OsciHead: Simulating Versatile Force Feedback on an HMD by Rendering Various Types of Oscillation

SUBMISSION #1013

Current haptic devices are usually designed for mainly providing one type of force feedback, but most VR scenarios require versatile force feedback, which may need to integrate different devices for providing various types of forces. However, besides the main haptic effects caused by the forces, multiple types of oscillation may also commonly accompany them, which are crucial to improving VR realism and immersion. Therefore, we propose to simulate versatile force feedback by rendering the corresponding types of oscillation as the effects caused by those forces. We take inertia and impact forces as examples in this paper and achieve versatility using the proposed device, OsciHead, on a head-mounted display (HMD) instead of integrating different devices. By controlling elastic bands' elasticity and stored power, OsciHead uses two rotatable oscillators on both sides of the HMD to render various multilevel and multidimensional oscillation feedback in 2D translation and 2D rotation directions on a head. We explored different scenarios in that multiple types of oscillation could be simulated by OsciHead in an exploratory study. We then observed oscillation level distinguishability in two just-noticeable difference (JND) studies and evaluated the oscillation type recognition rates in a recognition study. Based on the results, we performed a VR study to verify that the inertia and impact feedback simulated by OsciHead enhances realism and achieves versatility.

CCS Concepts: • **Human-centered computing → Haptic devices**; **Virtual reality**.

Additional Key Words and Phrases: Haptic feedback; Oscillation; HMD prototype; Virtual Reality.

ACM Reference Format:
Submission #1013. 2022. OsciHead: Simulating Versatile Force Feedback on an HMD by Rendering Various Types of Oscillation. In *MobileHCI '22: ACM International Conference on Mobile Human-Computer Interaction, September 28 - October 1, 2022, Vancouver, Canada.* ACM, New York, NY, USA, 22 pages. https://doi.org/10.1145/nnnnnnn.nnnnnnn

1 INTRODUCTION

Haptic feedback is critical for virtual reality (VR) realism and immersion. However, current haptic devices are usually designed mainly to provide one type of force feedback, which is insufficient for VR scenarios requiring various types of forces. To improve VR realism and immersion, integrating different hardware designs to achieve versatile force feedback may be needed. However, besides the main haptic effects caused by the forces, we observed that different types of oscillation might also commonly accompany them. For example, when car brakes sharply, inertia forces resist users from movement change, which shakes their head and causes slower but longer head oscillation. As punched, impact forces instantly apply to users and cause faster but shorter head oscillation. Although inertia and impact forces are pretty different and cause different haptic effects, oscillation commonly occurs and accompanies them despite various types of oscillation in different frequencies and duration. Therefore, we propose a novel concept to simulate versatile force feedback in VR,

---

MobileHCI '22, September 28 - October 1, 2022, Vancouver, Canada

ACM ISBN 978-1-4503-XXXX-X/18/06...$15.00
https://doi.org/10.1145/nnnnnnn.nnnnnnn

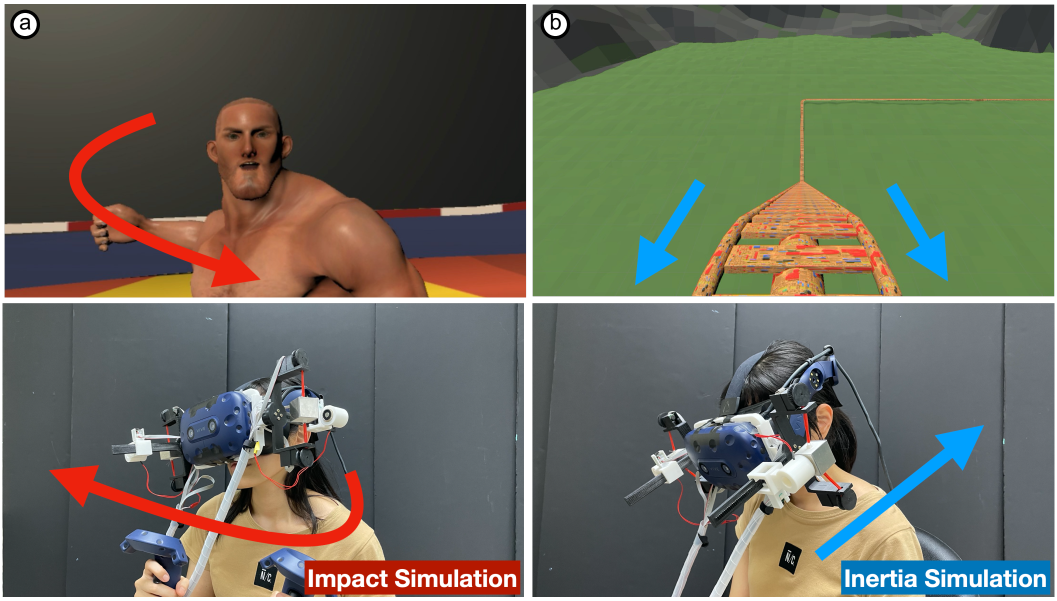


Fig. 1. OsciHead provides different types of oscillation feedback to simulate versatile force feedback in VR. (a) Oscillation of impact simulation in a fighting game. (b) Oscillation of inertia simulation in a roller coaster simulation.

e.g., inertia and impact, by rendering the corresponding types of oscillation as the effects caused by those forces.

