. [89], tying the actuators to a finger like Culbertson et al. [21], and using the pinch configuration [15]. The rendered MCAV did not elicit pseudo forces when the actuator was attached to a handle, but was able to elicit forces when attached to the finger and worked best with the pinch configuration. In our experience, the sensitivity of perceived pseudo forces on the body for MCAV is similar to continuous asymmetric vibration perception. We used the pinch configuration because it gave the strongest pseudo force sensation, due to the higher density of direction sensitive Meissner corpuscles on the fingertips [18, 41, 67]. Finally, the pinch configuration offers flexibility to change actuator orientations while holding the VR controllers (Figure 8).

3.3 Study Rationale

Our algorithm is based on the literature that describes foundational principles of human perception. In this paper, we confirm the observations from the literature and further advance the state-of-the-art by providing empirical data to better understand what might cause

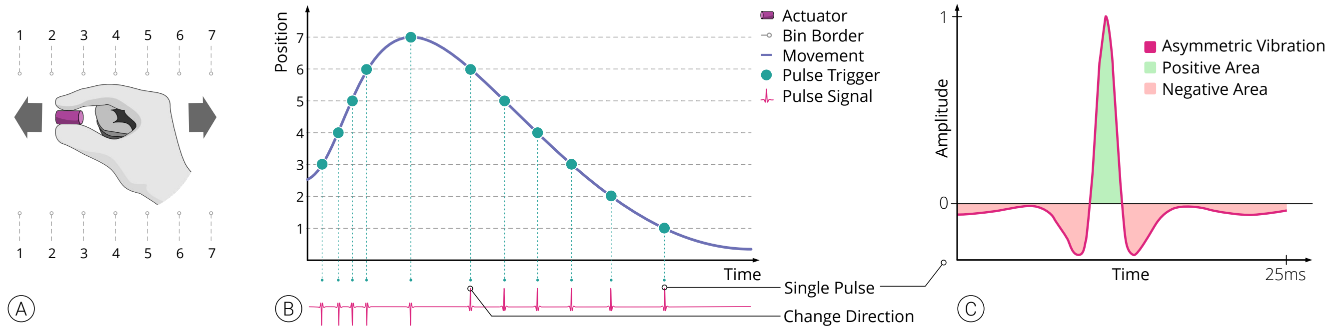

Figure 3: Motion-coupled asymmetric vibration algorithm: we sample the user movement Ⓐ and render vibrotactile pulses at predefined sensor thresholds Ⓑ. Depending on the dynamics of the movement, this results in a varying density of pulses that are timely synchronized with the movement (i.e., motion-coupled), as shown in Ⓑ. Each pulse is rendered as an asymmetric vibration Ⓒ that provides assistive or resistive forces depending on the direction of movement (see Ⓑ pulse signal).

the effect. We have conducted two studies: First, a controlled psychophysics study compares motion-coupled asymmetric vibration with traditional continuous asymmetric vibration. Using magnitude estimation, we aim to understand the overall effect of *coupling* asymmetric vibration to motion as well as the relative contributions of *continuity*, human *motion*. Magnitude estimation is an established method in psychophysics to obtain quantitative judgments of the perceived magnitudes of stimuli [33, 52] which is commonly used in investigations of haptic and visuo-haptic perception, both in- and outside VR [22, 26, 39, 96, 103–105]. In a follow-up study, we situate these results in real-world applications, in which users explore three interactive scenarios in VR. These explorations compare two state-of-the-art approaches (off-the-shelf vibrotactile haptics and continuous asymmetric vibration) with motion-coupled asymmetric vibration to provide insights about the type of interaction MCAV is best suited for. Study 1 presents primarily quantitative results, supplemented by semi-structured interviews, while study 2 provides primarily qualitative insights, supplemented with magnitude estimation scores.

4 Study 1: Sensory Attenuation of Vibration and Pseudo Forces

The goal of this study was to quantify the perceived intensity of vibration and force to compare motion-coupled asymmetric vibration with the state-of-the-art in a controlled task. Our investigation focuses on asymmetric vibration, which shows two qualities: vibration and pseudo force. Our research question is: *Can the perceived vibration be attenuated while preserving the perceptual quality of force?* Therefore, we compare motion-coupled asymmetric vibrations to continuous asymmetric vibrations. To better understand *what might specifically cause attenuation*, we investigate the relative contribution of *continuity*, human *motion*, and *coupling* to motion.

4.1 Study Design

We conducted a single-blind within-subject psychophysics study to compare motion-coupled asymmetric vibration and continuous asymmetric vibration. A direct comparison is meant to provide information on which algorithm performs better; however, because there are multiple differences between them, it does not explain what specifically caused this difference. These are three main differences between the two algorithms **(independent variables)**: (1) The *continuity* of vibration: Usually, asymmetric vibration is provided continuously. Motion-coupled asymmetric vibration is provided based on user movement. (2) The user *motion*: Continuous asymmetric vibration can be provided whether the user is moving or not. Motion-coupled asymmetric vibration can only be experienced during movement. (3) *Coupling* of vibration to user motion: For motion-coupled asymmetric vibration, the occurrence of pulses is proportional to the speed of user motion. However, a signal with the same variability, but decoupled from human movement, can be created. We designed four vibrotactile signals to individually assess the effect of these differences on the perceived vibration *(VibrationIntensity)* and perceived pseudo force *(PseudoForceIntensity)*, which are the **dependent variables**:

(A) **Motion-coupled asymmetric vibration (*MotionCoupled*):** These vibrations are rendered as pulses of asymmetric vibration coupled with the user's motion.
(B) **Motion-decoupled asymmetric vibration (*MotionDecoupled*):** Based on the vibrations triggered for condition *MotionCoupled*, the asymmetric vibration pulses are replayed in reverse, thus decoupling vibration from user movement.
(C) **Continuous asymmetric vibration when user is moving (*ContinousMoving*):** The asymmetric vibration is played continuously while the user moves for a certain duration.
(D) **Continuous asymmetric vibration when user is stationary (*ContinuousStationary*):** The asymmetric vibration is played continuously while the user is stationary for a certain duration.

We took care to make the signals equivalent in all other ways. The signal in *ContinousMoving* and *ContinuousStationary* has the same number of pulses as *MotionCoupled*, but stitched together as a continuous signal. Due to this stitching, the signal duration per trial in conditions *ContinousMoving* and *ContinuousStationary* is less than in *MotionCoupled* and *MotionDecoupled*. The signals *ContinousMoving* and *ContinuousStationary* have the same average power as *MotionCoupled*. Each signal was presented to the user at three different intensity levels: 40%, 70%, and 100% of maximum

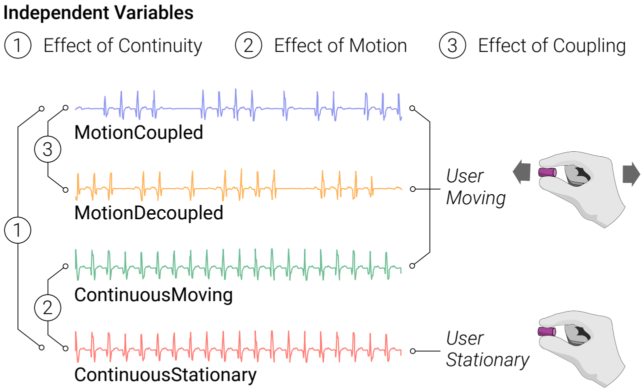

Figure 4: The signals generated with the four algorithms (vibration stimuli) described in subsection 4.1 with the respective user states (moving/ stationary) and the independent variables of the comparisons made.

amplitude. A schematic representation of the signals, including the comparisons made, is shown in Figure 4. We provide the measured output acceleration in Appendix A as well as a recorded movement profile of a participant for the four conditions, including pulse triggers, in Appendix B, Figure 13.

Hypotheses: The comparison between *MotionCoupled* and *ContinuousStationary* conditions tests our algorithm against the state-of-the-art, while comparing sensory attenuation during self generated (*MotionCoupled*) and external (*ContinuousStationary*) asymmetric vibrations. We hypothesize that *MotionCoupled* condition will result in weaker perceived vibration (H1a) and pseudo forces (H2a) compared to the *ContinuousStationary* condition (Table 1).

The *ContinousMoving* versus *ContinuousStationary* comparison focuses on the impact of user movement on sensory attenuation. We expect that vibration will be perceived as weaker in the *ContinousMoving* condition (H1b), but based on the findings of Amemiya and Gomi [3], we anticipate that the pseudo forces will feel stronger (H2b) when users are moving.

Finally, the comparison between *MotionCoupled* and *MotionDecoupled* examines how synchronizing vibrations with user movement affects sensory attenuation. We hypothesize that the *MotionCoupled* condition will lead to attenuated vibration (H1c) and stronger perceived pseudo forces (H2c), due to this alignment of stimuli with user movement.

4.2 Apparatus

The study setup is shown in Figure 5. For constraining participant movements, an area was laser cut with markings spaced 10cm apart and was enclosed on three sides to assure that participants move primarily in a single dimension. Time of flight (ToF) – VL53L4CD sensors[1], with a sampling frequency of 100Hz, were used to measure users' movements along a straight line and were placed on the left end of the box. We chose midair movements to prevent the influence of other forces on the participants' movements. Two ToFs were used post-calibration to increase the sensing accuracy, which

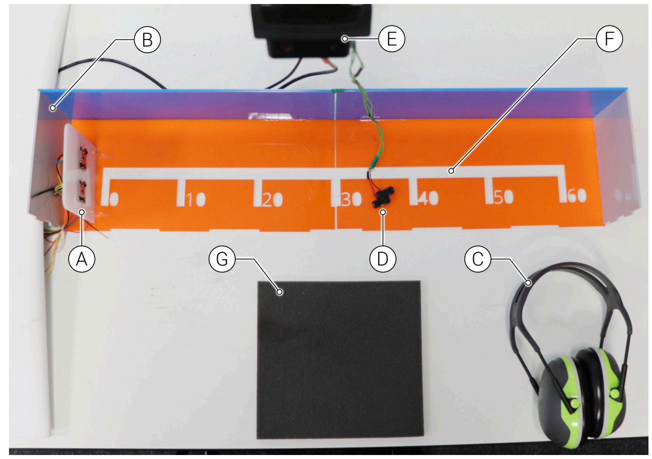

Figure 5: The study setup with the Time of Flight sensors Ⓐ, the semi-closed box in which participants moved Ⓑ, ear protection gear Ⓒ, the system of actuators Ⓓ, the wires (slack) to connect the actuators Ⓔ, 1-D trajectory for guiding participants' movements Ⓕ, and elbow pad to rest their elbow between conditions Ⓖ.

was crucial for generating motion-coupled asymmetric vibration. Further, we low-pass filtered the values received from the ToF sensors and used a jitter threshold to mitigate the noise of the sensors. The sensed data (users' hand motion) was measured by ToF sensors and sent to a microcontroller (Teensy 4.1). Based on the algorithm, the actuation pipeline (modified from Haptic Servos [74]) consisted of a Teensy, which was converted to an analog signal using a 16-bit digital-to-analog (pt8211 DAC) converter, and then amplified using a Visaton 2.2 voltage amplifier before feeding it to the low frequency DRAKE TacHammer[2], which converted the signal to vibrations. We used two TacHammers connected to each other to provide a stronger pseudo force sensation and enable ergonomic gripping. Sand-paper tape was attached to the actuators to provide better grip and avoid slipping between the fingers, which is important for pseudo force perception [21]. The two actuators do not provide torque since they are in the same direction, and they minimally affect each other's system dynamics. The signal provided to them is split using a wire-splitter. Further, the measured accelerations during the technical evaluation of the combined actuators did not show any significant differences compared to the driving signal, refer to Appendix A, Figure 11. For all practical purposes, the actuators can be considered as a single unit, without phase difference between the two actuators. The actuator wires were soft, flexible, and had minimal tension to not create any force or interfere with the movements of the participants. The maximum intensity was set using the Visaton amplifier. Individual adjustments were then done by modifying the strength of the output signal in the firmware. Vibrations were stopped using a velocity threshold to prohibit the vibrations participants might feel when they momentarily stop at either end of the play area. The asymmetric vibration pulses were

[1] SparkFun Distance Sensor, VL53L4CD: https://www.sparkfun.com/products/18993; accessed September 11, 2024

[2] TITAN Haptics DRAKE TacHammer (LF): https://titanhaptics.com/product/drake-haptic-actuator-kit-12-pack/; accessed September 11, 2024

Table 1: Hypotheses Tested for the Psychophysics Study

Effects of	Perceived Vibration is ...	Perceived Force is ...
Continuity	**weaker** for MotionCoupled than ContinuousStationary – **H1a**	**weaker** for MotionCoupled than ContinuousStationary – **H2a**
Motion	**weaker** for ContinuousMoving than ContinuousStationary – **H1b**	**stronger** for ContinuousMoving than ContinuousStationary – **H2b**
Coupling	**weaker** for MotionCoupled than MotionDecoupled – **H1c**	**stronger** for MotionCoupled than MotionDecoupled – **H2c**

provided such that there is a force towards the ToF sensors. The code with algorithms used in the study can be found in the online repository[3].

