DualVib: Simulating Haptic Sensation of Dynamic Mass by Combining Pseudo-Force and Texture Feedback

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ABSTRACT

We present *DualVib*, a compact handheld device that simulates the haptic sensation of manipulating *dynamic mass*; mass that causes haptic feedback as the user's hand moves (*e.g.*, shaking a jar and feeling coins rattling inside). Unlike other devices that require actual displacement of weight, DualVib dispenses with heavy and bulky mechanical structures and, instead, uses four vibration actuators. DualVib simulates a dynamic mass by simultaneously delivering two types of haptic feedback to the user's hand: (1) pseudo-force feedback created by asymmetric vibrations that render the kinesthetic force arising from the moving mass; and (2) texture feedback through acoustic vibrations that render the object's surface vibrations correlated with mass material properties. By means of our user study, we found out that DualVib allowed users to more effectively distinguish dynamic masses when compared to using either pseudo-force or texture feedback alone. We also report qualitative feedback from users who experienced five virtual reality applications with our device.

CCS CONCEPTS

• **Human-centered computing** → **Human computer interaction (HCI)**; *Haptic devices*; User studies.

KEYWORDS

Haptics, Virtual Reality, Mass Perception, Vibration

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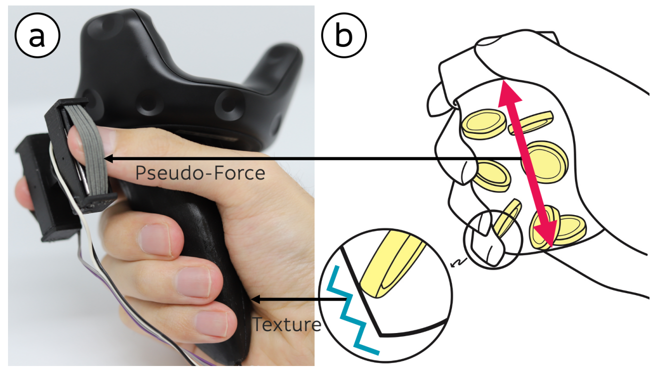

Figure 1: (a) DualVib renders haptic sensation of manipulating "dynamic mass" (*e.g.*, coins in a jar) with 1-DoF pseudo-force feedback and texture feedback. (b) The actuation methodology is rationalized by two sources of haptics involved in dynamic mass: kinesthetic force due to the mass movement (red), and surface vibration due to the collision between the inner mass and the object surface (blue).

1 INTRODUCTION

Along with the rise of consumer Virtual Reality (VR), recent research has investigated compact and wearable devices that can render haptic aspects of objects such as grasping [4], shape [35], and weight [3, 34]. While a majority of haptic devices is designed to simulate objects with static mass (*e.g.*, a solid block, an empty mug), in reality, a variety of objects contains *dynamic mass*, *i.e.*, mass that exhibits different patterns of movement and configuration along with a user's hand motion (e.g., coins in a piggy bank, water in a bottle).

Some haptic interfaces simulate the force feedback of dynamic mass by shifting center of mass with physical weights [32, 37, 38, 40]. However, since these devices involve heavy and bulky mechanical structures to move actual weights, they lead to users' fatigue and devices' fragility. Indeed, researchers in the community have argued the importance of lightweight form factor [25] and mechanical simplicity [20] for haptic devices to become appropriate for comfortable user experience. Further, these devices elude to render the texture feedback of dynamic mass, *i.e.*, tactile sensation due to the collision between a dynamic mass and its container object, which allows users to feel mass material properties such as the difference between solid and liquid (*e.g.*, coins vs. water) and the difference in viscosity (*e.g.*, water vs. yogurt).

We present *DualVib*, a handheld device that can render the haptic sensation of manipulating dynamic mass. DualVib simultaneously provides two types of haptic feedback: (1) pseudo-force feedback created by asymmetric vibrations that render the kinesthetic force arising from the moving mass; and (2) texture feedback through acoustic vibrations that render the object's surface vibrations correlated with mass material properties. DualVib has two advantages compared to other haptic devices designed for the similar end: (1)

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as it only consists of rigid vibration actuators and dispenses with heavy and bulky mechanical structures, DualVib prevents users' fatigue and secure maintenance reliability, both of which are essential for haptic devices to be commercially acceptable; and (2) as it simultaneously renders pseudo-force and texture feedback, DualVib can effectively exhibit material difference of dynamic mass.

Our user study with 12 participants found that, when compared to using either pseudo-force or texture feedback alone, DualVib allowed users to more effectively distinguish nine types of dynamic masses; three types of material (*i.e.*, water, yogurt, and marble chocolates) with three levels of mass (*i.e.*, small, medium, and large). Further, we introduce five example applications that feature our device and discuss qualitative feedback from users.

Our contributions are as follows:

- DualVib — a compact handheld haptic interface that renders haptic sensation of objects containing dynamic mass without heavy and bulky mechanical structures;
- An end-to-end pipeline that properly calculates the behavior of dynamic mass and renders the haptic feedback through real-time physics simulation and signal control;
- Quantitative and qualitative evaluations of DualVib that validate the effectiveness of rendering the haptic sensation of objects containing dynamic mass.

2 RELATED WORK

2.1 Handheld Haptic Interfaces

Commercial VR systems often adopt handheld controllers as they have advantages of portability and ease of equipment. However, off-the-shelf controllers (*e.g.*, HTC VIVE) only provide vibrotactile feedback for contact and notification. Leveraging their considerable sizes to incorporate various functions (*e.g.*, input buttons and mechanical structures for haptic feedback), researchers have well investigated handheld haptic interfaces. Choi et al. proposed CLAW to provide virtual grasping, texture, stiffness, and triggering sensation coexisting with functionality of commercial VR controller such as a select button and a joystick [5]. Haptic Revolver allows the typical functionality of VR controllers but also renders texture and contact feedback of various objects by attaching real materials onto the configurable wheel on the device [39]. Provancher developed a device to provide force and torque with sliding contactor plates [29]. Sun et al. proposed PACAPA, a gripping mechanism that can render resistance force and collision effect [36]. HaptiVec provides force vectors of different angles [2]. However, since those interfaces involve complex mechanical structures and thus unreliability for production and maintenance, and limited flexibility of form factor, they are often considered to be inadequate for commercial application. TORC [20] and PseudoBend [12] are designed to address the above problem by utilizing vibrotactile actuators, achieving rigid form factors (i.e., without having moving parts).