Previous methods rendered oscillation feedback by moving a weight or plates [1, 15, 17, 29] to simulate oscillatory behaviors corresponding to the hand movement. Still, the motor delay issue is inevitable, especially for irregular and complicated oscillation, as mentioned in [23]. To achieve realistic oscillation feedback, some works leverage objects' physical properties [3, 16, 23], e.g., water, elastic bands and a quaternion joint. However, the feedback is generated by shaking the devices and corresponding to users' movements but cannot be triggered by external events in VR. Although Pull-Ups [31] uses pneumatic artificial muscles (PAMs) to pull users and produce body oscillation, it is a grounded device that provides feedback in only one direction, which cannot simulate versatile force feedback. We take inertia and impact feedbacks, which are common force feedback on heads in VR, as examples in this paper to prove the proposed concept. For inertia, previous works leverage the skin stretch, gyroscopic effect, asymmetric vibration, propellers, and air jets [4, 7, 8, 11, 14] to provide resistive force or illusions of inertia feedback. For impact, current methods use elastic bands, electrical muscle stimulation (EMS), and air jets [6, 12, 22] to generate instant impact force. Although they render realistic feedback, they do not provide both inertia and impact feedback with limited versatility. Besides, the actuator delay issue makes head shaking and oscillation involving rapid and complicated resultant force change caused by inertia challenging to be simulated.

We propose OsciHead to provide different types of multilevel oscillation feedback on a head-mounted display (HMD) to simulate versatile force feedback in VR. OsciHead consists of a pair of oscillators mounted on both sides of an HMD, and a proxy is connected with two elastic bands in each oscillator. An oscillator pulls and releases the proxy to render oscillation feedback using the elastic force. Different types of oscillation are provided for simulation, inertia, and impact feedback by adjusting the elastic bands' elasticity. Furthermore, by rotating oscillators in the same or opposite directions, OsciHead renders symmetric or asymmetric oscillation on the head to generate feedback in 2D translation and 2D rotation directions, respectively. OsciHead renders oscillation feedback in multiple levels, dimensions and types to simulate various forces and achieve versatility (Figure 1).

We explored scenarios that could be simulated by different types of oscillation in an exploratory study, which shows that besides inertia and impact, versatile feedback could be simulated by OsciHead. We then conducted two just-noticeable difference (JND) studies to realize different force levels for oscillation in symmetric and asymmetric directions, respectively. Furthermore, we evaluated oscillation type recognition rates in a recognition study. Based on the results, we performed a VR experience study to verify that the inertia and impact simulated by oscillation from OsciHead with better versatility are still able to enhance realism and demonstrate some VR applications requiring versatile force feedback.

The contributions of this paper are the following:

(1) Proposing the concept of simulating versatile force feedback by rendering different types of oscillation as effects caused by those forces and implementing the proof-of-concept device to generate oscillation feedback on heads.
(2) Realizing the oscillation force level distinguishability and the oscillation type recognition ability on heads.
(3) Proposing and demonstrating VR applications involving inertia and impact feedback and verifying that oscillation feedback from OsciHead can simulate versatile force feedback and enhance users' VR experiences in realism, enjoyment, preference, and distinguishability.

2 RELATED WORK

This section briefly discusses approaches to render feedback for oscillation, inertia, and impact, which we took as examples in this paper.

2.1 Devices for Oscillation Feedback

Oscillation feedback is a complicated resultant force involving the center of mass change, inertia and reaction forces, and even forces from objects swinging or colliding, as mentioned in [23]. Previous methods achieve parts of oscillation feedback. Buru-navi [1] quickly moves a weight with asymmetric acceleration to produce oscillation in one dimension and perform 1D guidance. Reactive Grip [15] moves three plates asymmetrically on a controller to simulate torque and oscillation of swinging a flail or a fishing pole. SWISH [17] uses motors to actively move weight in a vessel to change its center of mass further and simulate fluid behaviors when swinging or shaking it. However, these methods only generate parts of the resultant force of oscillation, and the motor delay issue limits the oscillation simulation, especially for complicated and irregular oscillatory behaviors.

Some other works control objects' physical properties to provide authentic oscillation feedback. Gravity Cup [3] leverages two pumps to change the amount of water in two bags to give a dynamic weight sensation. With liquid in Gravity Cup, oscillation feedback is generated. ElastOscillation [23] connects a proxy with elastic bands and controls the elasticity of the bands to create the damped oscillation when users shake the handheld device. Similarly, ElaStick [16] dynamically changes the elasticity of elastic bands to simulate different stiffness of a quaternion joint and further render oscillation feedback when shaking the device. ReCompFig [30] also changes the elasticity of compliant mechanisms (CMs) with tensioning cables to recreate the haptic feel of liquids, sheets, and solids on the users' hands. Although these methods cause authentic oscillation feedback, they require the users to shake the devices to generate oscillation corresponding to the hand's movement.

Therefore, they cannot render oscillation feedback triggered by external events or forces in VR, e.g., sharply braking a car or being punched. Although Pull-Ups [31] uses PAMs and straps hooked up to the ceiling to pull the users' hands and further generate the body oscillation as triggered by external events in VR, it is a grounded device on the ceiling and requires a bulky air compressor for PAMs. The rendered oscillation feedback is only in one direction, limiting the versatility of VR feedback.

2.2 Devices for Inertia Feedback

To provide illusions of inertia feedback, Gravity Grabber [14] uses two motors and a belt to stretch the fingertip skin and render the weight and inertia mass of virtual objects. Furthermore, Grabity [4] uses voice coil actuators to generate asymmetric vibration and simulate inertia feedback from the handheld device. To render inertia force, TorqueBAR [21] uses motors to change the center of mass in real-time according to the hands' movements to provide one degree-of-freedom (1DoF) inertia force on the handheld device. iTorqU 2.0 [28] and GyroVR [7] leverage flywheels to generate the gyroscopic effect on a handheld device and an HMD, respectively, so when the users rotate the hand or head, inertia force resists the rotation movements. Aero-Plane [8] uses two propellers on both sides of a controller to shift the center of mass in 2DoF and produce inertia feedback. HeadBlaster [11] uses six air nozzles on an HMD to emit compressed air jets and generate lateral inertia forces to simulate acceleration/deceleration and move leftward/rightward. Although these methods render inertia illusions and forces, they do not focus on generating versatile types of force feedback, e.g., both inertia and impact. The methods using actuators, including propellers and air jets, might also be able to render impact feedback, although it is not mentioned or implemented in their works. However, the actuator delay issue could limit these methods to simulating complicated inertia feedback involving consecutive forces causing oscillation, as mentioned in [23].