4.3 Procedure

Before starting, we informed participants about the purpose of the study. They were asked to sign a consent form and complete a demographic questionnaire. Our study consisted of three phases:

Orientation Phase: During the orientation phase, participants were asked to hold the vibrotactile actuators between their index finger and thumb (Figure 8-A), move the device over the marked area, and provide scores using absolute magnitude estimation. The experimenter informed them that no vibration and no pseudo force would have a score of zero and should be used as a baseline to assign scores to the vibrotactile stimuli. Asymmetric vibration stimuli were provided alternately– towards and away from the ToF sensors for a duration of 3 seconds with a 500ms gap in between and repeated three times. They were told that they might feel a "directional cue" or "force" in either direction, which the experimenters called pseudo forces. All participants felt pseudo forces in both directions. Furthermore, they were asked to perform 4 to 7 movements from 5cm to 55cm and back, in a straight line within 15 seconds, to ensure that no participant moves too slowly or too fast during the study.

Study Phase: During the study phase, participants evaluated different algorithms of rendering pseudo forces by rating the perceived vibration and perceived force. To do so, we presented them with each condition at three intensity levels (40%, 70%, and 100% of maximum amplitude), resulting in 12 unique conditions per trial. Using a balanced Latin-square design, we created 12 trial combinations. Each participant completed two trials for both maximum perceived intensity of vibration and maximum perceived pseudo force. The two trials were combined to form a sequence with 24 conditions. The sequence was kept the same for both vibration and pseudo force, but half of the participants rated the vibration they perceived first, while the other half rated the pseudo force they perceived first. The condition *MotionCoupled* was played before *MotionDecoupled*, *ContinousMoving*, and *ContinuousStationary* as the latter were dependent on the condition *MotionCoupled.* Between the trials for rating pseudo forces and vibration, the participants took part in a game of ball-in-basket with 5 throws. This was done to reduce the fatigue of the participants and to add a fun element.

Task: Participants moved their hand in 1-D over a 50 cm distance 4 to 7 times based on the orientation phase (see Figure 5, Figure 1-A) within 15 seconds and assigned scores to the maximum perceived vibration and pseudo force for each stimulus, using absolute magnitude estimation. The participants were free to choose the scores on an arbitrary scale, and these were recorded manually. The stronger the maximum perceived intensity of vibration/ pseudo force elicited by the condition, the higher the score. Before *ContinuousStationary* condition, participants were patted on the shoulder to signal them to stay stationary for this condition.

Qualitative Interviews: We collected qualitative feedback on the elicited sensation for each condition by conducting a semi-structured interview. Prior work has shown that evaluating subjective experience has proven to be an effective method to investigate "what the haptic experience feels like", which is difficult to capture with other evaluation methods [39, 84]. Each condition was presented at 100% intensity level. The participants were asked to describe their experience of vibration, forces, and overall experience. They were asked to reflect on their experience and qualitative associations only if the participants hinted at them.

4.3.1 Participants: We recruited 12 healthy participants (7 identified as male, 5 as female; 10 were right-handed) aged 19 to 33 years *(M = 26.2; SD = 3.7)*. Seven participants had no experience in vibrotactile haptics, and the remaining five participants worked in haptics for 4 to 36 months and had experienced pseudo forces generated using continuous asymmetric vibration before. During the study, participants wore ear protection gear (NRR: 37dB) to cancel out audio cues generated by the vibrotactile actuators. The duration of the study was one hour and all participants received a financial compensation of 12 Euros for participating.

4.3.2 Measurements and Data Processing: The estimates of perceived vibration and pseudo force were collected using absolute magnitude estimation with two separate user-dependent numerical scales [33, 52]. The raw estimates of the maximum perceived intensity of vibration (*VibrationIntensity*) and the maximum perceived pseudo force (*PseudoForceIntensity*) were individually standardized (z-score normalization) by subtracting the grand mean of each participant's estimates from all individual estimates and dividing the resulting value by the standard deviation of the participant's grand mean. After standardization, the mean estimate over all conditions for each participant is zero, with larger and smaller estimates represented as positive and negative values, respectively. This type of normalization ensures that even though participants were allowed to choose the values they used for estimates freely, statistics are

[3]GitHub: https://github.com/sensint/Motion-Coupled-Asymmetric-Vibration

performed on data with a common scale. To assess significance, we calculate ~95% confidence intervals for differences between estimates. If the interval includes zero, there is no significant difference; otherwise, the difference is statistically significant.

Interviews were audio recorded, transcribed and themes were extracted. Coding of the interviews was done by one author, who approached the transcripts based on their dialogues with the participants during the study.

4.4 Absolute Magnitude Estimation Results

We conducted two RM-ANOVAs to understand the effects of the different vibration algorithms and intensity levels on vibration and pseudo force estimates. To address our hypotheses (Table 1), we conducted three post-hoc comparisons for each RM-ANOVA. We compared *MotionCoupled* and *ContinuousStationary* to gain insights on the effect of the *continuity* of the signal and how our algorithm compared to the state-of-the-art, see Figure 6, Figure 7. To understand the effects of *movement*, we compared *ContinuousMoving* to *ContinuousStationary*. Finally, to understand the effects of *coupling*, we compared *MotionCoupled* and *MotionDecoupled*. We preregistered our intention to make these comparisons on OSF[4].

4.4.1 Effects on Perceived Vibration. *MotionCoupled* received the lowest vibration estimates with M = -0.51 and SD = 0.25, while *ContinuousStationary* vibration received the highest vibration estimates with M = 0.56 and SD = 0.25 – more than a standard deviation apart. *MotionDecoupled* (M = -0.23, SD = 0.21) and *ContinuousMoving* (M = 0.19, SD = 0.12) were between, (Figure 6-Ⓐ). As expected, higher amplitude levels lead to higher perceived vibration, (Figure 6-Ⓑ).

The RM-ANOVA showed that the main effect of the *algorithm on perceived vibration* was statistically significant, $F(3, 33) = 44.48, p <$ .001, with a generalized eta squared (η_G^2) of 0.644. Similarly, we found a statistically significant main effect of *intensity level on perceived vibration*, $F(2, 22) = 238.72, p < .001$, with, $\eta_G^2 = 0.860$. The interaction between *algorithm* and *intensity level* was also statistically significant, $F(6, 66) = 6.35, p < .001$, with $\eta_G^2 = 0.134$, however, with a smaller effect size.

Bonferroni corrected post-hoc comparisons revealed a significant difference for all three preplanned comparisons, suggesting that *continuity*, *movement*, and *coupling* all contributed to the attenuation of perceived vibration, as shown in Figure 7 (left).

4.4.2 Effects on Perceived Pseudo Force. Results show that the algorithms lead to a similar estimate (*MotionCoupled*: M = 0.22, SD = 0.25; *ContinuousMoving*: M = 0.44, SD = 0.20; *ContinuousStationary*: M = 0.13, SD = 0.50), except for *MotionDecoupled*, which was much lower with a mean of -0.79 and SD of 0.34, (Figure 6-Ⓒ). We found that higher amplitude leads to stronger pseudo force estimates; however, the difference between medium and high amplitude was less pronounced than for vibration estimates, (Figure 6-Ⓓ).

The main effect of *the algorithm on perceived pseudo force* was statistically significant, $F(3, 33) = 22.88, p < .001$, with $\eta_G^2 = 0.520$. The main effect of *amplitude on perceived pseudo force* was also significant, $F(2, 22) = 71.74, p < .001$, with $\eta_G^2 = 0.653$. The interaction between *algorithm* and *amplitude* was statistically significant, $F(6, 66) = 8.78, p < .001$, with $\eta_G^2 = 0.133$. However, the effect size for the interaction was comparably small.

Bonferroni corrected post-hoc comparisons revealed that *coupling* had a significant effect: the *MotionDecoupled* condition was significantly lower than for *MotionCoupled*. Changes in participant *movement* and in *continuity* of the signal did not significantly impact the pseudo force estimates as seen in Figure 7 (right).

4.4.3 Comparison and Discussion of Statistical Results. The goal of motion-coupled asymmetric vibration was to reduce the perceived vibration while maintaining pseudo force. Comparing *MotionCoupled* with *ContinuousStationary* (Figure 7, top), vibration estimates were significantly lower, showing the largest effect on perceived vibration. Perceived pseudo force, however, showed no measurable difference, confirming that motion coupling reduces vibration without affecting pseudo force. *We, therefore, accept H1a and reject H2a.* This highlights that our design goal behind motion coupled asymmetric vibration is achieved: The perceived vibration can be reduced significantly without measurable change in the perceived pseudo force. The magnitude of the attenuation in the perceived vibration between *MotionCoupled* and *ContinuousStationary* is comparable to reducing the amplitude by ~30%, see Figure 6-Ⓑ.

To understand the role of *movement*, we compared *ContinuousMoving* and *ContinuousStationary* (Figure 7, mid). Movement significantly reduced perceived vibration but did not significantly affect pseudo force, despite slightly higher average estimates. *We accept H1b and reject H2b.* Finally, to understand the effect of *coupling*, we compare *MotionCoupled* with *MotionDecoupled* (Figure 7, bottom). Vibration was unaffected, but pseudo force was significantly reduced without coupling. *We accept H1c and H2c.*

In summary, the results highlight that motion-coupled asymmetric vibration is preferable over continuous asymmetric vibration, as it reduces the perceived vibration. We see that *continuity*, *motion*, and *coupling* all contribute to this reduced vibration perception. However, for perceived force, it appears that only *coupling* is required, as both continuous and motion-coupled asymmetric vibrations induced robust force sensations[5].

4.5 Qualitative Interview Themes

Asymmetric Vibration Obscures the Perceived Force: Participants often found it challenging to distinguish between the perceived vibration and pseudo forces with *ContinuousStationary* and *ContinuousMoving*, with sensations often blending together and complicating the perception of distinct pseudo forces. The confusion was indicated by P1 stating, “My confusion here is the vibration and the force that you’re talking... like the vibration. I can feel them vibrate. What’s the force that we’re talking about?” and P9 indicating for *ContinuousStationary* that “I feel sometimes the vibration also overpowers. ... it feels like if my mind is thinking about vibration then I feel the vibration but then if I try not to focus on the vibration... then I start feeling a bit of a pseudo force.” Moreover, P5 mentioned for *ContinuousStationary* and *ContinuousMoving*, “It’s hard to just extract the vibration out of it... sometimes it... screws up”.

[4]OSF preregistration link [75]: https://osf.io/rfw36

[5]We provide a visual overview of the estimates for each algorithm and intensity level in Appendix C, Figure 14

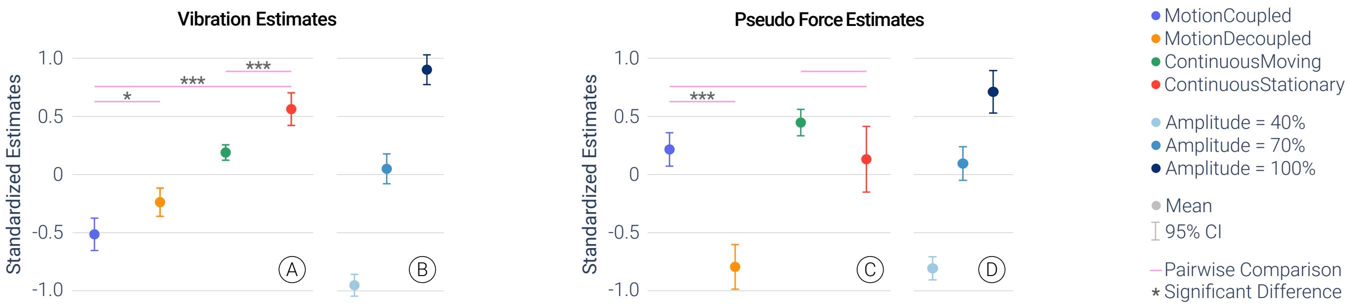

Figure 6: Results of study 1. Left figure shows the vibration estimates for each algorithm, Ⓐ along with the averaged vibration scores over all stimuli for each intensity Ⓑ. Right figure shows the pseudo force estimates for each stimulus Ⓒ along with the averaged pseudo force scores over all stimuli for each intensity Ⓓ. Plots depict mean and 95% confidence interval for comparing effects of algorithm and amplitude. The y-axes in all the figures show standardized scores (z-score normalization). We mark the statistical significance (if observed) for the six comparisons of interest ($* : p < .05$; $** : p < .01$; $*** : p < .001$).