2.2 Ungrounded Devices for Weight and Mass

Niiyama et al. proposed a handheld device that simulates variable weight of objects by moving a liquid metal between the device and an external reservoir [24]. Recently, researchers have simulated different masses and shapes by moving weights to displace the center of mass in one dimension [41] and two dimension [35]. Some interfaces focus on fingertip skin deformation to reproduce the sensation of weight and mass. Gravity Grabber presents the weight sensation by stretching fingertips with fabric belts controlled by DC motors [22]. Thor's Hammer enables users to feel 3-DoF force feedback, utilizing six motorized propellers [11]. Grabity simulates the weight and grasping sensation with a compact form factor by adopting asymmetric vibrations from voice coil actuators which provide pseudo-force feedback [3]. Prior to the work, the asymmetric vibration technique using small linear resonant actuators was introduced by Rekimoto [31] and was then modeled for voice coil actuators by Culbertson et al. [7].

While the above works only focus on rigid objects such as a block, other researchers investigated to simulate the haptics of an object involving dynamic mass (*e.g.*, movable inner structures or fluids). Hirota et al. developed handheld devices to provide the sensation of shaking objects containing inner portions by simulating kinesthetic force with mechanical sliding structures [37, 40]. SWISH simulates the weight shifting sensation of a fluid vessel in 3D scale with a motor-actuated weight [32]. Aero-plane is capable of emulating a shifting center of mass in 2 DoF (*e.g.*, the haptic sensation of a ball as it rolls on a handheld plane) by driving two jet-propellers [15]. ElastOscillation attached onto a HTC VIVE controller simulates force feedback caused by dynamic mass with a physical weight hanged by six elastic bands [38]. However, the above devices are too heavy to hold a period of time: 740 g [40]; 537 g [37]; 1477 g [32]; 1069 g [15]; and 930 g (including the weight of a VIVE controller) [38].

2.3 Distributing Multiple Sources of Feedback

Researchers have combined multiple sensory stimuli to complementarily overcome the limitations of individual actuators when it comes to render sensations which are difficult to be simulated by a single type of feedback. Ranasinghe et al. proposed a wearable accessory to a head-mounted-display (HMD) that consists of peltier actuators and small fans to simulate ambient temperatures and wind conditions [30]. Lopes et al. proposed a wearable device that simulates the haptic sensation of physical impact [21]. The device achieved a small and lightweight form factor by combining tactile feedback with a solenoid and impulse (i.e., moving a user's limb) with EMS. Kono et al. aimed to induce negative emotions such as fear by distributing tactile feedback with a solenoid and EMS to a user's head [17]. Sakashita et al. combined EMS and hanger reflex to provide the wrist with force feedback around multiple rotational axes (roll and pitch) [33]. Park et al. developed a handheld device that renders the realistic haptic sensation of collision with vibrotactile feedback to the thumb and impact feedback to the index and middle fingers [26]. In the current work, to simulate the haptic sensation of dynamic mass with compact and simple components, we respectively distribute asymmetric vibration and acoustic vibration to two parts of the hand: i) the thumb and index finger, and ii) the other fingers and the palm.

3 DUALVIB

DualVib is a handheld device designed to render the haptic sensation of manipulating dynamic mass by means of simultaneously applying pseudo-force and texture feedback to the hand. The device distributes both feedback to the different parts of the hand in the manner depicted in Figure 1. (a). For the actuation methodology, DualVib adopts Culbertson's approach of producing pseudo-force feedback with asymmetric vibrations [3, 7], and Minamizawa's method for utilizing acoustic vibrations to reproduce objects' surface vibrations to render texture feedback [23]. As both sources of haptics are vibrations, DualVib only involves rigid vibration actuators and thus the device weighs 151 g including the VIVE tracker (65 g without the tracker), which is obviously lighter than other similar devices [32, 37, 38, 40]. Unlike Minamizawa's system that does not control haptic feedback according to a user's manipulation, the unique contribution of DualVib is its end-to-end pipeline for haptic rendering. As shown in Figure 2, the system simulates the physical behavior of the target dynamic mass linked with the device's motion and controls haptic feedback according to the simulated kinetic energy (*i.e.*, acceleration) of dynamic mass on a real-time basis.

4 DESIGN

We first present the key concept that rationalizes DualVib's haptic rendering technique of decomposing the haptic sensation of dynamic mass into directional force and surface vibrations. We then explain the actuation techniques. Finally, we describe our design process of the device for distributing asymmetric and acoustic vibrations.

4.1 Decomposing Haptics of Dynamic Mass

As shown in Figure 1. (b), when an object containing movable mass (*i.e.*, coins) is in motion, the inner mass moves and hits the outer shell, which results in two sources of haptic sensation: i) kinesthetic force exterted from the inner mass to the outer shell and ii) surface vibrations due to the collision between the inner mass and the outer shell. In our perceptual mechanism, muscle spindles and golgi tendon organs in our limb sense proprioceptive feedback from the applied force [14]. In addition, mechanoreceptors in the skin senses skin stretch caused by the force and tactile pressure or distortion due to the surface vibrations [16, 27]. As a result, we perceive the haptic sensation of manipulating dynamic mass. This observation can be similarly applied to other types of dynamic mass such as water and viscous materials. Prior work has shown that it is possible to render force feedback by only stimulating mechanoreceptors [22]. Unlike prior work with a similar aim that simulates displacement of center-of-mass, we focus on rendering each of the skin stretch and the surface vibrations described above to provide haptic feedback for dynamic mass.

4.2 Selecting Actuation Techniques

To secure users' comfort and the device's mechanical reliability upon a period of use, it is necessary for actuators on our device to be lightweight and rigid. Thus, we adopted actuation techniques based on small and rigid vibration actuators.

4.2.1 Force. To represent the kinesthetic force, DualVib utilizes pseudo-force feedback generated by asymmetric vibrations from voice coils, which have been investigated by prior work [3, 8, 31]. The principle of feedback is that the motion of the magnet inside the actuator in response to asymmetric-shaped signals causes fingertips' skin stretch in one axis and enables users to sense pseudo-force sensation.

4.2.2 Surface vibrations. To simulate the object's surface vibrations, DualVib utilizes Minamizawa's method of rendering texture feedback by means of acoustic vibrations [23]. In this method, actual surface vibrations upon the movement of target dynamic mass are captured by a contact microphone as a source of stimulus. Then the vibration actuators output the captured signal as acoustic vibrations.