2.3 Devices for Impact Feedback

Previous methods leverage motors to pull/push the users' body parts to stimulate impact feedback. ExoInterface [25] and FacePush [2] use DC motors and belts to pull the users' forearm and HMD to simulate impact for recoil or being punched in VR games. Furthermore, Wind-Blaster [9] attaches two propellers on a wrist to simulate the recoil of gun shooting, and Unident [19] uses DC motors and a weight module to simulate impact sensation of hitting a ball or swinging a sword. However, these methods require delays to gradually provide strong force feedback, which is different from impact occurring instantly, as proven in [24]. To render instant impact, To render instant impact, Jetto [6] emits a jet of airflow on a smartwatch. However, such a mechanism is still not implemented on an HMD to provide impact for a head. Impacto [12] and Virtual Walls [13] utilize EMS to render impact on the users' hands and arms. By storing power in elastic bands, a series of works [22, 24, 27] leverage elasticity to render instant impact on a hand, a head, and between controllers. . Although these methods achieve realistic impact feedback, and ElastImpact [22] further accomplishes impact with multiple levels and dimensions on an HMD, they still focus on one type of feedback, especially for those rendering feedback on a head.

Notably, we do not try to prove or claim that the proposed method achieves more realistic feedback than that from the current inertia or impact methods in this paper. However, we intend to show that the proposed method is able to simulate various types of force feedback by rendering the corresponding types of oscillation, and the simulated force feedback can still enhance users' VR experiences in the scenarios requiring versatile force feedback. Although we take inertia and impact as examples, OsciHead can also simulate other versatile types of force feedback described in the *Exploratory Study*. Therefore, its ability and versatility are beyond a device integrating current devices to render both inertia and impact, which is also still not achieved. Furthermore, by integrating more devices, the size and weight are also increased, which limits the scalability, especially for head-worn devices.

3 OSCIHEAD

We propose OsciHead to render different types of oscillation to simulate versatile force feedback and enhance users' VR experiences. Oscillation may commonly accompany the main haptic effects caused by various forces, and different forces cause various types of oscillation. Therefore, we propose a concept of simulating versatile forces by rendering corresponding types of oscillation as effects caused by those forces. Oscillation not only occurs corresponding to the users' movement but also is caused by external events or virtual characters. We focus on the latter and take inertia and impact forces as examples in this paper. Inertia is a fictitious force produced when an external force changes the object's movement. It resists the change of the object's state or movement, based on Newton's first law of motion. Therefore, sharply accelerating, decelerating, or turning directions cause the inertia force to oscillate the car, body, and head in a constant velocity car. Furthermore, when suddenly turning the car leftward and then rightward back to the road to dodge an obstacle, two consecutive inertia forces applying to the users in different or even opposite directions could make the oscillation even more obvious and complicated. Impact force occurs when punched or hit and causes the body or head to oscillate. Although the types of oscillation, including frequency and duration, from these forces, are different, oscillation is a common subcategory of inertia and impact. Therefore, OsciHead renders corresponding types of oscillation, or more precisely damped oscillation, for simulation.

In an oscillatory system, damping is a physical influence reducing oscillation. Damping is caused by external air resistance or internal mechanical resistance in the oscillatory system, and it gradually depletes the energy in the system, decays the amplitude of oscillation and then stops the oscillatory behavior, which is called damped oscillation. In a damped harmonic oscillator system, the damping model is defined as:

$$F_d = -cv \tag{1}$$

where F_d means the damping force, c represents the viscous damping coefficient and v is the velocity of the object or mass. Furthermore, in an oscillator system, the restoring force is defined as:

$$F_r = -kx \tag{2}$$

where F_r means the restoring force, k is a constant, and x is the displacement of the object. Based on Equation 1 and 2 and Newton's second law, the balance of forces for the damped harmonic oscillator system is:

$$F = -cv - kx = ma \tag{3}$$

where m means the mass of the object and a is the acceleration of the object. Based on these equations, we realize that by changing the constant k and displacement x of the restoring force F_r and the viscous damping coefficient c, the oscillatory behavior changes and oscillation feedback with different types and levels for simulating versatile forces, including inertia and impact, can be achieved. Indeed, the actual condition is usually not a perfectly controlled damped harmonic oscillator system in physics, but this can explain our design concept.

3.1 Hardware Implementation

The OsciHead prototype comprises a pair of rotatable oscillators mounted on two sides of a Vive Pro HMD. Each oscillator consists of a proxy, two elastic bands, four DC motors, and an electromagnet. The elastic bands connect a proxy on the two sides, and two motors further control the bands, respectively, as shown in Figure 2. The OsciHead prototype has three changeable parameters