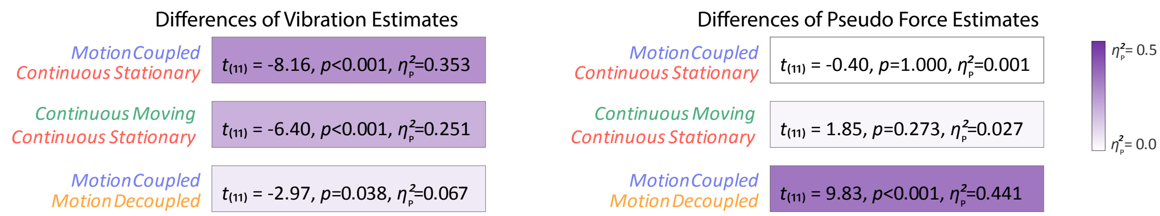

Figure 7: t-statistics, significance levels and partial eta squared (η_p^2) of post-hoc comparisons. Colors correspond to effect sizes.

Participants preferred motion-coupled asymmetric vibration for pseudo force rendering because they perceived the vibrations less intensely. For *MotionCoupled*, P12 stated, "I like the ones that have the more like subtle ticks. Yeah, the subtle ones *pull* nicely actually.", and, "Sometimes I feel more of the force, but it's just that the vibration is weaker right?". Furthermore, P9 stated, "The force is more intense than the vibration… if the force is intense then it's clear, and then you understand direction [of pull]." Moreover, P11 mentioned, "The drag with the more subtle ones [*MotionCoupled*] felt more natural... the continuous sensations sometimes felt overwhelming."

Onset Behavior and Response to Pseudo Forces: Participants highlighted the onset behavior of pseudo forces, noting the time it took to detect and respond to these forces during the study. For some, the forces were apparent from the beginning, while others required multiple interactions to recognize them. The clarity and timing of these forces depended on both the stimuli and the participants' movements. P3 mentioned that the fastest onset behavior was when they were moving in the *ContinuousMoving* case, "It wasn't apparent from the very first instant, but then as you move, you are able to perceive it fairly clearly." P7 noted that they quickly understood the direction for the *MotionCoupled* case stating "It feels like inertia for this condition [*MotionCoupled*], when I move faster the pull becomes stronger". However, P9 mentioned "At first I can feel really strong force... but as the thing [actuator] keeps going [vibrating] I can't feel it", and P11 said "This was strong in the beginning... after a second it got down", showing that the perceived force decreased for the continuous case over time.

Qualitative Associations and Real-World Analogies: Participants associate sensations elicited during different vibration conditions in the study with their real-world experiences. For instance, for the continuous asymmetric vibration condition, P4 mentioned "it's sort of like a magnet. So I definitely feel more attraction when I move to the left." P6 said that for *ContinuousStationary*, "my dog is trying to run away", whereas for *MotionCoupled*, the pseudo forces felt like "the dog is trying to sniff at different flowers". Moreover, rotating the actuators by 90 degrees, P3 mentioned that the *MotionCoupled* clearly gave them a feeling of pull which was equal to "holding a (electronic) tablet in the vertical direction, against gravity". Participants also referred to the feeling of force by many names while trying to describe the experience like, "Pull" (P2, P8, P12), "Tug and Nudge" (P7), and "Drag" (P3, P11). P5 also stated that the pseudo force elicited using motion-coupled asymmetric vibration, "reminds me of plucking my guitar string". P4 was excited to have these effects of pseudo forces on a cane for blind people (similar to [89]).

5 Study 2: Exploration of Pseudo Force Rendering Approaches for Virtual Reality

This study investigated the effectiveness of the motion-coupled asymmetric vibration algorithm in providing realistic sensations, compared to the two common approaches representing state-of-the-art in product (controller vibrations) and research (continuous asymmetric vibration). Here we are primarily concerned with the resulting realism and less concerned with the magnitude of vibration or force. In this study, magnitude is tangential to our primary objective, similar to how the brightness of a display is only tangentially related to the realism of the image it depicts.

5.1 Study Design

To understand the effectiveness of motion-coupled asymmetric vibration in creating realistic experiences in VR, we compared the perceived realism with widely available systems, preserving their unique vibration characteristics. We use the built-in controller of the Meta Quest 3 (*Controller*) with continuous symmetric vibration, as an example of consumer products, and we use continuous asymmetric vibrations (*Continuous*) to represent the state-of-the-art in research, to compare with motion-coupled asymmetric vibrations (*MotionCoupled*). Moreover, we rendered continuous vibrations for the controller condition to optimize for realism using a physics-based approach and previous work where vibration intensity is used to display the force and weight of the object [57]. We designed three application scenarios, Figure 9-Left:

- Bow and Arrow (Scene-B): This application evaluates the linear increase in tension. (Amplitude is linearly modulated between 40% and 100%)
- Lifting Weights (Scene-W): This application evaluates weight rendering with different sizes of boxes.
- Haptic Magnets (Scene-M): This bimanual application evaluates force changes cubically (cubic mapping of amplitude) based on the distance between magnets.

5.2 Apparatus

We used a Meta Quest 3 headset for displaying the virtual scenes. The hand controllers were used to render vibrotactile feedback for the scenes as control condition. Further, for rendering the continuous as well as motion-coupled asymmetric vibrations, we used the TacHammer DRAKE (LF) with the same actuation pipeline from study 1, where two actuators were used together for the bow-and-arrow and weight rendering scenes. For the magnet scene, however, we used two separate actuators, one in each hand. The hand controllers have a lower intensity of vibration compared to the TacHammers (Figure 12). Rendering of the virtual environment was done in Unity (2022.3.34f1), with Oculus link transmitting the data to the headset using a USB-C cable. A unidirectional communication protocol was used to communicate the message from Unity to the microcontroller over serial. The amount of bow pulled and the distance between the magnets was used to modulate the amplitude of the pseudo forces linearly for the bow and cubically for the magnets. A mobile phone with automatic transcription feature was used to audio record the interviews. The scenes, algorithms, and communication protocol can be found in the repository[6].

5.3 Procedure

We used the method of open design exploration to assess the type of preferred vibration feedback for representing forces and weights in virtual reality in three scenarios. Participants were informed about the study and were asked to give their consent. Next, participants were introduced to the VR system with the headset, hand controllers, and vibrotactile actuators. They were also instructed on how to hold the actuator while holding the controller. For the bow-arrow and weights, two actuators (similar to study 1) were given in a single hand (Figure 8-Ⓑ, Ⓒ) with horizontal and vertical configurations, respectively, whereas for the magnets, one actuator was given in each hand (Figure 8-Ⓓ). The trigger key on each of the hand-controllers was used to grab objects in the scenes. Pressing the trigger once attached the object to the controller in VR, and, to release the object, they had to press the trigger again.

All tasks were performed while seated. The chair for the participants was calibrated using the Quest's calibration procedure. The scenes and vibration conditions were randomized between the participants. To familiarize themselves with the scene, participants explored the scenes with the hand controllers, while holding the actuators, but without vibration feedback.

Participants then performed the study with 3 scenes (B, M, W) × 3 vibration conditions (*Controller, Continuous, MotionCoupled*). After exploring all the vibration conditions for a particular scene, participants set aside their VR headset, hand controllers, and actuators and were asked to mark their experience of vibration, force, and realism on a paper-based semantic differential scale, and a semi-structured qualitative interview was conducted.

After all the scenes were completed, participants were asked to select their favorite scene to perform the task partially with visual and partially without visual feedback, sequentially for each vibration condition. Finally, they were asked to describe and differentiate between their overall experience of the scene with and without visual feedback. This comparison aimed to capture the effect of pseudo forces elicited by MCAV with and without the presence of visual feedback, as well as the presence of potential pseudo forces generated by the visual dominance effect [55, 81]. Furthermore, this approach enabled us to uncover the contribution of visual and haptic stimuli on subjective force perception, similar to related work in visuo-haptic perception in VR [23, 103, 104].

5.3.1 Task. There were particular tasks for every scene to not have the participants focus on the vibration. Every scene lasted as long as the duration needed to complete the task or 1 minute of exploration, whichever finished first. For scene B, participants had to shoot at least 5 arrows; for scene M, they had to do 2 attractions and 2 repulsions, with their hands significantly apart for each repetition; for the weights, they were asked to lift the brown boxes once and then place each blue box of a particular size (big, medium, small) on the corresponding sizes of the brown boxes. During the final phase of with and without visual feedback, participants were asked to perform the same task partially, for example, shooting two arrows with visual feedback and then two arrows without visual feedback.

5.3.2 Participants. Eight healthy participants (6 male, 2 female) aged 24 to 32 years (*M = 27.6; SD = 2.9*) took part in the study. Four participants had taken part in the first study, two of them not working in the field of haptics. The other four were new participants, only one of them working in the field of haptics. The other three new participants had never experienced pseudo forces, and one had never experienced VR before. The duration of the study was on average one hour, and all participants received a financial compensation of 12 Euros for their participation. Participants were not told anything about pseudo forces. The vibration conditions were

[6]GitHub: https://github.com/sensint/Motion-Coupled-Asymmetric-Vibration

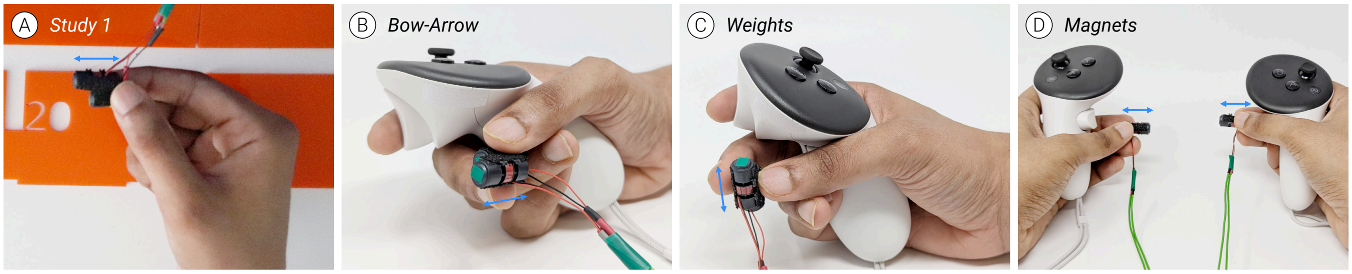

Figure 8: Ⓐ shows how the participants held the combined actuator system in the psychophysics study. The other images show how the participants held the actuators with the hand-controller for bow-arrow Ⓑ, weights Ⓒ and magnets Ⓓ scenes, respectively, during the VR study. The actuators are held horizontally for the bow-arrow and vertically for weights to provide forces in the respective directions, indicated by blue arrows. One actuator is held in each hand for the magnets scene.

referred to as *Controller*, *Buzz* and *Tick* for controller vibration, *Continuous* asymmetric vibration and *MotionCoupled* asymmetric vibration, respectively. White noise was played through the headset to mask audio-cues.

5.3.3 Measurements and Analysis. To understand participants' perceptions and experiences of vibration, forces, and realism, we applied a mixed-method approach and collected the following data:

Semantic Differential: After experiencing all the conditions for a single scene, participants were asked to mark each of the conditions with respect to the other on a scale on paper. The realism scale was inspired by realism studies of VR experience [42] and was marked from "unreal" to "real" to rate the overall experience. We also collected the perceived force and vibration data, which is reported in Appendix C.

Qualitative Interview: After experiencing all the conditions for a single scene, a short semi-structured qualitative interview was conducted. The questions for the qualitative interview were:

- Which type of vibration feedback (*Controller, Buzz, Tick*) do you prefer and why?
- Can you describe how the experience of forces (if any) and vibration feedback affected your experience?

After the exploration with and without visual feedback, participants were asked to describe the effects of visual feedback on the overall experience of the scene they explored. Based on the participant's responses, additional questions were asked.

Analysis: The qualitative analysis was done similar to study 1. For the semantic differential, post-standardization, RM-ANOVA was performed for each dependent variable, followed by pairwise t-tests using Bonferroni correction.