4.3 Distributing Two Types of Vibrations

As we uniformly feel both force and surface vibrations through the hand while moving dynamic-mass objects, the most natural way of providing both feedback is applying the combined stimulus to the whole palm. Prior research distributed asymmetric vibration and high frequency vibration to the same location of fingertips to simultaneously present direction and speed of the haptic sensation of sliding fingers [13]. The researchers found that applying the two different vibrations to the same location of the hand resulted in a deterioration in recognizing each stimulus. Thus, to achieve better perceptual quality of asymmetric and acoustic vibrations, we explored applying each stimulus to different parts of the hand. Further, as discussed by prior research, pseudo-force sensation through asymmetric vibrations only occurs when the actuators are grasped by fingertips [7]. Building on the above consideration, we adopt the following distribution of haptic stimuli: the user grasps two voice coil actuators for asymmetric vibration with the thumb and index finger while grabbing the device's body with rest of the palm where actuators for acoustic vibration are embedded (Figure 1. (a)).

5 IMPLEMENTATION

5.1 Hardware

As depicted in Figure 2. (a), our device consists of three components: *(i)* VIVE tracker, *(ii)* the mold equipped with two voice coil actuators (red blocks) for pseudo-force feedback (*i.e.*, pseudo-force component), and *(iii)* the grip in which two vibration actuators (blue blocks) for texture feedback are embedded (*i.e.*, texture component). We chose to use Haptuator Mark II for emitting asymmetric vibrations to generate pseudo-force feedback, following the prior works for the same end [3, 8]. We adopted Haptic Reactor for texture feedback, as its feasibility for reproducing objects' surface vibrations with acoustic vibrations has been shown in prior works [1] [18, 23]. The pseudo-force component and the texture component are connected with thin wire threads to prevent different types of vibrations from being mixed on the device. The device molds are 3D printed using a Ultimaker S5 (Ultimaker B.V.). The total weight of the device is 151 grams (without VIVE Tracker: 65 grams), which is lighter than a VIVE controller (205 g). We also carefully selected the attaching point of the VIVE tracker to prevent its weight from being applied to the pseudo-force component. Since the weight of the tracker (85 g) dominantly causes skin stretch, the virtual force sensation is interfered if its weight is applied to the thumb and forefinger. In our device, the weight of the tracker is only applied to the texture component, and thus does not impose weight on the thumb and forefinger.

[1] We developed two prototypes for the texture component with Haptuator Mark II and Haptic Reactor. And confirmed Haptic Reactor worked better through a pilot user study.

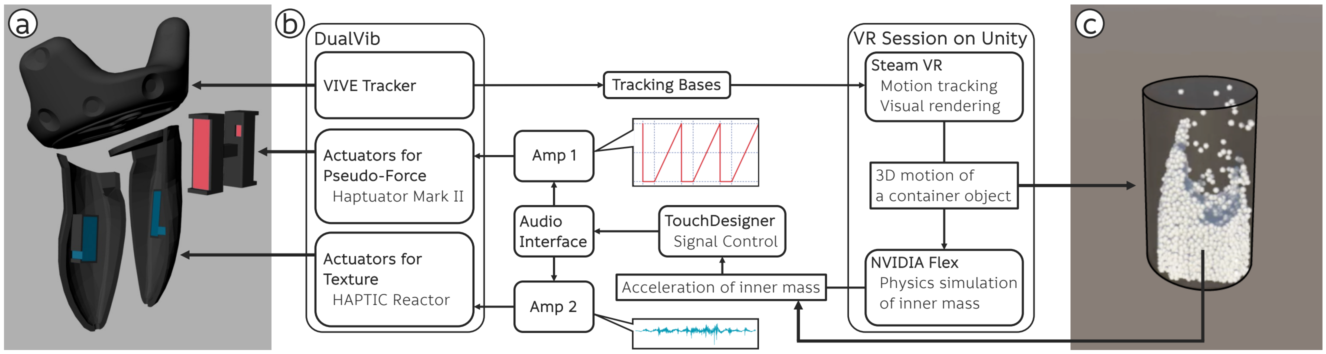


Figure 2: (a) Exploded view showing hardware components of DualVib. (b) Architecture of the DualVib system. (c) The system utilizes NVIDIA Flex to calculate the real-time behavior of dynamic mass by means of particle based physics simulation.

5.2 Tracking and Integration to VR

The VIVE tracker is responsible for sensing the position of the device in 3D coordinates on every frame. It passes the information to Steam VR running on Unity 3D game engine on a real time basis (Figure 2. (b)). Then, the game engine renders visual appearance of the virtual object so that it precisely aligns with the device's motion in reality. We compile the Unity project on a desktop machine (Dell XPS 8930) with a 2.8 GHz Intel Core i5-8400 CPU. The computer has 8 GB of RAM and is equipped with an NVIDIA GeForce GTX1060 GPU. The VR system renders 30 frames per second, limited by the update rate of a physics simulation technique that we use (NVIDIA Flex).

5.3 Physics Simulation

To control pseudo-force and texture feedback, The DualVib system simulates acceleration of dynamic mass. This is because the amount of force acting upon an object is proportional to acceleration when its mass is constant (∵Newton's second law of motion), which also dominantly determines the intensity of surface vibrations caused by dynamic mass. To appropriately model the acceleration of dynamic mass, our system utilizes NVIDIA Flex, a particle-based real-time physics simulation technique [6]. Flex defines a dynamic mass as a cluster of particles and simulates each particle's behavior and interaction between particles to render the overall behavior of the mass. By adjusting parameters of particle features (*e.g.*, size, viscosity, adhesion, and friction., etc), Flex is able to simulate the virtual mass of a variety of volume and material properties (*e.g.*, liquid or solid, viscosity, and granularity., etc). As illustrated in Figure 2. (c), upon the interaction with a virtual object containing dynamic mass, Flex computes the behavior of every particle on a real-time basis in response to the motion of the device captured by the tracking system. Based on the simulation, in each frame, our system calculates the inner portion's center of mass as the mean local position of all particles in the container. Then, the system obtains the acceleration of the center of mass as its second derivative with respect to time.

5.4 Signal Control

On the basis of the calculated acceleration, our system controls asymmetric vibrations for pseudo-force feedback and acoustic

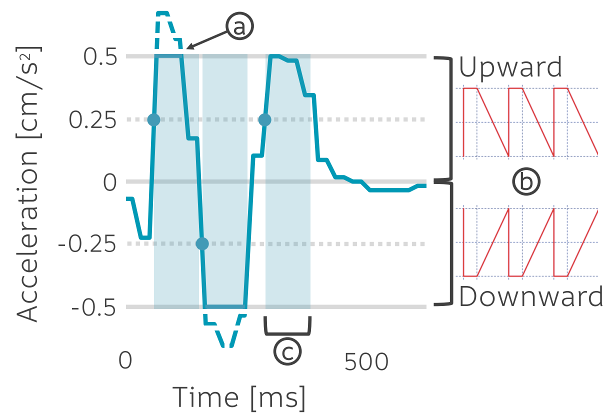
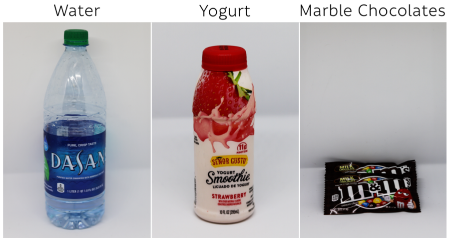