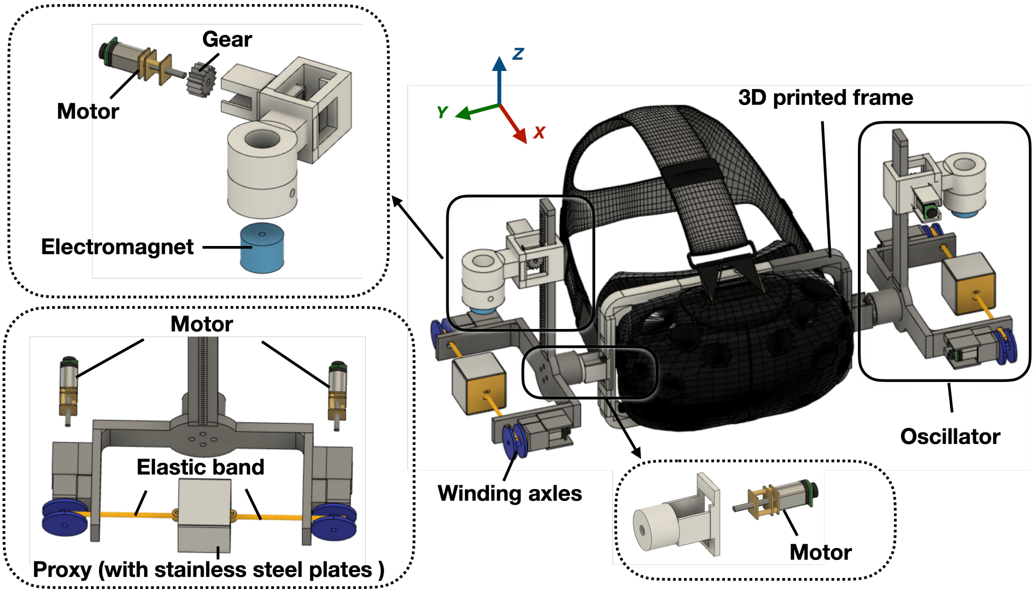


Fig. 2. The 3D model of the OsciHead prototype.

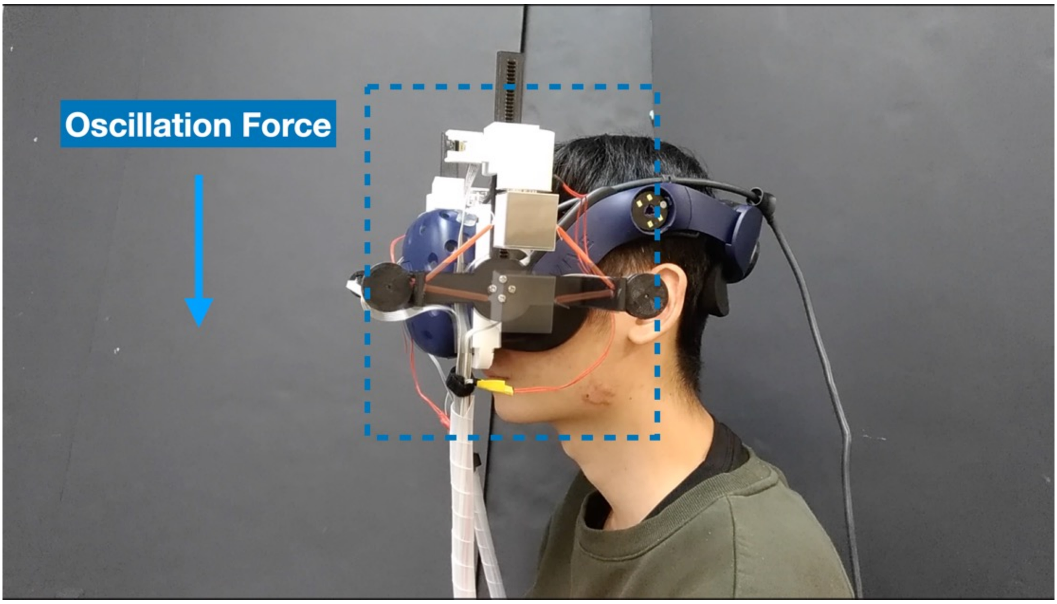


Fig. 3. The procedure of generating oscillation feedback. An electromagnet attracts a proxy moved by a motor to extend elastic bands. When the electromagnet releases the proxy, the oscillation is generated.

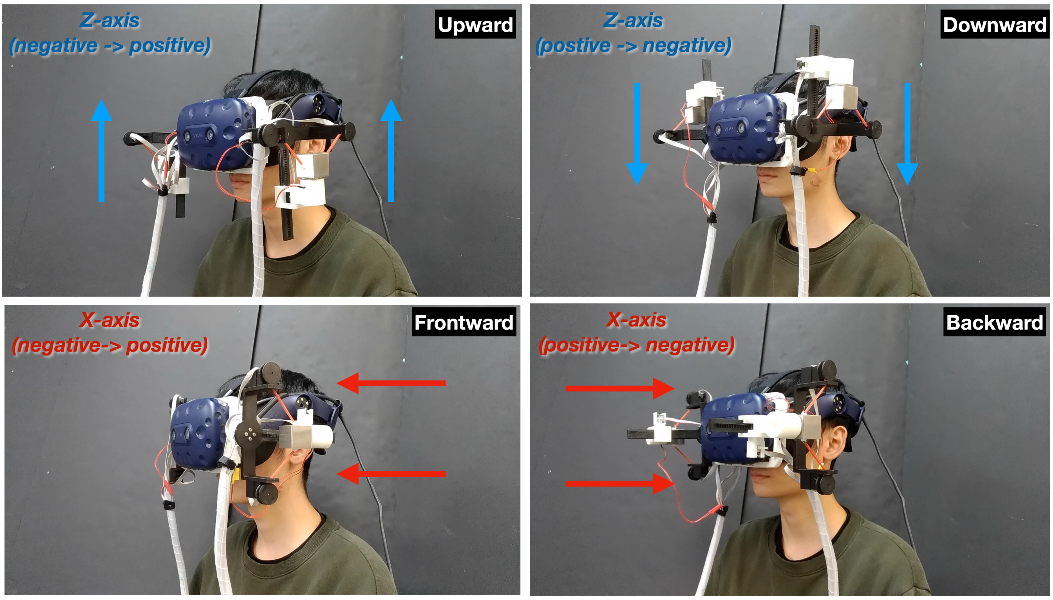


Fig. 4. Four symmetric directions as an example show the directions of oscillation force applying to the HMD. The blue lines mean the force applied on the Z-axis, and the red lines indicate the force applied on the X-axis.