5.4 Results

5.4.1 Semantic Differential. Figure 9 shows that the vibration conditions had a statistically significant effect on the perceived realism for all the scenes, (Bow-Arrow: $F(2, 14) = 21.63, p < 0.05, \eta^2 = 0.75$; Weights: $F(2, 14) = 36.72, p < 0.05, \eta^2 = 0.84$); Magnets: $F(2, 14) = 4.91, p < 0.05, \eta^2 = 0.41$. Pairwise comparisons showed that the *MotionCoupled* and *Continuous* conditions significantly improved the realism compared to the *Controller* condition for bow-arrow (*Continuous* and *Controller*: $t(7) = 3.77, p < 0.05$; *MotionCoupled* and *Controller*: $t(7) = 17.61, p < 0.05$) and weights scene (*Continuous* and *Controller*: $t(7) = 6.81, p < 0.05$; *MotionCoupled* and *Controller*: $t(7) = 16.50, p < 0.05$). In none of the scenes were the realism ratings different for *Continuous* and *MotionCoupled* conditions. Detailed results of perceived vibration and pseudo forces are in Appendix C.

5.4.2 Qualitative Interviews.

Vibrotactile Feedback Preferences for Perceived Realism. *MotionCoupled* was preferred for its pseudo force experience and responsiveness, particularly during tasks involving motion such as pulling a bowstring. Participants (P1,P2, P4, P5, P7) found this condition aligned well with the sensation of exerting force (tension) and weight, which enhanced realism. P4 mentioned, "I preferred *Tick* because it was not just pure vibration like previous two (*Controller, Buzz*). It felt more like a force." P2 added, "When pulling the string, *Tick* felt like it matched the resistance I was expecting. It gave me a sense of force." *Continuous* was often described as providing a strong and continuous sensation that contributed more to the feeling of weight or a continuous force. P3 noted, "The *buzz* had a strong, clear feedback that made it easy to tell the size of the box," which hints at vibration helping the lifting of weights, and P6 said, "*Buzz* had more force, especially for smaller actions like moving a magnet." However, some found the continuous nature of *Continuous* "too intense" (P3), "a bit too much" (P4), and "*Buzz* felt too constant, like it didn't match the force needed" (P5). The *Controller* was often seen as less immersive compared to other conditions, with many participants stating that it contributed "too little," "spoke a different language" (P2), "felt like background vibration" (P3), and "couldn't tell if what I was doing matched the vibration at all—it didn't feel connected to the action" (P7).

Impact of Visual and Vibrotactile Feedback on Experience: Out of 8, 6 participants chose bow-arrow as their favorite scene, with 5 participants choosing the *MotionCoupled* condition as their favorite. The other two participants preferred the magnets scene with the *Continuous* condition. Without visual feedback (lights-out), participants relied more heavily on the vibration feedback to gauge their actions, particularly noting that *MotionCoupled* helped compensate for the lack of visual information. P1 mentioned, "Without the lights, *Tick* really helped me know how much I was pulling

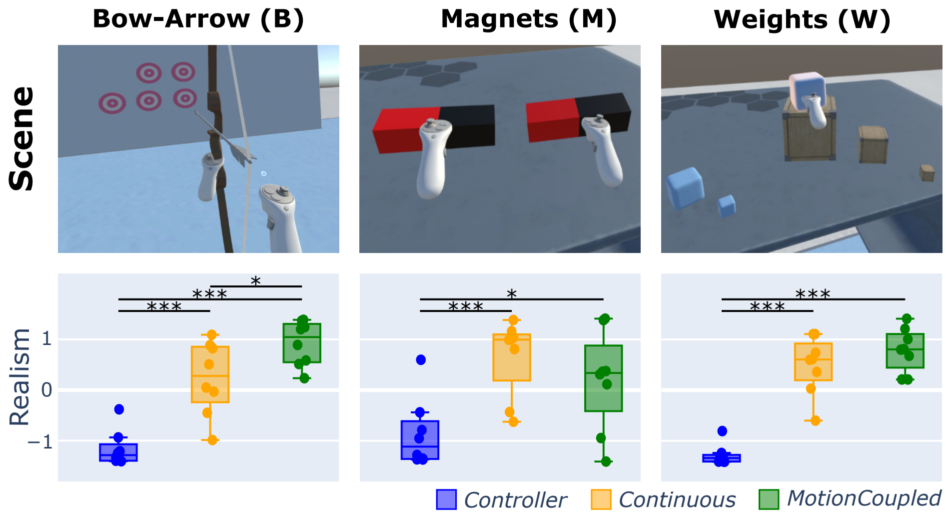

Figure 9: The top row shows the three scenes explored in the VR study. The bottom row shows the standardized realism scores for the scenes for the three vibration conditions: *Controller, Continuous, MotionCoupled*. Each point is a user estimate. The y-axis for realism represents the standardized scores, and each box-plot represents the median and the interquartile range. ($* : p < .05$; $** : p < .01$; $* * * : p < .001$)

the bow," and P6 said, "Without visual feedback, the *Controller* vibrations didn't help much—it was hard to tell what I was doing." Participants perceived more clearly that the *MotionCoupled* and *Buzz* conditions had a force aspect. P1 mentioned, "second (*Continuous*) felt like first (*Controller*), but with force," and P2 said, "I felt more force with eyes closed compared to eyes open in second (*MotionCoupled*) and third condition (*Continuous*)."

6 Discussion

The goal of designing motion-coupled asymmetric vibration was to separate the experience of vibration from the experience of force. The qualitative results of study 1 underscore how important this separation is:

The interviews (subsection 4.5) indicate that continuous asymmetric vibrations distracted participants from perceiving pseudo forces clearly, with P5 saying, "It's hard to just extract the vibration out of it... sometimes it... screws up" and P9 adding that the perception of forces depends on where they were focusing attention. Conversely, interviews showed that motion-coupled asymmetric vibrations provides much clearer directional cues, with P9 stating that "you understand direction" and P3 feeling a force in the vertical direction after orienting the actuators vertically. Another insight from the qualitative interview was that the pseudo force elicited using continuous vibration decreased after constant exposure, which can be linked with sensory habituation [93]. However, motion-coupled asymmetric vibration did not show this effect in our studies, likely due to the dynamic nature of the signal. These results highlight both the need and benefit of minimizing the experience of vibration while providing force sensations.

6.1 Sensory Attenuation as Design Resource

Literature mentions that vibration has led to confusion in perceiving forces elicited by continuous asymmetric vibrations, mainly for opposite directions in the same dimension [21] and for two actuators being close and vibrating opposite each other [63]. This is simply considered as a limitation of this type of vibrotactile feedback.

Our work, however, suggests that one reason for being confused with the continuous asymmetric vibration might be the experience of vibration itself, which is perceived as originating from an external source and therefore is not attenuated by our perception. Katz calls this a distal stimulus [43]. In contrast, motion-coupled asymmetric vibration is perceived "less in vibrations" (P7) and "more natural" (P11). As these vibrations are generated based on human motion, we assume they are experienced as self-caused, or proximal [43] stimuli, leading to sensory attenuation [87]. This highlights how motion-coupled asymmetric vibration, perceived as self-caused, leverages sensory attenuation to address the limitations of traditional vibrotactile feedback.

Building on the attenuation of perceived vibration while preserving the sensation of force through motion-coupled asymmetric vibrations, we hypothesize that a similar sensory attenuation occurs with symmetrical vibration pulses coupled to user motion. This attenuation could potentially explain how diverse material experiences—such as virtual texture [74, 86], compliance [96], movement [26], and deformation (e.g., stretching or bending) [37]—are induced while masking the underlying vibrations. Moreover, this attenuation of perceived vibration might also be the reason why Sabnis et al. [73] found motion-coupled vibration to improve the sense of agency. However, future research needs to experimentally confirm the attenuation phenomenon associated with symmetrical vibrations and its role in shaping tactile experiences.

6.2 Perceived Vibration and Force in Rendering Motion-Coupled Asymmetric Vibrations

The first part of this paper investigated perceived vibrations and pseudo forces. The key to understanding our results lies in the differentiation between stimuli and qualia (e.g. [85]): A stimulus is a physical phenomenon, for example, asymmetric vibration. Although the vibration itself is purely mechanical, how the user interprets it (whether as a sense of force or annoying vibration)depends on the interaction between the stimulus and their sensory processing. We explored this distinction by comparing different algorithms for rendering asymmetric vibrations (stimuli) to elicit pseudo forces (qualia). Therefore, we asked: Can the same basic stimulus be perceived differently depending on the algorithm used to control it, effectively shaping the resulting qualia?

6.2.1 Comparing our contribution to baseline: We first compared motion-coupled asymmetric vibration and baseline continuous asymmetric vibration. Referring to Figure 6-Ⓒ, there is no significant difference between the magnitude of the perceived force. The difference in perceived vibration, however, is both large and statistically significant (Figure 6-Ⓐ). For context, this reduction in perceived vibration with motion-coupled asymmetric vibration to generate the same level of pseudo forces as continuous asymmetric vibration is equal to a 30% reduction in the intensity of vibration, see Figure 6-Ⓑ. Our results showed that motion-coupled asymmetric vibration successfully attenuates vibration, in line with literature on sensory attenuation, and can be thought of as self-generated. However, our comparison does not explain why this occurs, as there are multiple differences between these two experiences.

6.2.2 Effect of movement: The obvious difference between our algorithm and state-of-the-art is that users move when experiencing motion-coupled vibration, while the state-of-the-art measures are typically experienced without movement. However, since movement attenuates external stimuli [7, 46], it is possible that the difference in perceived vibration is due to movement. To examine this effect, we compared *ContinuousStationary* (Figure 6-red) and *ContinuousMoving* (Figure 6-green). We confirmed that movement reduces the perceived vibration similar to sensory attenuation literature [7, 47]; however, the average rating of pseudo force was not significantly higher with movement, differing from the literature [3]. We believe that this might be due to the differences in the setup and evaluation methods, as in our study, participants were allowed to rate the force on a free scale. However, this observation is not enough to fully explain the strong attenuation of perceived vibration for motion-coupled asymmetric vibration.

6.2.3 Effect of Coupling: To understand the effects of motion-coupling, we compared *live* motion-coupled signal to *replayed* motion-coupled signal while participants were moving. The only difference being the exact correspondence to movements for the live motion-coupled signal and a non-correspondence for the replay condition. We found that the replayed signal also displayed strong attenuation, larger in magnitude than the attenuation by movement alone. However, the pseudo-force was no longer perceived. The higher attenuation for a replayed signal compared to continuous vibrations shows that the latter are perceived stronger than the same number of individually spaced pulses in time, concurring to previous findings in the vibrotactile perception literature [74, 76].

In summary, there are three differences between our suggested algorithm and the state-of-the-art: (1) continuity of vibration, (2) user motion, and (3) coupling of vibration to user motion. We found that movement leads to slight attenuation of vibration, but likely contributes to the success of preserving forces with motion-coupled asymmetric vibration. We also found that the replayed signal attenuates vibration but destroys the force illusion. This leads us to believe that the tight coupling of pulse occurrence to a user's motion is key to optimizing the pseudo-force illusion.

These findings are relevant because stimuli induced by self-generated actions are attenuated and leading to higher levels of Sense of Agency (SoA) [11, 73]. Moreover, Tanabe and Kaneko [90] show that pseudo forces can decrease the SoA of the user, leading to the user's feeling that pseudo forces cause the movement, with continuous asymmetric vibration stimuli. In contrast, we can increase the SoA by using motion-coupled asymmetric vibration, thus giving the user an experience of *self-caused* forces.

6.3 Motion-Coupled Asymmetric Vibration in the Presence of Visual Information

Using vibrations to render perceptually pure forces has practical implications for designing more immersive and intuitive haptic feedback systems in VR. Results showed that motion-coupled asymmetric vibration was preferred for dynamic tasks like shooting arrows or lifting weights. One reason for the increase in realism for dynamic tasks using motion-coupled asymmetric vibration might be because, in the absence of visual feedback, motion-coupled vibration helped users understand the intermediate states of the action they were performing, for example, "how far the bow is stretched" (P1). Despite the controllers being ergonomically optimized, and the other conditions were "holding a motor in fingers", asymmetric vibration still performed better for the application scenarios. Reasons could be that controller vibrations "spoke a different language" (P2) or "felt like background vibration" (P3), but it might also be due to the controller vibrations being symmetric. Interestingly, continuous asymmetric vibrations were preferred in the bimanual handling of haptic magnets, with participants expressing, "I can clearly feel the attraction and repulsion" (P3) and "there is nothing to improve" (P6), which might be due to the fact that magnetic force is an external force for the user. In contrast, pulling a bow or lifting a weight is based on the user's applied force, which makes motion-coupled asymmetric vibration the preferred choice.

It should be noted though that the controller is a fully integrated and ergonomically optimized, whereas the TacHammer system used for rendering motion-coupled asymmetric vibration is a simplified device optimized for output. Future work should investigate the integration of MCAV with commercial devices, which might require ergonomic modifications (e.g. to have a pinch-grip), which is beyond the scope of this paper. Here, we wanted to demonstrate that our rendering approach can be beneficial in VR environments.