Figure 3: The system controls asymmetric and acoustic vibrations according to the simulated acceleration of dynamic mass. (a) the amplitude of asymmetric vibrations is proportional to the acceleration. (b) the direction of asymmetric vibrations corresponds to that of the mass. (c) DualVib outputs a 100 [ms] sample of acoustic vibrations when the acceleration surpasses the threshold (blue dots).

vibrations for texture feedback using TouchDesigner [9] (Figure 2. (b)). Then, the outputs from TouchDesigner in 4-channel (*i.e.*, pseudo-force L/R and texture L/R) are distributed to each actuator component via an audio interface (Roland Rubix 44) and two audio amplifiers (Fostex AP15d). The system controls the amplitude of asymmetric vibrations so that it proportionally changes to the acceleration within the range of ± 0.5 [cm/s^2] (Figure 3. (a)). Figure 3. (b) shows the current signals of asymmetric vibrations which have been shown to be optimal for causing the pseudo-force sensation with the Haptuator motors; signal loops of 40Hz frequency with pulse width of 7ms hold and 18ms ramp [7]. The wave shape of asymmetric vibrations is reversed when the acceleration is negative (*i.e.*, upward for positive acceleration and downward for negative acceleration), so that it can properly render the direction of pseudo-force in accordance with the inner mass movement. To keep the amplitude of asymmetric vibrations within the range, the system regards the acceleration beyond the range as the fixed values of



	Water	Yogurt	Marble Chocolates
Numbers of particles	1600, 4000, 6400	1600, 4000, 6400	26, 64, 102
Particle radius [cm]	0.09	0.09	0.375
Fluidity	On	On	Off
Viscosity	0	300	0
Adhesion	0	0.2	0

Figure 4: The three target materials and their particle properties on NVIDIA Flex.

Volume of Dynamic Mass	Small	Medium	Large
Amplitude of Voltage [mV]	440	720	1040
Gain of Asymmetric Acceleration [G]	5.2	13.8	20.8

Figure 5: Maximum amplitude voltage and achievable asymmetric acceleration for the three volume levels.

± 0.5 $[cm/s^2]$ (dotted blue lines in Figure 3)[2]. This treatment is based on the fact that if the amplitude becomes too large, asymmetric vibrations can no longer render pseudo-force sensation [3]. With respect to acoustic vibrations, the system outputs a recorded sample of the vibrations when the acceleration surpasses the threshold of ± 0.25 $[cm/s^2]$ (Figure 3. (c)). The sample corresponds to the object's surface vibrations caused by a single stroke of the object containing dynamic mass so that the actuation of acoustic vibrations aligns with the motion of the virtual object.

6 CONFIGURATION

In this section, we describe the configuration of DualVib to be able to properly render pseudo-force and texture feedback for specific target objects which were used in our user study and example applications. It is also possible to customize DualVib for other types of objects by applying the principle explained here and described in Appendix 2 and 3.

We assume the situation when a virtual container (8 cm height × 6 cm diameter) contains different types of inner portion (*i.e.*, dynamic mass), because it can be regarded as common in describing dynamic mass. We simulated nine types of inner portion; three materials shown in Figure 4 (*i.e.*, water, yogurt smoothie (yogurt), and marble chocolates) with three levels of mass in the container (i.e, small: 16%, medium: 40%, and large: 64%). We decided to use these three materials with the aim to evaluate DualVIb's capability of rendering solid-liquid (water vs marble chocolates) and viscosity (water vs yogurt) difference. We simulated three different volumes of dynamic mass using NVIDIA Flex with the number of particles depicted in Figure 4. Figure 5 shows the three voltage amplitudes

[2] Appendix 1 describes the rationale behind deciding the specific range of ± 0.5 $[cm/s^2]$.

Figure 6: Acoustic vibration samples recorded with a contact microphone in the form of digital audio signals. All samples are 100 ms long and in the same amplitude (y-axis) scale.

to simulate the three levels of mass by means of asymmetric vibrations transmitted from voice coils [3]. Figure 6 shows the samples of acoustic vibrations for the nine types of dynamic mass [4].

7 USER STUDY

To validate the reliability of DualVib upon rendering the haptic sensation of dynamic mass, we conducted a user study with two tasks. In the first task, we evaluated whether DualVib could properly convey directional pseudo-force feedback corresponding to the rapid motion of dynamic mass. In the second task, we investigated whether users could properly sense both pseudo-force and texture feedback while they were distributed simultaneously to the hand.

We recruited 12 participants (8 male, 4 female) aged between 22 and 25 from one of the authors' university. In each study session, after a brief introduction of the aim and the procedure, we first asked participants to fill out a consent form, then asked them to perform *Task 1*. After *Task 1* was finished, participants took a 5-minute break and went on to *Task 2*. Each session took about 45 minutes and subjects received \$ 15 Amazon Gift Card for their participation.

7.1 Task1: Directional pseudo-force

It is crucial for DualVib to convey proper direction cue of pseudo-force because the mismatch between the actual motion and the rendered direction may results in the deterioration of realistic haptic sensation. To evaluate whether the motion of inner mass is properly conveyed as directional pseudo-force, we asked participants to identify the motion pattern of the virtual object rendered with asymmetric vibrations. We prepared two motion patterns (↑↓↑↓ and ↓↑↓↑) of 1 second. And we prepared three signal conditions of asymmetric vibrations for three levels of intensity corresponding to volumes of mass: small (440mV), medium (720mV), and large (1040mV). In addition, we prepared the signal condition of

[3] Please see Appendix 2 for how we measured asymmetric acceleration caused by the actuator and decided the amplitudes of voltage.

[4] Please see Appendix 3 for how we prepared the samples using a dedicated contact microphone [1].

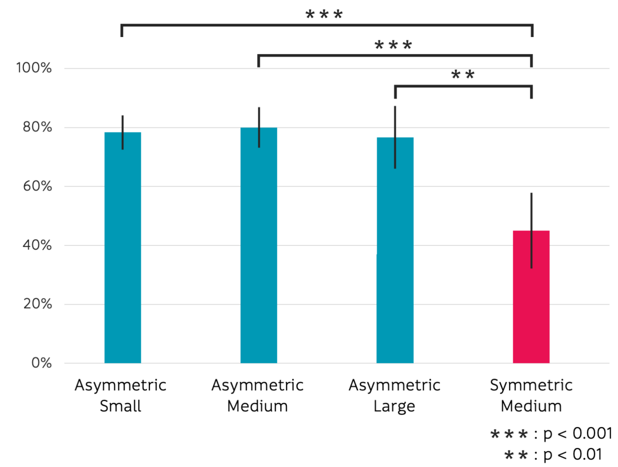


Figure 7: The results of task 1. Error bars indicate 95% confidence interval.

symmetric square vibrations (720mV) as a reference because, in contrast to asymmetric vibrations, the symmetric vibrations do not render the directional pseudo-force [3].