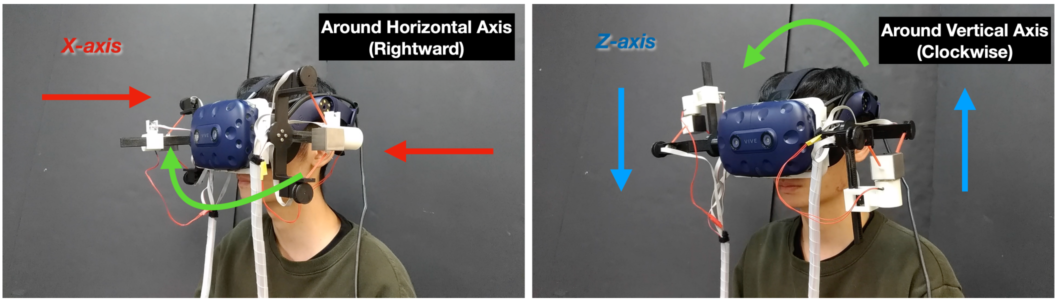


Fig. 5. Two asymmetric directions, as an example, demonstrate the directions of oscillation force applying to the HMD. The red and blue lines mean the force generate on X/Z-axis separately, and the green lines show the rotational directions of the head movement.

for each oscillator: **(1)** ***elasticity***, **(2)** ***extension distance***, and **(3)** ***direction***. For the *elasticity* parameter, the two motors (Pololu Micro Metal Gearmotor with gear ratio 210:1) with rotary encoders (Pololu Magnetic Encoder 12 counts per revolution) and winding axles (radius: 14mm) control the elastic bands’ elasticity to provide various types of oscillation further. This setting alters the constant k and the viscous damping coefficient c in Equation 3 and generates different types of oscillation feedback based on the concept in [23]. Secondly, we use an electromagnet (KL-P20/15) to attract the proxy to change the *extension distance* parameter. The electromagnet is moved by another motor (gear ratio 1000:1) using a rack and pinion design to extend the elastic bands and store the power, like a slingshot. Therefore, the oscillation feedback is rendered when the electromagnet releases the proxy (Figure 3). To be attracted smoothly by the electromagnet, the proxy comprises a 3D printed cube with four stainless steel plates attached to the four sides. The other two sides are connected with the elastic bands, respectively. In a pilot study, we observed that the combination of the proxy weighing 60g and each elastic band consisting of two small rubber bands performs the most proper oscillation feedback on the head. A 3D printed frame is used to attach the oscillators to the HMD. The oscillator generated multilevel feedback for broad VR scenarios by different extension distances. Lastly, the third parameter is *direction*. We first defined three axes of the OsciHead prototype, as shown in Figure 2. The X-axis means the proxy oscillates, aligning with a direction from the back to the front of the HMD; The Y-axis means the proxy oscillates, aligning with the horizontal plane of the HMD; The Z-axis means the proxy oscillates, aligning with the vertical plane of the HMD. To provide different oscillation directions, the other motor (gear ratio 1000:1) mounted on the frame of the side of the HMD connects and rotates the oscillator on a 2D plane (XZ plane) around the horizontal axis of the HMD. The OsciHead prototype can provide symmetric and asymmetric directions of oscillation feedback to achieve versatility. For the symmetric directions, the two oscillators rotate in the same direction in the 2D plane (XY plane) to move the head in 1D movement (X/Z-axis) and 2D movement (XZ plane). As an example, we take four symmetric directions (*upward*, *downward*, *frontward*, and *backward*), as shown in 4. The *upward* and *downward* directions mean the direction of oscillation force applied on the HMD in the positive/negative direction of the Z-axis. The *frontward* and *backward* directions express the direction of the oscillation force lies in the positive/negative direction of the X-axis. For the asymmetric directions, the two oscillators rotated in opposite directions and generated oscillation force to turn the head in 2D movement (XY/YZ plane). Figure 5 shows two asymmetric directions (e.g., *rightward*, *clockwise*). The *rightward* direction consists of a backward oscillation on the left side of the HMD and a frontward oscillation on the right side. The two forces simultaneously applied on the two sides of the HMD make the head turn to the right side (rotating head in XY plane). The *clockwise* direction includes an upward oscillation on the left side and a downward oscillation on the right side, making the head rotate in the clockwise direction (YZ plane).

The four motors and an electromagnet are controlled by three Dual TB6612FNG motor drivers connected to an Arduino Mega board for each oscillator. A laptop controls the board using a USB cable. 12V power is used for the motors and the electromagnets. Furthermore, the earphones of the HMD are removed to prevent the oscillators from colliding with the earphones during rotation. The weight of the OsciHead prototype, including the HMD and two oscillators, is 1270g. The weight of a Vive Pro HMD without earphones is 315g.

3.2 Exploratory Study

We performed pilot and exploratory studies to explore the proper parameters of elasticity and oscillation types. In the pilot study, we gradually adjusted the motor revolution number from 0.7 to 3.1 to increase the bands' extension distance and elasticity. We found five distinguishable oscillation types with revolutions: 0.8, 1.2, 1.5, 1.8, and 2.1. 10 participants (5 female) aged 22-27 (mean:24) were recruited for the exploratory study. They experienced the five oscillation types in the horizontal backward direction, thought aloud the oscillation's physical properties, and mapped it to haptic feedback in real life. Notably, we explored the oscillation type instead of force level in this study, so we used a force sensor to measure and guarantee the stored force for each oscillation type is the same by moving the proxies to the corresponding distances. Therefore, the oscillation from weaker elasticity had a larger amplitude and vice versa.