6.4 Limitations and Future Work

One of the primary limitations of motion-coupled asymmetric vibration is that force experiences cannot be provided when the user is stationary. Similar to pseudo forces rendered by continuous asymmetric vibrations, the pseudo forces elicited by MCAV are limited to body locations with a higher density of Meissner corpuscles, such as fingertips and lips. Further research should investigate different body locations for MCAV along with integrating it with other devices [89]. Moreover, coupling user motion with asymmetric vibrations in time rather than amplitude might offer opportunities to provide stronger pseudo force sensations [91]. Similar to continuous asymmetric vibrations, motion-coupled asymmetric vibrations can induce pseudo forces with a wide array of systems [64]. The psychophysics study was conducted in a non-naturalistic setting, where participants performed a controlled task. The results for vibration perception are more robust and less dependent on the actuator type compared to the pseudo force perception, while the effect sizes of amplitude are larger for vibration than for pseudo force, which highlights that pseudo force is less amplitude dependent. Although there were no noticeable phase differences in the actuators, future research should investigate this, along with how holding the actuators and movement affect the output accelerations. While our qualitative interviews hinted at the onset behavior of perceiving pseudo forces, more in-depth study is needed to understand the intricacies of what happens on a perceptual level while perceiving pseudo forces. The VR study was conducted with fewer participants, so the statistical power was low. We were interested in comparing how different devices contribute to the sense of realism in VR. Hence, we did not account for the differences in the strength of vibration between the hand controllers and TacHammers. Although rendering continuous symmetric vibration using hand controllers in VR did not induce force sensations, controller-based motion-coupled symmetric vibrations should be investigated to assess the individual effects of motion-coupling and the type of vibration on attenuation of vibration in commercial devices.

We presented motion-coupled asymmetric vibrations based on fundamental principles of sensory attenuation. Our method provides seemingly continuous pseudo forces to induce a feeling of force by sampling the user movement fast enough. The sampled movement to output vibration has multiple possibilities: from encoding pseudo forces as vectors in 3D VR-environments to real-environments with force fields. Future research should systematically explore whether the perceptual mechanism of sensory attenuation contributes to reducing perceived vibration when using motion-coupled symmetric vibrations, as suggested by anecdotal evidence in [84]. Although we looked at linear, constant, and cubic mappings, the design space and modulations of the algorithm to generate uni-directional and multi-directional force effects need to be explored systematically. With appropriate sensing, motion-coupled asymmetric vibration can generate a range of experiences in VR, ranging from linear and torsional springs to damping and viscous elements for single-handed and bimanual applications with appropriate adaptations of the algorithm. Finally, integrating MCAV with other material experiences rendered using vibrotactile feedback can contribute towards generic tactile displays.

7 Conclusion

We present motion-coupled asymmetric vibration, a novel algorithm based on sensory attenuation mechanisms that provides asymmetric vibration pulses coupled with dynamic changes in user movement. To evaluate our algorithm, we compared to continuous asymmetric vibrations and conducted a psychophysics study that evaluated perceived vibration and force. Our findings showed that motion-coupled asymmetric vibrations were able to reduce perceived vibration by 30%, while maintaining the force sensations. In VR scenarios like shooting arrows and lifting weights, participants preferred motion-coupled asymmetric vibrations, highlighting the algorithm's potential for enhancing realism. Motion-coupled asymmetric vibration offers a wide range of force effects in VR and a potential to facilitate the creation of versatile, immersive tactile displays in both virtual and real environments.

References

[1] Tomohiro Amemiya, Hideyuki Ando, and Taro Maeda. 2005. Phantom-DRAWN: direction guidance using rapid and asymmetric acceleration weighted by nonlinearity of perception. In *Proceedings of the 2005 international conference on Augmented tele-existence*. 201–208.

[2] T. Amemiya, H. Ando, and T. Maeda. 2005. Virtual force display: direction guidance using asymmetric acceleration via periodic translational motion. In *First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics Conference*. 619–622. doi:10.1109/WHC.2005.146

[3] Tomohiro Amemiya and Hiroaki Gomi. 2016. Active manual movement improves directional perception of illusory force. *IEEE transactions on haptics* 9, 4 (2016), 465–473.

[4] Tomohiro Amemiya and Taro Maeda. 2008. Asymmetric oscillation distorts the perceived heaviness of handheld objects. *IEEE Transactions on Haptics* 1, 1 (2008), 9–18.

[5] Tomohiro Amemiya and Taro Maeda. 2009. Directional force sensation by asymmetric oscillation from a double-layer slider-crank mechanism. *Journal of computing and information science in engineering* 9, 1 (2009).

[6] Paul M Bays, J Randall Flanagan, and Daniel M Wolpert. 2006. Attenuation of self-generated tactile sensations is predictive, not postdictive. *PLoS biology* 4, 2 (2006), e28.

[7] Paul M Bays, Daniel M Wolpert, and J Randall Flanagan. 2005. Perception of the consequences of self-action is temporally tuned and event driven. *Current Biology* 15, 12 (2005), 1125–1128.

[8] Hrvoje Benko, Christian Holz, Mike Sinclair, and Eyal Ofek. 2016. Normaltouch and texturetouch: High-fidelity 3d haptic shape rendering on handheld virtual reality controllers. In *Proceedings of the 29th annual symposium on user interface software and technology*. 717–728.

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

[10] Sarah-J Blakemore, Daniel M Wolpert, and Chris D Frith. 1998. Central cancellation of self-produced tickle sensation. *Nature neuroscience* 1, 7 (1998), 635–640.

[11] Harriet Brown, Rick A Adams, Isabel Parees, Mark Edwards, and Karl Friston. 2013. Active inference, sensory attenuation and illusions. *Cognitive processing* 14 (2013), 411–427.

[12] Grigore Burdea, Jiachen Zhuang, Edward Roskos, Deborah Silver, and Noshir Langrana. 1992. A Portable Dextrous Master with Force Feedback. *Presence: Teleoperators and Virtual Environments* 1, 1 (02 1992), 18–28. doi:10.1162/pres.1992.1.1.18

[13] C Elaine Chapman and Evelyne Beauchamp. 2006. Differential controls over tactile detection in humans by motor commands and peripheral reafference. *Journal of Neurophysiology* 96, 3 (2006), 1664–1675.

[14] C Elaine Chapman, MC Bushnell, D Miron, GH Duncan, and JP Lund. 1987. Sensory perception during movement in man. *Experimental brain research* 68 (1987), 516–524.

[15] Inrak Choi, Heather Culbertson, Mark R Miller, Alex Olwal, and Sean Follmer. 2017. Grabity: A wearable haptic interface for simulating weight and grasping in virtual reality. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology*. 119–130.

[16] Inrak Choi, Eyal Ofek, Hrvoje Benko, Mike Sinclair, and Christian Holz. 2018. CLAW: A Multifunctional Handheld Haptic Controller for Grasping, Touching, and Triggering in Virtual Reality. 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. doi:10.1145/3173574.3174228

[17] Francisco L Colino, Gavin Buckingham, Darian T Cheng, Paul van Donkelaar, and Gordon Binsted. 2014. Tactile gating in a reaching and grasping task. *Physiological reports* 2, 3 (2014), e00267.

[18] Giulia Corniani and Hannes P Saal. 2020. Tactile innervation densities across the whole body. *Journal of Neurophysiology* 124, 4 (2020), 1229–1240.

[19] Heather Culbertson, Samuel B Schorr, and Allison M Okamura. 2018. Haptics: The present and future of artificial touch sensation. *Annual review of control, robotics, and autonomous systems* 1, 1 (2018), 385–409.

[20] Heather Culbertson, Julie M Walker, and Allison M Okamura. 2016. Modeling and design of asymmetric vibrations to induce ungrounded pulling sensation through asymmetric skin displacement. In *2016 IEEE Haptics Symposium (HAPTICS)*. IEEE, 27–33.

[21] Heather Culbertson, Julie M Walker, Michael Raitor, and Allison M Okamura. 2017. WAVES: a wearable asymmetric vibration excitation system for presenting three-dimensional translation and rotation cues. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. 4972–4982.

[22] Donald Degraen, Bruno Fruchard, Frederik Smolders, Emmanouil Potetsianakis, Seref Güngör, Antonio Krüger, and Jürgen Steimle. 2021. Weirding Haptics: In-Situ Prototyping of Vibrotactile Feedback in Virtual Reality through Vocalization. In *The 34th Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '21)*. Association for Computing Machinery, New York, NY, USA, 936–953. doi:10.1145/3472749.3474797

[23] Donald Degraen, André Zenner, and Antonio Krüger. 2019. Enhancing Texture Perception in Virtual Reality Using 3D-Printed Hair Structures. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 1–12. doi:10.1145/3290605.3300479

[24] Alexandra Delazio, Ken Nakagaki, Roberta L Klatzky, Scott E Hudson, Jill Fain Lehman, and Alanson P Sample. 2018. Force jacket: Pneumatically-actuated jacket for embodied haptic experiences. In *Proceedings of the 2018 CHI conference on human factors in computing systems*. 1–12.

[25] Andrea Desantis, Carmen Weiss, Simone Schütz-Bosbach, and Florian Waszak. 2012. Believing and perceiving: Authorship belief modulates sensory attenuation. *PLoS One* 7, 5 (2012), e37959.

[26] 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*. 1–16. doi:10.1145/3613904.3642499

[27] Takahiro Endo, Haruhisa Kawasaki, Tetsuya Mouri, Yasuhiko Ishigure, Hisayuki Shimomura, Masato Matsumura, and Kazumi Koketsu. 2010. Five-fingered haptic interface robot: HIRO III. *IEEE transactions on haptics* 4, 1 (2010), 14–27.

[28] Sarah Faltaous, Marvin Prochazka, Jonas Auda, Jonas Keppel, Nick Wittig, Uwe Gruenefeld, and Stefan Schneegass. 2022. Give Weight to VR: Manipulating Users' Perception of Weight in Virtual Reality with Electric Muscle Stimulation. In *Proceedings of Mensch Und Computer 2022* (Darmstadt, Germany) *(MuC '22)*. Association for Computing Machinery, New York, NY, USA, 533–538. doi:10.1145/3543758.3547571

[29] Cathy Fang, Yang Zhang, Matthew Dworman, and Chris Harrison. 2020. Wireality: Enabling complex tangible geometries in virtual reality with worn multi-string haptics. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–10.

[30] Jamie Ferguson, John Williamson, and Stephen Brewster. 2018. Evaluating mapping designs for conveying data through tactons. In *Proceedings of the 10th Nordic Conference on Human-Computer Interaction* (Oslo, Norway) *(NordiCHI '18)*. Association for Computing Machinery, New York, NY, USA, 215–223. doi:10.1145/3240167.3240175

[31] Lindsey E Fraser and Katja Fiehler. 2018. Predicted reach consequences drive time course of tactile suppression. *Behavioural Brain Research* 350 (2018), 54–64.

[32] Patricia Garrido-Vásquez and Tanja Rock. 2020. Sense of agency in multi-step actions. *Advances in Cognitive Psychology* 16, 2 (2020), 85.

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

[34] Sebastian Günther, Mohit Makhija, Florian Müller, Dominik Schön, Max Mühlhäuser, and Markus Funk. 2019. PneumAct: Pneumatic kinesthetic actuation of body joints in virtual reality environments. In *Proceedings of the 2019 on Designing Interactive Systems Conference*. 227–240.

[35] Nur Al-huda Hamdan, Adrian Wagner, Simon Voelker, Jürgen Steimle, and Jan Borchers. 2019. Springlets: Expressive, Flexible and Silent On-Skin Tactile Interfaces. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–14. doi:10.1145/3290605.3300718

[36] Seongkook Heo, Christina Chung, Geehyuk Lee, and Daniel Wigdor. 2018. Thor's Hammer: An Ungrounded Force Feedback Device Utilizing Propeller-Induced Propulsive Force. 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, 1–11. doi:10.1145/3173574.3174099

[37] 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. doi:10.1145/3332165.3347941

[38] Inwook Hwang and Seungmoon Choi. 2012. Effect of mechanical ground on the vibrotactile perceived intensity of a handheld object. In *Haptics: Perception, Devices, Mobility, and Communication: International Conference, EuroHaptics 2012, Tampere, Finland, June 13-15, 2012 Proceedings, Part II*. Springer, 61–66.

[39] Arata Jingu, Nihar Sabnis, Paul Strohmeier, and Jürgen Steimle. 2024. Shaping Compliance: Inducing Haptic Illusion of Compliance in Different Shapes with Electrotactile Grains. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. 1–13.

[40] 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. doi:10.1038/nrn2621

[41] Roland S Johansson and Ake B Vallbo. 1979. Tactile sensibility in the human hand: relative and absolute densities of four types of mechanoreceptive units in glabrous skin. *The Journal of physiology* 286, 1 (1979), 283–300.