To create the haptic stimulus, we prepared a virtual container in the VR space, which contained fluid particles to simulate different volumes of mass. As the virtual container moves in (↿⇂↿⇂) or (⇂↿⇂↿) way, independent of motion in reality, users are expected to feel pseudo-force corresponding to movement patterns.

We conducted five trials for each signal condition. In each trial, we randomly chose either of the two movement patterns and presented it to a participant for three times. After the presentation, the participant answered the pattern on a questionnaire using a laptop. The accuracy for a participant was given as the average of five trials (*e.g.*, if one got 4 correct and 1 incorrect answers, his/her accuracy is 80%). During the procedure, a participant held DualVib in the right hand while wearing a noise canceling headphones playing white noises to shut out auditory cues. The presentation order of the four signal conditions was counter-balanced across the 12 participants. Prior to getting down to the tasks, we let participants recognize the relation between the movement patterns and stimulation by presenting both patterns to them with the medium asymmetric vibrations.

7.2 Results and Discussion

Figure 7 shows that participants could overall properly recognize directions rendered by asymmetric vibrations with the accuracy of around 80% in the three levels of volume. On the other hand, as expected, the symmetric vibrations could not help users with perceiving directional pseudo-force; the performance was around chance rate (50%). We conducted Wilcoxon rank-sum tests and found the statistical significance between small asymmetric and symmetric (U=11.5, Z=-3.49, p=0.00048); medium asymmetric and symmetric (U=11, Z=-3.52, p=0.00043); and large asymmetric and symmetric (U=20.5, Z=-2.97, p=0.00295). The results suggest that DualVib can render directional pseudo-force feedback with asymmetric vibrations for all three levels of mass in dynamic motion. Our finding is in consistent with prior work, that found a user could identify steady directions presented by asymmetric vibrations (*i.e.*, ↿ or ⇂) [31].

Figure 8: A setup for task 2.

7.3 Task2: Variable Mass and Material

In this task, we aimed to evaluate whether DualVib can simultaneously render pseudo-force and texture feedback without mutual interference (*i.e.*, pseudo-force feedback negatively affects the perceptual quality of texture feedback and vice versa).

We asked participants to identify nine types of dynamic mass; three different materials (water, yogurt, and marble chocolates) with three levels of mass (small, medium, and large). We tested three conditions for haptic feedback: pseudo-force+texture, pseudo-force only, and texture only for understanding the comparison between DualVib and either pseudo-force or texture feedback alone.

Figure 8 depicts a setup for task 2. A participant held DualVib in the right hand and wore noise canceling headphones playing white noises to shut out auditory cues. During the task, the participant could freely switch from one object to another across the nine types (three materials × three volumes) by pressing the left or right arrow keys on the keyboard. The display showed the number label (1 to 9) of the object being presented. As the participant moved the device, the system rendered the haptic feedback. The participant interacted with the virtual objects without time limitation and answered the type of each object on a questionnaire form via a laptop. We did not show the true labels for the haptic stimuli before the task to prevent participants from memorizing the answers. And the correspondence between label numbers and object types was randomized. The participant could revise his/her answers whenever s/he wanted.

Before the task, we allowed the participant to manipulate three 120 ml jars containing 50 g of water, yogurt, and marble chocolates as references for texture feedback. The participant was allowed to interact with the reference jars whenever they wanted to during the task. The session finished with the participant's request after s/he answered for all of the nine objects. All participants finished the task for each condition within 10 minutes. We repeated the above procedure for the three conditions in a counter-balanced order.

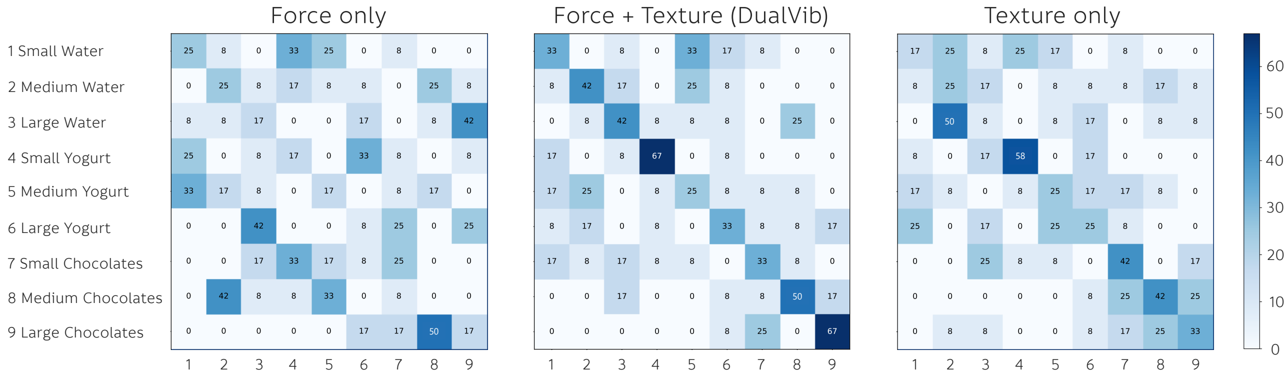


Figure 9: Confusion matrices derived from the results of the experiment. Each row shows the average accuracy [%] of all participants for correctly answering the target dynamic mass. For increasing visibility, the color scale is consistent across the matrices and normalized between 0 and 67 [%]. Rows and columns represent true and predicted labels respectively.

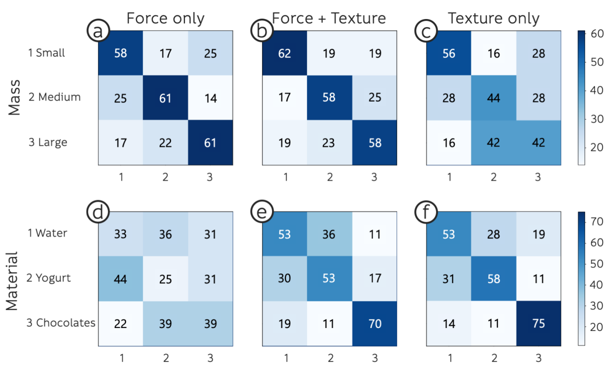


Figure 10: Reorganized confusion matrices with respect to mass identification (upper three matrices; (a),(b),(c)) and material identification (lower three matrices; (d),(e),(f)) as function of the average accuracy [%]. The color scale is consistent across the matrices in the same row and normalized between 0 and 62 [%] (upper), and 0 and 75 [%] (lower).