8 participants mentioned that the slower and less intense oscillation due to lower frequency with longer duration (from revolution numbers 0.8 and 1.2 with weaker elasticity) was similar to the feedback as in a braking car, sailing, hit by waves, driving through a bumpy road or feeling shock waves from earthquakes or explosions. They also supposed that the faster and intenser oscillation

with shorter duration (from revolution numbers 1.8 and 2.1 with stronger elasticity) was similar to the feedback of being hit by a ball, bumped by a car, punched, or getting an electric shock. Five of them further specified that they could feel the first one or two peaks more clearly in the oscillation types with higher frequency, which caused these impressions. The oscillation type with middle elasticity from revolution number 1.5 seemed to mix the impression from both. On the other hand, *P8* and *P9* thought that all types of oscillation felt like being hit by objects. However, *P2*, *P3*, *P4*, *P5*, *P6*, and *P9* mentioned that the oscillation with lower frequency felt like being hit by softer or lighter objects, such as jelly, beach ball, water ball, or plastic bottle, and vice versa.

We observed that being shaken with oscillation lasting for a longer period and being hit with oscillation faster and intenser were commonly mentioned by most participants. Based on the consensus, we found that inertia and impact cause most proposed scenarios in these two types of oscillation, respectively. Therefore, we chose two types of oscillation with the motor revolution numbers 0.8 and 1.8 for inertia and impact feedback and focused on them in this paper. However, other types of oscillation with the remaining revolutions can simulate different scenarios and be distinguished from the two revolutions simulating inertia and impact feedback.

3.3 Software Control Procedure

With the parameters for the software control, initially, the oscillators stay upward with the electromagnets slightly above the proxies, and the elastic bands in each oscillator are taut but not extended. The motors extend the bands with revolutions of 0.8 and 1.8 and delay 1641ms and 1845ms for inertia and impact feedback, respectively. The oscillators are then rotated to the corresponding directions within a half revolution clockwise and counterclockwise. The delay of oscillator rotation in a half revolution is 1583ms. Then, the electromagnets extend the proxies to the corresponding distances to store power for different feedback levels and release the proxies to generate oscillation feedback. The longest distance we used in this paper requires 5609ms for moving the proxies. Notably, although the proxies move back and forth repeatedly during oscillation, users can still clearly perceive the direction when the proxies are released, rapidly moving to the other side and applying force to the head, which is regarded as the oscillation feedback direction.

In summary, OsciHead renders various types of multilevel and multidimensional oscillation feedback to simulate versatile forces in VR. The oscillators are not only symmetrically rotated to the same direction on the 2D plane (XY plane) for oscillation in 2D translation directions (X/Z-axis and XZ plane) but also asymmetrically rotated to the opposite directions for oscillation, rotating the head in 2D rotation directions (XY/YZ plane). Therefore, by controlling the elasticity of the bands, different types of oscillation are rendered. By extending the elastic bands at different distances to store power, multiple levels of oscillation are achieved. By changing the directions of the oscillators, multiple dimensions of oscillation are provided.

3.4 Technical Evaluation

To evaluate the force level of inertia and impact simulation, we used the stored force magnitude for oscillation to quantify the force level. To understand the relationship between the extension distance for storing power and the stored force for oscillation of inertia and impact simulation, we used two force sensors to measure the force magnitude. We attached two motors with winding axles connected with the elastic bands and one proxy in an oscillator of OsciHead to two force sensors (load cell TAL220 with an HX711 amplifier). We then attached the force sensors to two bars of an aluminum extrusion frame. The distance between the motors was the same as in the oscillator. After adjusting the elasticity of the bands for oscillation of inertia and impact simulation, we moved the proxy to extend the bands horizontally in extension distance from 10 to 90 mm in steps of 10 mm. And then, we measured the stored force magnitude from the force sensors

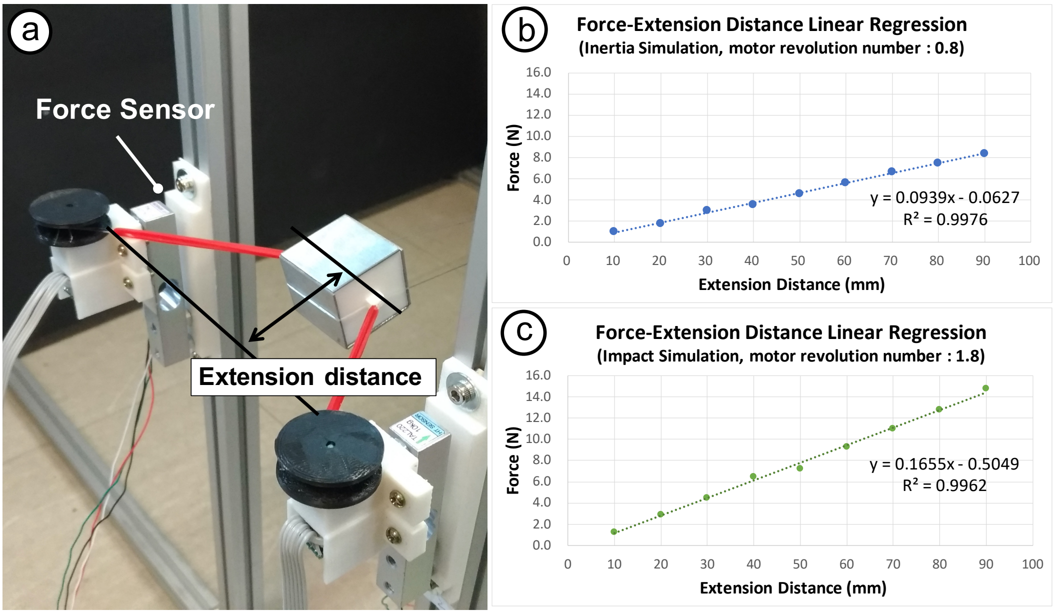


Fig. 6. The linear regression charts of inertia and impact simulation.