[42] Sungchul Jung and Robert W Lindeman. 2021. Perspective: Does realism improve presence in vr? suggesting a model and metric for vr experience evaluation. *Frontiers in virtual reality* 2 (2021), 693327.

[43] David Katz. 1989. *The world of touch*. Psychology Press, London, England.

[44] Fabian Kiepe, Nils Kraus, and Guido Hesselmann. 2021. Sensory attenuation in the auditory modality as a window into predictive processing. *Frontiers in Human Neuroscience* 15 (2021), 704668.

[45] 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* (Beijing, China) *(ICMI-MLMI '10)*. ACM, New York, NY, USA, Article 21, 8 pages. doi:10.1145/1891903.1891931

[46] Konstantina Kilteni and H Henrik Ehrsson. 2017. Sensorimotor predictions and tool use: Hand-held tools attenuate self-touch. *Cognition* 165 (2017), 1–9.

[47] Konstantina Kilteni and H Henrik Ehrsson. 2022. Predictive attenuation of touch and tactile gating are distinct perceptual phenomena. *Iscience* 25, 4 (2022).

[48] Konstantina Kilteni, Christian Houborg, and H Henrik Ehrsson. 2019. Rapid learning and unlearning of predicted sensory delays in self-generated touch. *Elife* 8 (2019), e42888.

[49] Erin Kim and Oliver Schneider. 2020. Defining haptic experience: foundations for understanding, communicating, and evaluating HX. In *Proceedings of the 2020 CHI conference on human factors in computing systems*. 1–13.

[50] Hwan Kim, HyeonBeom Yi, Hyein Lee, and Woohun Lee. 2018. HapCube: A wearable tactile device to provide tangential and normal pseudo-force feedback on a fingertip. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 1–13.

[51] Taejun Kim, Youngbo Aram Shim, Youngin Kim, Sunbum Kim, Jaeyeon Lee, and Geehyuk Lee. 2024. QuadStretcher: A Forearm-Worn Skin Stretch Display for Bare-Hand Interaction in AR/VR. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. 1–15.

[52] Frederick A. A. Kingdom and Nicolaas Prins. 2016. *Psychophysics: a practical introduction* (second edition ed.). Elsevier/Academic Press, Amsterdam.

[53] Jarrod Knibbe, Adrian Alsmith, and Kasper Hornbæk. 2018. Experiencing electrical muscle stimulation. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 2, 3 (2018), 1–14.

[54] Anatole Lecuyer, Sabine Coquillart, Abderrahmane Kheddar, Paul Richard, and Philippe Coiffet. 2000. Pseudo-haptic feedback: can isometric input devices simulate force feedback?. In *Proceedings IEEE Virtual Reality 2000 (Cat. No.00CB37048)*. IEEE Computer Society, New Brunswick, NJ, USA, 83–90. doi:10.1109/VR.2000.840369

[55] 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. doi:10.1109/VR.2000.840369

[56] Jaeyeon Lee, Mike Sinclair, Mar Gonzalez-Franco, Eyal Ofek, and Christian Holz. 2019. TORC: A virtual reality controller for in-hand high-dexterity finger interaction. In *Proceedings of the 2019 CHI conference on human factors in computing systems*. ACM, 1–13.

[57] Woan Ning Lim, Kian Meng Yap, Yunli Lee, Chyanna Wee, and Ching Chiuan Yen. 2021. A systematic review of weight perception in virtual reality: techniques, challenges, and road ahead. *IEEE Access* 9 (2021), 163253–163283.

[58] Yilong Lin, Peng Zhang, Eyal Ofek, and Seungwoo Je. 2024. ArmDeformation: Inducing the Sensation of Arm Deformation in Virtual Reality Using Skin-Stretching. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. 1–18.

[59] Pedro Lopes and Patrick Baudisch. 2017. Interactive Systems Based on Electrical Muscle Stimulation. *Computer* 50, 10 (Oct. 2017), 28–35. doi:10.1109/MC.2017.3641627

[60] Pedro Lopes, Alexandra Ion, and Patrick Baudisch. 2015. Impacto: Simulating Physical Impact by Combining Tactile Stimulation with Electrical Muscle Stimulation. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software and Technology* (Charlotte, NC, USA) *(UIST '15)*. Association for Computing Machinery, New York, NY, USA, 11–19. doi:10.1145/2807442.2807443

[61] Pedro Lopes, Sijing You, Lung-Pan Cheng, Sebastian Marwecki, and Patrick Baudisch. 2017. Providing Haptics to Walls & Heavy Objects in Virtual Reality by Means of Electrical Muscle Stimulation. 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, 1471–1482. doi:10.1145/3025453.3025600

[62] Pedro Lopes, Sijing You, Alexandra Ion, and Patrick Baudisch. 2018. Adding Force Feedback to Mixed Reality Experiences and Games Using Electrical Muscle Stimulation. 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. doi:10.1145/3173574.3174020

[63] Tomosuke Maeda, Takayoshi Yoshimura, Junnosuke Yamamoto, Hiroyuki Sakai, and Kouta Minamizawa. 2024. Design and Validation of Pseudo-Force Haptic Device for Actual Walking. In *2024 IEEE Haptics Symposium (HAPTICS)*. IEEE, 104–110.

[64] Rubén Martín-Rodríguez, Alexandre L Ratschat, Laura Marchal-Crespo, and Yasemin Vardar. 2024. Tactile Weight Rendering: A Review for Researchers and Developers. *arXiv preprint arXiv:2402.13120* (2024).

[65] Thomas H Massie, J Kenneth Salisbury, et al. 1994. The phantom haptic interface: A device for probing virtual objects. In *Proceedings of the ASME winter annual meeting, symposium on haptic interfaces for virtual environment and teleoperator systems*, Vol. 55. Chicago, IL, 295–300.

[66] James W Moore, Daniel M Wegner, and Patrick Haggard. 2009. Modulating the sense of agency with external cues. *Consciousness and cognition* 18, 4 (2009), 1056–1064.

[67] Miyuki Morioka, Darren J Whitehouse, and Michael J Griffin. 2008. Vibrotactile thresholds at the fingertip, volar forearm, large toe, and heel. *Somatosensory & motor research* 25, 2 (2008), 101–112.

[68] Sajid Nisar, Melisa Orta Martinez, Takahiro Endo, Fumitoshi Matsuno, and Allison M. Okamura. 2019. Effects of Different Hand-Grounding Locations on Haptic Performance With a Wearable Kinesthetic Haptic Device. *IEEE Robotics and Automation Letters* 4, 2 (April 2019), 351—-358. doi:10.1109/LRA.2018.2890198

[69] William Provancher. 2014. Creating greater VR immersion by emulating force feedback with ungrounded tactile feedback. *IQT Quarterly* 6, 2 (2014), 18–21.

[70] Jun Rekimoto. 2014. Traxion: a tactile interaction device with virtual force sensation. In *ACM SIGGRAPH 2014 Emerging Technologies*. Association for Computing Machinery, 1–1.

[71] DN Rushton, JC Roghwell, and MD Craggs. 1981. Gating of somatosensory evoked potentials during different kinds of movement in man. *Brain* 104, 3 (1981), 465–491.

[72] Nihar Sabnis. 2021. Pseudo forces from asymmetric vibrations can provide movement guidance. (2021).

[73] Nihar Sabnis, Ata Otaran, Dennis Wittchen, Johanna Didion, Jürgen Steimle, and Paul Strohmeier. 2025. Foot Pedal Control: The Role of Vibrotactile Feedback in Performance and Perceived Control. In *Nineteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Bordeaux / Talence, France) *(TEI '25)*. Association for Computing Machinery, New York, NY, USA, 15 pages. doi:10.1145/3689050.3704937

[74] 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* (Hamburg, Germany) *(CHI '23)*. Association for Computing Machinery, New York, NY, USA, Article 522, 17 pages. doi:10.1145/3544548.3580716

[75] Nihar Sabnis, Dennis Wittchen, and Paul Strohmeier. 2024. Sensory Attenuation of vibration and pseudo forces. https://doi.org/10.17605/OSF.IO/RFW36 [Online; accessed 26. Jan. 2025].

[76] 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.

[77] Oliver S Schneider, Ali Israr, and Karon E MacLean. 2015. Tactile animation by direct manipulation of grid displays. In *Proceedings of the 28th annual ACM symposium on user interface software & technology*. 21–30.

[78] Hasti Seifi, Kailun Zhang, and Karon E MacLean. 2015. VibViz: Organizing, visualizing and navigating vibration libraries. In *2015 IEEE World Haptics Conference (WHC)*. IEEE, 254–259.

[79] Mike Sinclair, Eyal Ofek, Mar Gonzalez-Franco, and Christian Holz. 2019. CapstanCrunch: A Haptic VR Controller with User-Supplied Force Feedback. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology* (New Orleans, LA, USA) *(UIST '19)*. Association for Computing Machinery, New York, NY, USA, 815–829. doi:10.1145/3332165.3347891

[80] Evgeniy N Sokolov. 1963. Higher nervous functions: The orienting reflex. *Annual review of physiology* 25, 1 (1963), 545–580.

[81] Marco Speicher, Jan Ehrlich, Vito Gentile, Donald Degraen, Salvatore Sorce, and Antonio Krüger. 2019. Pseudo-Haptic Controls for Mid-Air Finger-Based Menu Interaction. 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—-6. doi:10.1145/3290607.3312927

[82] Carolin Stellmacher, Michael Bonfert, Ernst Kruijff, and Johannes Schöning. 2022. Triggermuscle: Exploring Weight Perception for Virtual Reality Through Adaptive Trigger Resistance in a Haptic VR Controller. *Frontiers in Virtual Reality* 2 (2022). doi:10.3389/frvir.2021.754511

[83] Carolin Stellmacher, André Zenner, Oscar Javier Ariza Nunez, Ernst Kruijff, and Johannes Schöning. 2023. Continuous VR Weight Illusion by Combining Adaptive Trigger Resistance and Control-Display Ratio Manipulation. In *2023 IEEE Conference Virtual Reality and 3D User Interfaces (VR)*. 243–253. doi:10.1109/VR55154.2023.00040

[84] Paul Strohmeier, Sebastian Boring, and Kasper Hornbæk. 2018. *From Pulse Trains to "Coloring with Vibrations": Motion Mappings for Mid-Air Haptic Textures*. ACM, New York, NY, USA, 1–13. https://doi.org/10.1145/3173574.3173639

[85] 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* (Virtual Event, USA) *(UIST '20)*. ACM, New York, NY, USA, 579–593. doi:10.1145/3379337.3415828

[86] 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.

[87] Matthis Synofzik, Gottfried Vosgerau, and Albert Newen. 2008. Beyond the comparator model: A multifactorial two-step account of agency. *Consciousness and Cognition* 17, 1 (2008), 219–239. doi:10.1016/j.concog.2007.03.010

[88] Shinya Takamuku, Tomohiro Amemiya, Sho Ito, and Hiroaki Gomi. 2016. Design of illusory force sensation for virtual fishing. *Trans. Hum. Interface Soc* 18 (2016), 87–94.

[89] Takeshi Tanabe, Yasuhiro Fujimoto, Kiyohiko Nunokawa, Kouki Doi, and Shuichi Ino. 2023. White Cane-Type Holdable Device Using Illusory Pulling Cues for Orientation & Mobility Training. *IEEE Access* 11 (2023), 28706–28714.

[90] Takeshi Tanabe and Hidekazu Kaneko. 2024. Illusory Directional Sensation Induced by Asymmetric Vibrations Influences Sense of Agency and Velocity in Wrist Motions. *IEEE Transactions on Neural Systems and Rehabilitation Engineering* (2024).

[91] Takeshi Tanabe, Hiroaki Yano, Hiroshi Endo, Shuichi Ino, and Hiroo Iwata. 2020. Pulling illusion based on the phase difference of the frequency components of asymmetric vibrations. *IEEE/ASME Transactions on Mechatronics* 26, 1 (2020), 203–213.

[92] Yudai Tanaka, Arata Horie, and Xiang'Anthony' Chen. 2020. DualVib: Simulating haptic sensation of dynamic mass by combining pseudo-force and texture feedback. In *Proceedings of the 26th ACM Symposium on Virtual Reality Software and Technology*. 1–10.

[93] Richard F Thompson and William A Spencer. 1966. Habituation: a model phenomenon for the study of neuronal substrates of behavior. *Psychological review* 73, 1 (1966), 16.