7.4 Results and Discussion

According to Figure 9, apparently, force+texture achieved relatively higher accuracy compared to the other conditions. The average accuracy across nine objects and its standard deviation are as follows: 16.8% and 8.4% in force only, 30.6% and 15.0% in texture only, and 43.6% and 15.1% in force+texture. Yet, the absolute performance in force+texture condition is not high (accuracy for some objects is around 30%). We interpret that complexity of the task contributed to the low performance; the number of objects to be compared was large and one mistake could cause subsequent mistakes.

For further understanding, we decomposed the raw matrices (Figure 9) into six matrices (Figure 10) with respect to mass identification (upper three matrices) and material identification (lower three matrices). We derived Figure 10 by calculating the accuracy when at least either of mass or material was correct, disregarding the correctness of the other. For example, a participant's answer: *large yogurt* for *large water* as the target object was counted as *correct* for deriving the upper three matrices for mass.

According to Figure 10, with respect to mass identification, force only and force+texture similarly demonstrate reasonably high accuracy (a vs. b), and they are superior to texture only (a&b vs. c). For material identification, force+texture achieves almost the same level of performance compared with texture only (e vs. f), while the accuracy of force only is no better than chance rate, *i.e.*, 30% (d vs. e&f). These findings strongly suggest that DualVib can simultaneously provide both pseudo-force and texture feedback without mutual interference.

Figure 10. (e) and (f) suggest that water and yogurt are less distinguishable than chocolates, which may be because acoustic vibrations for water and yogurt are similar as shown in Figure 6. To sum up, the results support that DualVib enables users to more effectively identify the nine types of dynamic mass compared to either pseudo-force or texture alone because the system is able to render pseudo-force and texture feedback to the hand without mutual interference.

8 EXAMPLE APPLICATIONS

We created the following virtual reality scenes to explore the applications for DualVib. We describe each application in terms of its *scenario*: what users experience in the application, *highlight*: what type of haptic sensation the application aims to emphasize to users, and *source*: how we prepared the haptic stimuli for the application.

(a) Coin Boxes.
- Scenario: Comparing three barrels where different amounts of coins are contained and estimating which barrel has the most coins (Figure 11. (a)). A user feels the haptics of coins rattling inside as s/he manipulates a barrel.
- Highlight: Rendering dynamic mass of solid particles. Comparing different volumes of mass.
- Source: Physical behavior of virtual coins were simulated with the same parameter values as marble chocolates on NVIDIA Flex. For texture feedback, we recorded vibration of coins with three volumes (20g - small, 50g - medium, 80g - large) of coins in a plastic bottle with a contact microphone.

(b) Hot Sauce / Milk.

Figure 11: Demo applications: (a) shaking boxes of coins, (b) pouring hot sauce and milk, (c) shaking a cocktail mixer, (d) feeling the resistance when using a chainsaw to cut a tree, and (e) feeling the recoil when firing a bazooka.

- Scenario: Adding hot sauce on a food plate and pouring milk into a glass (Figure 11. (b)). A user feels the haptics of hot sauce/milk as s/he shakes or tilts a bottle to pour and sees a visual appearance of liquid while pouring.
- Highlight: Rendering dynamic mass of viscous fluid (hot sauce)
- Source: We reused yogurt and water data to simulate hot sauce and milk respectively.

(c) Cocktail Shaker.
- Scenario: Shaking a transparent cocktail shaker at a bar counter (Figure 11. (c)). A user feels the haptics of the cocktail liquid inside as s/he shakes the shaker and sees a visual appearance of simulated inner liquid portion.
- Highlight: Rendering dynamic mass of non-viscous fluid (cocktail)
- Source: We reused water data to simulate feedback for the cocktail liquid.

(d) Chainsaw.
- Scenario: Cutting a tree with a chainsaw (Figure 11. (d)). As a chainsaw hits a tree, s/he feels continuous resistance force and texture feedback due to vibrations of the chainsaw engine.
- Highlight: Rendering steady pseudo-force and texture feedback.
- Source: We generated 80Hz square-shaped symmetric vibrations using TouchDesigner as texture feedback which we found appropriate to represent the intense mechanical vibration.

(e) Bazooka.
- Scenario: Shooting a bazooka to hit targets (Figure 11. (e)). As a user shoot the bazooka, s/he feels instant recoil force and the vibration due to the collision between the rocket and the launcher.
- Highlight: Rendering instantaneous pseudo-force and texture feedback.
- Source: To represent the collision between the metalic objects, we reused the 80Hz square-shaped symmetric vibrations as texture feedback.

8.1 User Feedback

To validate whether DualVib's method of combining pseudo-force and texture feedback enhance the realism of haptic experiences in VR applications, we asked participants to experience the above five applications with different settings of haptic feedback. We prepared force+texture and texture only settings of DualVib because, based on the results of *Task 2*, we estimated that the force only setting was not adequate to render the haptics of dynamic mass as it could not inform texture sensation (Figure 10. (d)). Further, the texture only setting was chosen as a baseline since it can be regarded similar to commertial vibrotactile devices such as a Nintendo Switch Joy-Con that simulates material textures of objects [10].

We recruited another group of 8 participants (4 male, 4 female) aged between 19 and 30 from the same university. In each session, a participant started with experiencing one of five scenes with one interface setting. After experiencing the scene, s/he switched to the other setting and went through the same scene again, then moved to another scene and repeated the same procedure until the participant experienced all scenes. We counter-balanced the presentation order of the applications and the interface settings across the participants.

While users were experiencing the scenes, we conducted a semi-structured interview focusing on how they felt haptic sensation in each setting and general aspects of usability to elicit direct user feedback. Upon the ending of each scene, we asked participants to rate the haptic realism of each device setting on a 5-point Likert scale for a question ("How well did the haptic rendering match your visual impression of the scene?"). Each session took about 30 minutes and participants were compensated with $10 Amazon gift card.