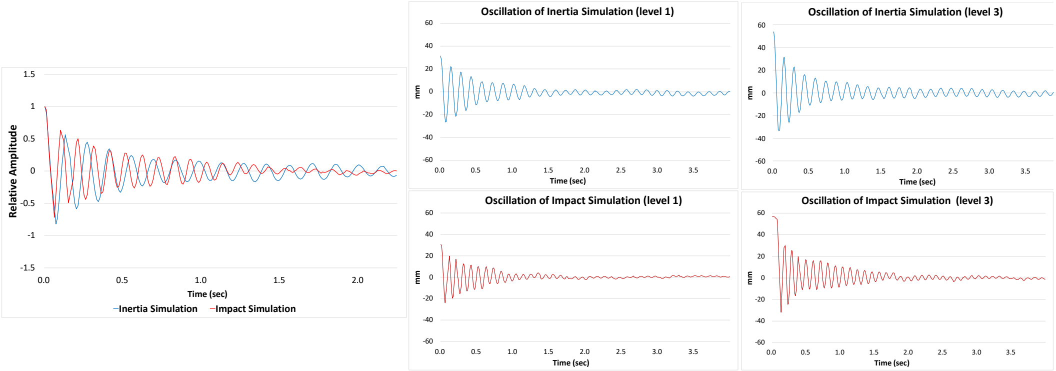


Fig. 7. The trajectories of the proxy in different types and levels of oscillation. (left) The comparison of oscillation of inertia and impact simulation. (right) The amplitudes of haptic level 1 and level 3 in inertia and impact simulation, respectively. We took the x-axis to demonstrate because it was the most obvious.

(Figure 6). Therefore, we obtained the relationships with two linear regression lines for inertia (y = 0.0939x - 0.0627, $R^2 > 0.9$) and impact (y = 0.1655 x - 0.5049, $R^2 > 0.9$), respectively. Since the elasticity of the bands in impact is stronger than the one in inertia, the extension distance to store the same force magnitude in impact is shorter than that in inertia. Notably, the gravity issue of the proxy weight is not included in the results, so we will add or subtract the proxy weight to adjust the stored force when the oscillator prepares to provide upward or downward oscillation.

A spring-mass system is usually used to explain the harmonic oscillator system in physics. Hook's law ($F = -kx$) is the same as Equation 2 for oscillation, and the spring constant k in Hook's law is the constant k in Equation 2. Therefore, we can regard the oscillator as a spring-mass system. Based on the results in regression, we can obtain that the spring constant k in Hook's law are 0.092292705 and 0.150850347 for oscillation of inertia and impact simulation, respectively. The spring constant of impact simulation is 1.6 times as large as the one of inertia simulation. This result shows the properties and differences between the two types of oscillation.

To show the physical properties of oscillation in different types and levels, we leveraged the motion tracking system, Vicon (in 100FPS), and attached four markers to the proxy of an oscillator to show the trajectories of the proxy in different types and levels of oscillation. Figure 7 (left) shows the oscillation of inertia and impact simulation from the same stored force and normalized amplitude. The oscillation frequency and duration from inertia are lower and longer than those from impact. This measure is consistent with the results of the exploratory study that users prefer slow and less intense oscillation with a longer duration for inertia, and fast and intense oscillation with a short duration for impact. Furthermore, Figure 7 (right) shows that the larger oscillation force causes the larger amplitude and longer duration in inertia and impact.

4 JND STUDY I: SYMMETRIC OSCILLATION

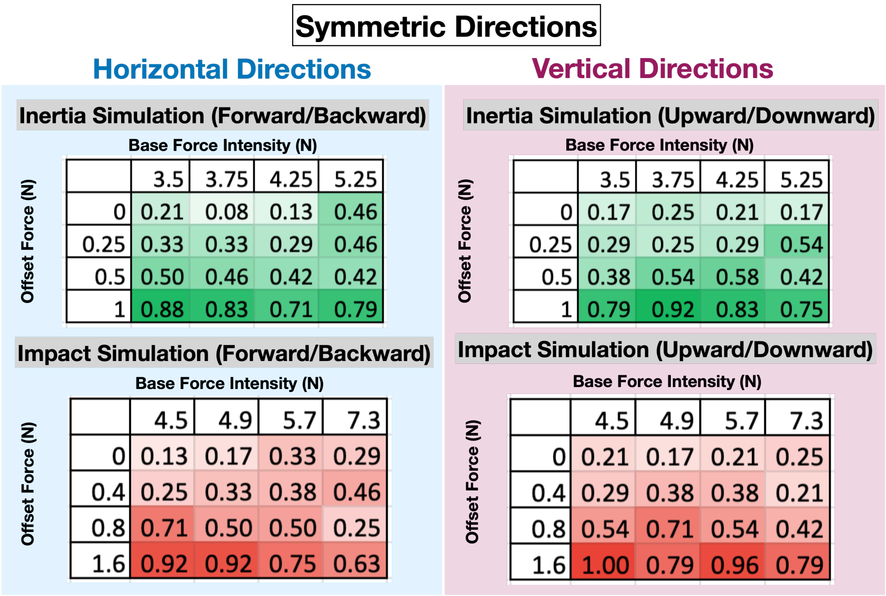
To observe users' distinguishability of oscillation force levels in symmetric directions, we conducted a just-noticeable difference (JND) study using the method of constant stimuli [31] to prevent fatigue. The two types of oscillation feedback for inertia and impact simulation were examined, separately. Furthermore, since the oscillators rotate on a 2D plane to render symmetric oscillation in the 2D translation directions, the oscillation forces in the two axes (forward/backward and upward/downward) were examined, separately.