[94] Ching-Yi Tsai, I-Lun Tsai, Chao-Jung Lai, Derrek Chow, Lauren Wei, Lung-Pan Cheng, and Mike Y. Chen. 2022. AirRacket: Perceptual Design of Ungrounded, Directional Force Feedback to Improve Virtual Racket Sports Experiences. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 185, 15 pages. doi:10.1145/3491102.3502034

[95] Dianne Vasseur, Sima Ipakchian Askari, Sandra Suijkerbuijk, Henk Herman Nap, and Wijnand IJsselsteijn. 2024. Sensory, Affective, and Social Experiences with Haptic Devices in Intramural Care Practice. *Nursing Reports* 14, 1 (2024), 230–253.

[96] Gabriela Vega, Valentin Martinez-Missir, Dennis Wittchen, Nihar Sabnis, Audrey Girouard, Karen Anne Cochrane, and Paul Strohmeier. 2024. vARitouch: Back of the Finger Device for Adding Variable Compliance to Rigid Objects. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. 1–20.

[97] Ingrid MLC Vogels. 2004. Detection of temporal delays in visual-haptic interfaces. *Human Factors* 46, 1 (2004), 118–134.

[98] Martin Voss, James N Ingram, Daniel M Wolpert, and Patrick Haggard. 2008. Mere expectation to move causes attenuation of sensory signals. *PLoS One* 3, 8 (2008), e2866.

[99] Dimitris Voudouris and Katja Fiehler. 2021. Dynamic temporal modulation of somatosensory processing during reaching. *Scientific Reports* 11, 1 (2021), 1928.

[100] Dennis Wittchen, Valentin Martinez-Missir, Sina Mavali, Nihar Sabnis, Courtney N. Reed, and Paul Strohmeier. 2023. Designing Interactive Shoes for Tactile Augmented Reality. In *Proceedings of the Augmented Humans International Conference 2023 (AHs '23)*. Association for Computing Machinery, New York, NY, USA, 1–14. doi:10.1145/3582700.3582728

[101] Daniel M Wolpert, Zoubin Ghahramani, and Michael I Jordan. 1995. An internal model for sensorimotor integration. *Science* 269, 5232 (1995), 1880–1882.

[102] Hsin-Yun Yao and Vincent Hayward. 2010. Design and analysis of a recoil-type vibrotactile transducer. *The Journal of the Acoustical Society of America* 128, 2

(2010), 619–627.
[103] André Zenner and Antonio Krüger. 2019. Drag:On: A Virtual Reality Controller Providing Haptic Feedback Based on Drag and Weight Shift. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. ACM, New York, NY, USA, 1–12. doi:10.1145/3290605.3300441 own.
[104] André Zenner and Antonio Krüger. 2017. Shifty: A Weight-Shifting Dynamic Passive Haptic Proxy to Enhance Object Perception in Virtual Reality. *IEEE Transactions on Visualization and Computer Graphics* 23, 4 (2017), 1285–1294. doi:10.1109/TVCG.2017.2656978
[105] André Zenner, Kristin Ullmann, and Antonio Krüger. 2021. Combining dynamic passive haptics and haptic retargeting for enhanced haptic feedback in virtual reality. *IEEE Transactions on Visualization and Computer Graphics* 27, 5 (2021), 2627–2637.

A Technical Evaluation

The technical setup used for measuring the output accelerations of the actuators and hand controller is shown in Figure 10-left and Figure 10-right, respectively. An MPU6050 inertial measurement unit (IMU) with an on-board accelerometer is attached to the actuators with a medical grade double-sided tape to ensure that there is no slipping between the actuator and the IMU sensor, and no dampening of the vibrations. For accurate acceleration measurements of the actuator, the IMU-actuators system was placed on a sponge to ensure that the recorded accelerations were representative of the actuator's true dynamic output. The sponge served as a vibration isolator while reducing mechanical coupling with external surfaces [30, 38]. The IMU was calibrated to measure the accelerations in G-values up to a maximum of 8 G. The sampling frequency of the IMU is 1 kHz. The pulses for motion-coupled asymmetric vibration were generated by sampling the movement trajectory of a participant from Study 1 as input. The continuous asymmetric vibration was generated by stitching together the generated pulses during the motion-coupled asymmetric vibration (see section 4).

Figure 12- Ⓐ shows the measured acceleration of the TacHammers for the four input conditions with three amplitudes used in Study 1. The input pulses are rendered with high-fidelity as observed in the measured accelerations in Figure 11, indicating little to no phase difference being introduced by having two actuators connected to each other. The differences in the driving signal (Figure 11, blue) and measured acceleration (Figure 11, red) can be attributed to actuator characteristics, additional mass of the IMU, and the mechanical coupling between the sensor and the actuator. Further, we observed a delay of ~10 milliseconds between the oscilloscope and the accelerometer output, adhering to the actuator latency [7]. The output acceleration of the hand controller is shown in Figure 12-Ⓑ. To characterize the signal and provide summary statistics, we calculated the sliding window RMS (*slidingRMS*) with 50 samples window size (i.e., 50 ms interval) to account for the difference in the number of pulses of all the measured output signals. We also calculated the mean of the maximum accelerations (*MeanPeak*) for each condition to account for low-frequency oscillatory behavior. Referring to Table 2, the *slidingRMS* and *MeanPeak* closely follow the amplitude of the input signal. The results show that the *HandController* has lower vibration intensity compared to the *TacHammers*.

[7] Latency in the TacHammer Datasheet: https://titanhaptics.com/wp-content/uploads/2023/05/TacHammer-Drake-Datasheet-1.pdf

B Grain-Based Behavior

Referring to Figure 13, the rugged line corresponding to each magenta dot represents one pulse of the asymmetric vibration for the specific condition. In the motion-coupled asymmetric vibration condition Ⓐ, the amount of pulses triggered corresponds to the speed of movement, and no pulses are triggered in the absence of movement. For motion-decoupled asymmetric vibration Ⓑ, the vibration pulses are replayed from the sequence of triggered pulses for condition Ⓐ in reverse. In contrast, for the continuous asymmetric vibration, the pulses are played continuously at a frequency of 40 Hz, independent of whether the user moving Ⓒ or stationary Ⓓ.

C Detailed Results

Figure 14 shows the individual conditions of the vibration stimuli compared in Study 1 along with the results of the comparison at all three amplitude levels: 40%, 70% and 100% of the maximum amplitude. Post-hoc results with Bonferroni correction showed that the differences between intensity levels were significant whenever the main effects were significant and vice versa.

Table 3 shows the perceived vibration and perceived force scores for controller vibration, continuous asymmetric vibration, and motion-coupled asymmetric vibration for the different scenes explored in section 5 Referring to Figure 15 and Table 3, the RM-ANOVA showed a statistically significant effect of vibration condition on participants' vibration estimates for all the scenes. Post-hoc analysis with Bonferroni correction showed that *Continuous* was perceived to be significantly stronger in vibration. For perceived force, the *Continuous* and *MotionCoupled* conditions were higher rated compared with the *Controller* condition for the bow-arrow and weights scenes. However, for the Magnets, only the difference between *Continuous* and *Controller* force scores was significant. In neither of the scenes was there a statistical difference between the force ratings for the *Continuous* and *MotionCoupled* conditions.

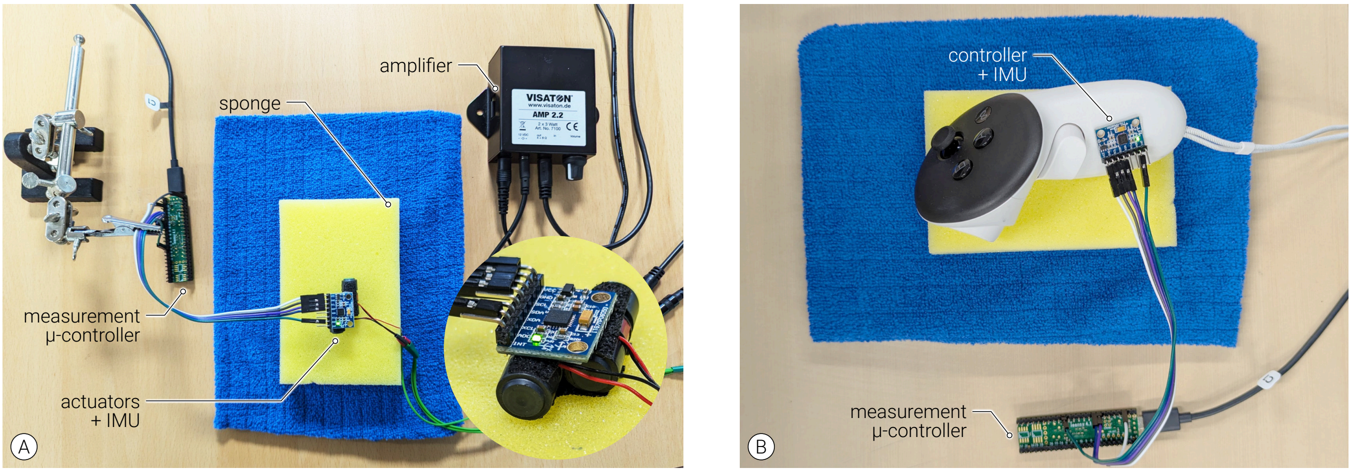

Figure 10: Technical setup used for measuring the output accelerations of the TacHammers (left) and the hand controller (right).

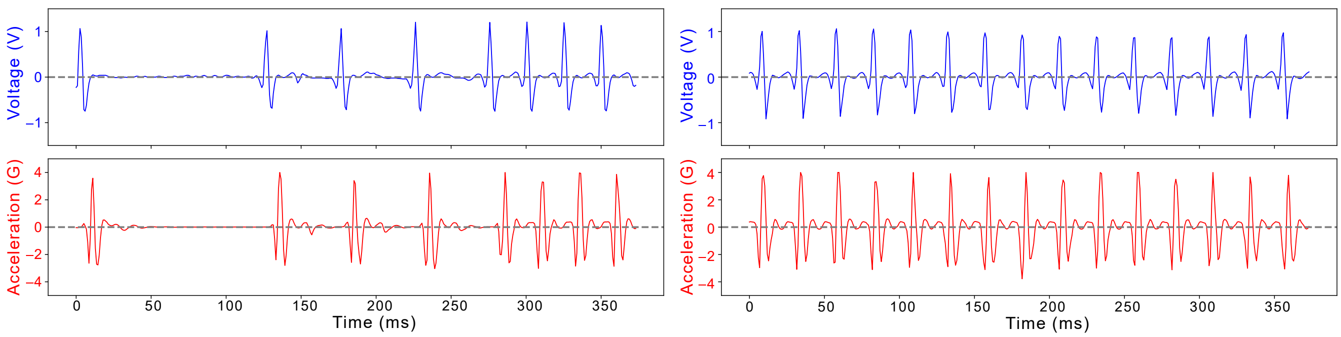

Figure 11: The driving signal (blue) used for generating motion-coupled asymmetric vibration (left) as well as continuous asymmetric vibration (right) along with the measured accelerations (red). These are the same signals at the 100% amplitude level for *MotionCoupled* and *ContinuousStationary* in Figure 12.

Table 2: Summary statistics of measured acceleration.