8.2 Results and Discussion

As shown in Figure 12, users rated force+texture setting more realistic with the overall means of around 4.5. Based on Wilcoxon signed-rank tests, we found significant differences of $p < .05$ between two settings across coins (Z=2.03, p=0.043), chainsaw (Z=2.10, p=0.036), and bazooka (Z=2.52, p=0.012). We did not get significant differences in the viscous and non-viscous fluids; hot sauce/milk (Z=1.68, p=0.093) and cocktail (Z=1.40, p=0.161). Here we discuss why DualVib did not work out for fluids (*i.e.*, hot sauce and cocktail). One likely reason is that texture feedback for the fluids did not contribute to the realism compared to that of coins. As we discussed in the result section of *Task 2*, the accuracy of identifying fluids was lower than that of solid particles, implying that texture feedback for the fluids was not well characterized (Figure 10. (e) and (f)). Another possible reason is that humans rely more on the force aspect of haptics when they feel dynamic mass of fluids because, compared to solid particles, fluids exhibit richer force feedback caused by seamless 3D movement of center of mass. Thus, the difficulty in rendering fluids with DualVib might be attributed to that it outputs

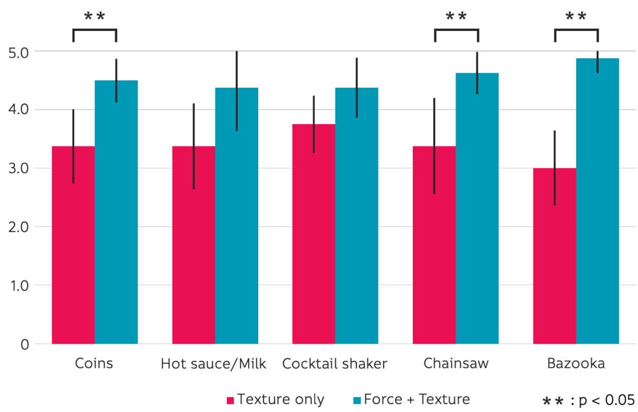


Figure 12: The results of user rating. Error bars indicate 95% confidence interval.

one-axis pseudo-force feedback instead of weight displacement in 3D coordinates.

According to qualitative feedback from users, it seems that they derived more realistic haptic sensation from force+texture setting, and the combination of force and texture feedback could render the kinesthetic sensation that sole texture feedback could not provide. User comments included "When the force component is active, it is more realistic to perceive weight difference between the boxes" (P5, coins), "I feel the resistance, which makes the cutting experience more realistic" (P4, chainsaw).

Interestingly, some users mentioned that they were more excited about chainsawing and shooting bazooka scenes because they have not experienced the situations in reality, as indicated by comments such as "I think it is really cool. I've never shot a bazooka before and I don't know how it feels like. That's why I'm satisfied with the feedback." (P8, bazooka). Thus, we speculate that simulating various extreme haptic sensations such as using weapons and exploding objects can be a good opportunity of demonstrating DualVib.

We also elicited user feedback facilitating future improvement of DualVib. Some users reported vibrations from voice coil actuators were disturbing. User comments include "I don't feel that strong vibrations when I shake a water bottle and it's noisy" (P2, cocktail). It seems that the hand grasping posture due to the device's form factor caused some participants to feel uncomfortable, as indicated by comments such as "This pinching makes my thumb and index finger numb." (P8, chainsaw). Further, one participant mentioned pseudo-force feedback appeared to be small when the virtual object was large with a comment, "The milk bottle should be heavier. I feel like holding an almost empty one" (P5, hot sauce/milk). We discuss the possible solutions to address the above issues in the next section.

9 LIMITATION AND FUTURE WORK

While our results overall indicate that DualVib can render the haptic feedback from dynamic mass and enhance the haptic realism in several VR applications, we also identified some limitations, which we hope to address in future work.

9.1 Rendering Haptic Sensation of Fluid

The statistical analysis of user rating indicated that DualVib did not work out for fluids. We would like to investigate how we can make the interaction with fluids more realistic without sacrificing DualVib's lightweight and simple form factor in future work. One possible way is to leverage visuo-haptic matches by designing visual appearance of fluid so that it will be consistent with DualVib's one-axis pesudo-force feedback, *e.g.*, fluid only moves linearly in appearance upon the user's manipulation.

9.2 Pseudo-force with Asymmetric Vibrations

As some users pointed out, our method of using asymmetric vibrations from voice coils for pseudo-force feedback has the following limitations: *(i)* the vibratory effect disturbs user experiences, and *(ii)* maximum gain of the virtual force is still around 30 grams as shown by Grabity that used the same actuators [3]. To address the issues, we would like to explore our future device version with recently proposed CHASM, a compact screw-based actuator that can render 4.8 N maximum force in one axis without involving vibrations [28].

9.3 Generalized Texture Feedback

Since we collected acoustic vibrations with one way of stroke at a fixed speed, our current system has only one type of signal source for texture feedback of each target object. Thus, it is not adequate to accurately render a variety of texture vibrations corresponding to different types of stroke. One possible solution is to collect vibrations with various types of movement and speed and adaptively output them. Ideally, to precisely simulate the surface vibration texture, we should fully generalize vibration rendering in a similar way to an advanced form of sound rendering method through physically based simulation [19].

9.4 Ergonomics

Through user feedback, we found that the grasping posture for the pseudo-force component decreased comfort of the device. Our future work also includes investigating solutions for this issue such as designing an ergonomically-shaped actuator shell made of a soft material as discussed by Pacchierotti et al. [25].

10 CONCLUSION

DualVib is a handheld device that simulates the haptic sensation of manipulating objects including dynamic mass. The device allows compact and simple form factor as it does not involve heavy and bulky mechanical structures and, instead, uses vibration actuators. DualVib simultaneously delivers pseudo-force feedback created by asymmetric vibrations and texture feedback through acoustic vibrations correlated with mass material properties. Our end-to-end haptic solver properly controls both feedback based on the simulated physical behavior of dynamic mass. The results of our user study suggest that: (i) DualVib can properly deliver pseudo-force and texture feedback to the hand without mutual interference, and (ii) DualVib performs significantly better than conventional vibrotactile feedback when it comes to simulating solid particles. Lastly, qualitative feedback from users suggests that DualVib enhances haptic realism for several applications such as shaking a coin box, chainsawing, and shooting a bazooka.

REFERENCES

[1] P Bifulco, GD Gargiulo, G d'Angelo, A Liccardo, M Romano, F Clemente, M Cesarelli, G Angelo, A Liccardo, M Romano, et al. 2014. Monitoring of respiration, seismocardiogram and heart sounds by a PVDF piezo film sensor. *measurement* 11 (2014), 786–789.

[2] Daniel KY Chen, Jean-Baptiste Chossat, and Peter B Shull. 2019. HaptiVec: Presenting Haptic Feedback Vectors in Handheld Controllers using Embedded Tactile Pin Arrays. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. ACM, 171.

[3] 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*. ACM, 119–130.

[4] Inrak Choi, Elliot W Hawkes, David L Christensen, Christopher J Ploch, and Sean Follmer. 2016. Wolverine: A wearable haptic interface for grasping in virtual reality. In *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 986–993.

[5] 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*. ACM, 654.

[6] NVIDIA Corporation. 2017. NVIDIA Flex 1.1.0 documentation. http://www.cyberglovesystems.com/cybergrasp.

[7] 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.

[8] 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*. ACM, 4972–4982.

[9] Derivative. 2020. TouchDesigner User Guide. https://docs.derivative.ca/Main_Page.

[10] Yui Ehara, Yuko Zenri, Junichiro Miyatake, Tetsuya Akama, and Hitoshi Tsuchiya. 2018. Controller for computer. US Patent App. 29/595,220.

[11] 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*. 1–11.

[12] 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*. 803–813.

[13] Arata Horie, Nagano Hikaru, Konyo Masashi, and Satoshi Tadokoro. 2017. Sliding Direction and Speed Presentation Combining High Frequency and Asymmetric Vibration. In *The 22nd Annual Conference of the Virtual Reality Society of Japan*. VRSJ, 2D2–05.

[14] James Houk and William Simon. 1967. Responses of Golgi tendon organs to forces applied to muscle tendon. *Journal of neurophysiology* 30, 6 (1967), 1466–1481.

[15] Seungwoo Je, Myung Jin Kim, Woojin Lee, Byungjoo Lee, Xing-Dong Yang, Pedro Lopes, and Andrea Bianchi. 2019. Aero-plane: A Handheld Force-Feedback Device that Renders Weight Motion Illusion on a Virtual 2D Plane. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*. 763–775.

[16] Kenneth O Johnson. 2001. The roles and functions of cutaneous mechanoreceptors. *Current opinion in neurobiology* 11, 4 (2001), 455–461.

[17] Michinari Kono, Takashi Miyaki, and Jun Rekimoto. 2018. In-pulse: Inducing fear and pain in virtual experiences. In *Proceedings of the 24th ACM Symposium on Virtual Reality Software and Technology*. 1–5.

[18] Tadatoshi Kurogi, Masano Nakayama, Katsunari Sato, Sho Kamuro, Charith Lasantha Fernando, Masahiro Furukawa, Kouta Minamizawa, and Susumu Tachi. 2013. Haptic transmission system to recognize differences in surface textures of objects for telexistence. In *2013 IEEE Virtual Reality (VR)*. IEEE, 137–138.

[19] Timothy R Langlois, Steven S An, Kelvin K Jin, and Doug L James. 2014. Eigenmode compression for modal sound models. *ACM Transactions on Graphics (TOG)* 33, 4 (2014), 40.

[20] 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*. 1–13.

[21] 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 & Technology*. 11–19.

[22] Kouta Minamizawa, Souichiro Fukamachi, Hiroyuki Kajimoto, Naoki Kawakami, and Susumu Tachi. 2007. Gravity grabber: wearable haptic display to present virtual mass sensation. In *ACM SIGGRAPH 2007 emerging technologies*. ACM, 8.

[23] Kouta Minamizawa, Yasuaki Kakehi, Masashi Nakatani, Soichiro Mihara, and Susumu Tachi. 2012. TECHTILE toolkit: a prototyping tool for design and education of haptic media. In *Proceedings of the 2012 Virtual Reality International Conference*. ACM, 26.

[24] Ryuma Niiyama, Lining Yao, and Hiroshi Ishii. 2014. Weight and volume changing device with liquid metal transfer. In *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction*. ACM, 49–52.

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

[26] Chaeyong Park, Jaeyoung Park, Seungjae Oh, and Seungmoon Choi. 2019. Realistic Haptic Rendering of Collision Effects Using Multimodal Vibrotactile and Impact Feedback. In *2019 IEEE World Haptics Conference (WHC)*. IEEE, 449–454.

[27] Mark Paterson. 2007. *The senses of touch: Haptics, affects and technologies*. Berg.

[28] Pornthep Preechayasomboon, Ali Israr, and Majed Samad. 2020. Chasm: A Screw Based Expressive Compact Haptic Actuator. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–13.

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

[30] Nimesha Ranasinghe, Pravar Jain, Shienny Karwita, David Tolley, and Ellen Yi-Luen Do. 2017. Ambiotherm: enhancing sense of presence in virtual reality by simulating real-world environmental conditions. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. 1731–1742.

[31] Jun Rekimoto. 2013. Traxion: a tactile interaction device with virtual force sensation. In *Proceedings of the 26th annual ACM symposium on User interface software and technology*. ACM, 427–432.

[32] Shahabedin Sagheb, Frank Wencheng Liu, Alireza Bahremand, Assegid Kidane, and Robert LiKamWa. 2019. SWISH: A Shifting-Weight Interface of Simulated Hydrodynamics for Haptic Perception of Virtual Fluid Vessels. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*. 751–761.

[33] Mose Sakashita, Satoshi Hashizume, and Yoichi Ochiai. 2019. Wrist-Mounted Haptic Feedback for Support of Virtual Reality in Combination with Electrical Muscle Stimulation and Hanger Reflex. In *International Conference on Human-Computer Interaction*. Springer, 544–553.

[34] Samuel B Schorr and Allison M Okamura. 2017. Fingertip tactile devices for virtual object manipulation and exploration. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM, 3115–3119.

[35] Jotaro Shigeyama, Takeru Hashimoto, Shigeo Yoshida, Takuji Narumi, Tomohiro Tanikawa, and Michitaka Hirose. 2019. Transcalibur: A Weight Shifting Virtual Reality Controller for 2D Shape Rendering based on Computational Perception Model. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. ACM, 11.

[36] Yuqian Sun, Shigeo Yoshida, Takuji Narumi, and Michitaka Hirose. 2019. PaCaPa: A Handheld VR Device for Rendering Size, Shape, and Stiffness of Virtual Objects in Tool-based Interactions. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. ACM, 452.

[37] Yasuhiro Tanaka and Koichi Hirota. 2012. Shaking a box to estimate the property of content. In *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications*. Springer, 564–576.

[38] Hsin-Ruey Tsai, Ching-Wen Hung, Tzu-Chun Wu, and Bing-Yu Chen. 2020. ElastOscillation: 3D Multilevel Force Feedback for Damped Oscillation on VR Controllers. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–12.

[39] Eric Whitmire, Hrvoje Benko, Christian Holz, Eyal Ofek, and Mike Sinclair. 2018. Haptic revolver: Touch, shear, texture, and shape rendering on a reconfigurable virtual reality controller. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, 86.

[40] Takeshi Yamamoto and Koichi Hirota. 2014. Device for estimation of weight and material of contents by shaking. In *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications*. Springer, 403–410.

[41] Andre 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.