Condition	Amplitude (%)	Sliding RMS	Mean Peak (G)
MotionCoupled (A)	40	0.57 (40.15%)	1.60 (40.68%)
	70	0.99 (70.22%)	2.75 (69.72%)
	100	1.41 (100.00%)	3.94 (100.00%)
MotionDecoupled (B)	40	0.57 (40.15%)	1.60 (40.68%)
	70	0.99 (70.22%)	2.75 (69.72%)
	100	1.41 (100.00%)	3.94 (100.00%)
ContinousMoving (C)	40	0.51 (34.13%)	1.64 (40.94%)
	70	1.01 (67.12%)	2.99 (74.63%)
	100	1.50 (100.00%)	4.00 (100.00%)
ContinuousStationary (D)	40	0.51 (34.13%)	1.64 (40.94%)
	70	1.01 (67.12%)	2.99 (74.63%)
	100	1.50 (100.00%)	4.00 (100.00%)
HandController	40	0.36 (36.81%)	0.51 (38.72%)
	70	0.71 (72.45%)	0.93 (71.22%)
	100	0.98 (100.00%)	1.31 (100.00%)

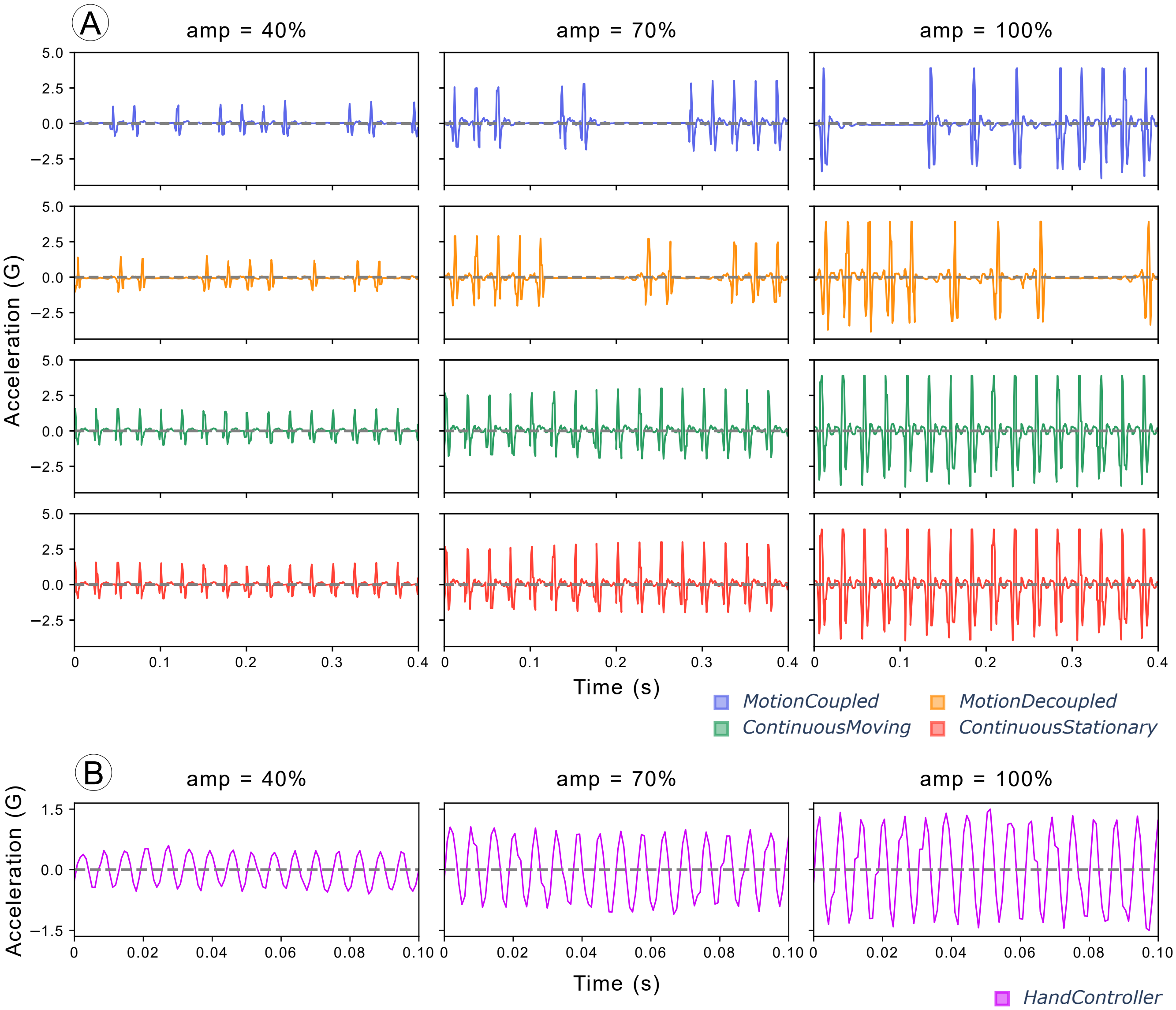

Figure 12: Measured acceleration (cropped) of the actuators are shown for each of the signals used in Study 1. The measured hand controller vibrations used in Study 2 are also shown in pink.

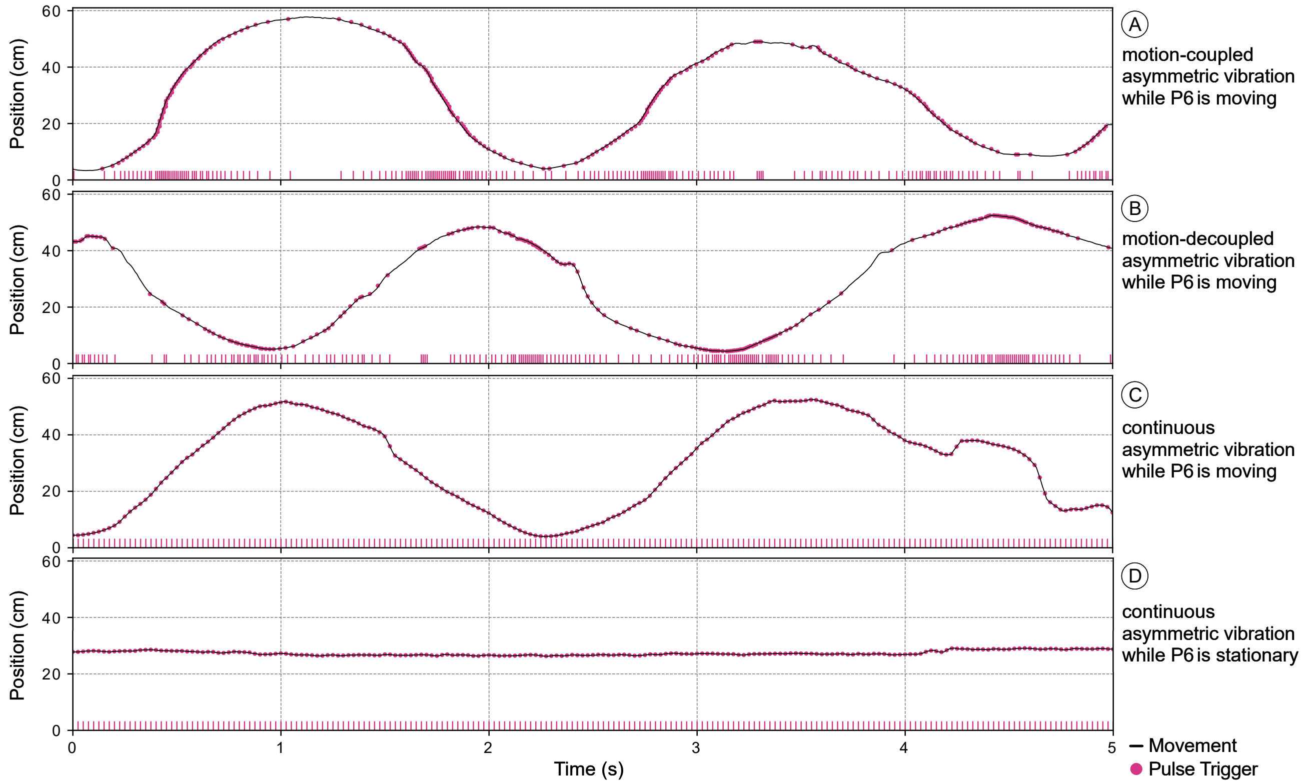

Figure 13: Four cropped sequences illustrate the movement profiles (black line) of a participant (P6) during Study 1 for four test conditions along with the corresponding vibrotactile feedback (magenta dots). The rugged lines below each movement profile show the density of played pulses (asymmetric vibration).

Table 3: Post-hoc vibration and force perception scores for different scenes and feedback conditions in Study 2.

Scene	Perceived Quantity	Comparison	t(df)-value	p-value
Bow-Arrow (B)	*Vibration*	Controller vs Continuous	t(7) = 2.99	p <0.05
		Controller vs MotionCoupled	t(7) = 0.17	Not Significant
		Continuous vs MotionCoupled	t(7) = 5.78	p <0.05
	Force	Controller vs Continuous	t(7) = 4.26	p <0.05
		Controller vs MotionCoupled	t(7) = -3.06	p <0.05
		Continuous vs MotionCoupled	t(7) = -0.27	Not Significant
Magnets (M)	*Vibration*	Controller vs Continuous	t(7) = 2.41	p <0.05
		Controller vs MotionCoupled	t(7) = 0.50	Not Significant
		Continuous vs MotionCoupled	t(7) = 2.27	p <0.05
	Force	Controller vs Continuous	t(7) = 5.19	p <0.05
		Controller vs MotionCoupled	t(7) = -1.51	Not Significant
		Continuous vs MotionCoupled	t(7) = 1.06	Not Significant
Weights (W)	*Vibration*	Controller vs Continuous	t(7) = 3.48	p <0.05
		Controller vs MotionCoupled	t(7) = -0.57	Not Significant
		Continuous vs MotionCoupled	t(7) = 4.22	p <0.05
	Force	Controller vs Continuous	t(7) = 12.06	p <0.05
		Controller vs MotionCoupled	t(7) = -5.03	p <0.05
		Continuous vs MotionCoupled	t(7) = 0.25	Not Significant

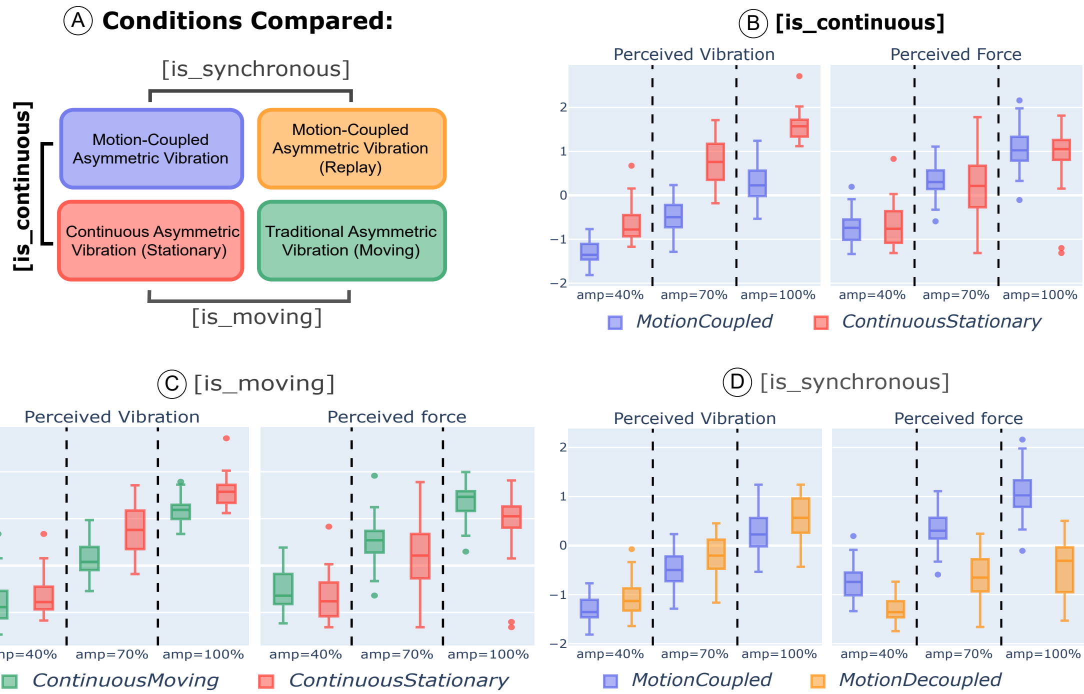

Figure 14: Ⓐ shows the conditions compared, Ⓑ, Ⓒ, and Ⓓ show the comparisons at every intensity for the independent variables.

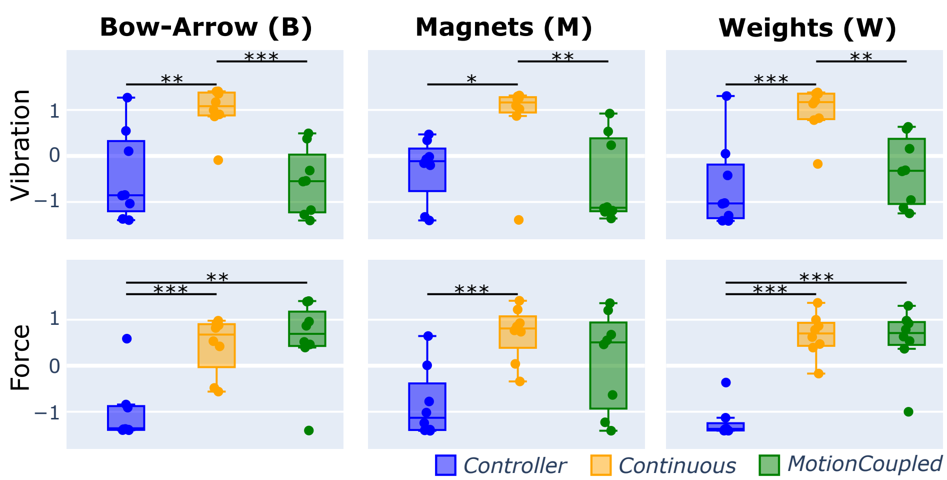

Figure 15: Perceived vibration and force estimates for each vibration condition: *Controller, MotionCoupled, Continuous* for each scene is shown. Each box-plot represents the median and the interquartile range. Each point is a user estimate. ($* : p < .05$; $** : p < .01$; $*** : p < .001$)