4.1 Apparatus and Participants

The OsciHead prototype described in the previous section was worn to provide the oscillation feedback. The participants further wore noise-canceling earbuds, and white noise was played to eliminate the noise from the motors. A controller was held by the dominant hand to select the answers to the JND study. To prevent the additional weight of OsciHead from affecting the distinguishability, we leveraged a pulley system with a pulley on the ceiling and a bottle of water to eliminate the extra weight from the HMD. We used Unity3D and SteamVR SDK to build a VR scene. 12 participants (6 female) aged 22-29 (mean: 24.75) were recruited.

4.2 Task and Procedure

The stored force magnitude for oscillation (Figure 6) was used as the oscillation force intensity of JND stimuli. We performed a pilot study and obtained that the minimum oscillation forces, which could be clearly perceived by users, for inertia and impact simulation were 3.5N and 4.5N, respectively. For inertia and impact, the maximum oscillation forces, which could be rendered by the device and did not make users uncomfortable or dizzy, were 6.5N and 9.7N, respectively. In each trial, a pair of oscillation force stimuli were rendered. The participants needed to respond to whether the force intensity of the stimuli was the *same* or *different* using the controller to select the corresponding buttons. If they were unsure of the answer, they could select the *retry* button to playback the stimuli as many times as they wanted to ensure the answer. Each pair of stimuli consisted of a base and an offset force intensities. For inertia, four base force intensities were (3.5N, 3.75N, 4.25N, 5.25N), and four offset force intensities were (0N, 0.25N, 0.5N, 1N). For impact, four base force intensities were (4.5N, 4.9N, 5.7N, 7.3N), and four offset force intensities were (0N, 0.4N, 0.8N, 1.6N). The increasing base and offset intensities complied with the JND standard [31]. All 16 conditions of stimuli from the base and offset intensities were between the minimum and maximum oscillation forces of inertia and impact, respectively.



Symmetric Directions

Horizontal Directions

Inertia Simulation (Forward/Backward)

Base Force Intensity (N)

Offset Force (N)

	3.5	3.75	4.25	5.25
0	0.21	0.08	0.13	0.46
0.25	0.33	0.33	0.29	0.46
0.5	0.50	0.46	0.42	0.42
1	0.88	0.83	0.71	0.79

Impact Simulation (Forward/Backward)

Base Force Intensity (N)

Offset Force (N)

	4.5	4.9	5.7	7.3
0	0.13	0.17	0.33	0.29
0.4	0.25	0.33	0.38	0.46
0.8	0.71	0.50	0.50	0.25
1.6	0.92	0.92	0.75	0.63

Vertical Directions

Inertia Simulation (Upward/Downward)

Base Force Intensity (N)

Offset Force (N)

	3.5	3.75	4.25	5.25
0	0.17	0.25	0.21	0.17
0.25	0.29	0.25	0.29	0.54
0.5	0.38	0.54	0.58	0.42
1	0.79	0.92	0.83	0.75

Impact Simulation (Upward/Downward)

Base Force Intensity (N)

Offset Force (N)

	4.5	4.9	5.7	7.3
0	0.21	0.17	0.21	0.25
0.4	0.29	0.38	0.38	0.21
0.8	0.54	0.71	0.54	0.42
1.6	1.00	0.79	0.96	0.79

Fig. 8. The percentage of responses that judged the two stimuli as different for inertia and impact simulation in symmetric directions, respectively.

In inertia and impact simulation, oscillation in the horizontal and vertical axes were separately examined. In each axis, oscillation in one of two directions of the axis was examined by half participants, and oscillation in the other direction was tested by the others. The order of stimuli within a pair was randomized, and each condition was repeated once. Therefore, a total of 128 (= 2 (types of oscillation) × 2 (axes) × 16 (conditions) × 2 (repetitions)) trials were examined by each participant in this study. The orders of the oscillation types and axes were counterbalanced. The participants could take a break between sessions. The participants were asked to fill outs a questionnaire for some qualitative feedback after the experiment. The study took about two and a half hours.

4.3 Results and Discussion

The JND study results of symmetric oscillation are shown in Figure 8. For inertia, we observed that participants could distinguish the pairs with offset intensity 1N and base intensities 3.5N and 3.75N on the horizontal axis. In the vertical axis, the pairs with offset intensity 1N and base intensities 3.5N, 3.75N, and 4.25N are discernible. For impact, for offset intensity 1.6N, the pairs with base intensities of 4.5N and 4.9N are discernible on the horizontal axis. The pairs with all base intensities are distinguishable on the vertical axis. In the results, the pairs with the same base intensities and larger offset intensities are generally easier to be distinguished. The pairs with the same offset intensities and smaller base intensities are generally easier to be differentiated, which loosely conforms with the concept of Weber's law (constant = (offset intensity) / (base intensity), where the constant is Weber fraction).

In the results for inertia and impact, stimuli in vertical directions seem easier to distinguish than those in horizontal directions, which 7 participants also mentioned. *P2* and *P11* commented that the HMD oscillated more sharply in the vertical axes, which may be caused by the HMD design that the HMD is fixed on the head mainly using the straps around the head. Therefore, the same stored force causes more obvious oscillation in the vertical axis. *P5*, *P10*, *P11* further mentioned that the oscillation duration in horizontal directions was longer. The oscillation in horizontal directions made them feel more uncomfortable and dizzy, which reduced the distinguishability in the horizontal axis. Furthermore, 8 participants supposed that impact stimuli were easier to differentiate than those in inertia. *P5* and *P6* commonly proposed a similar reason that the oscillation duration of inertia was generally longer than that of impact, which made oscillation of inertia harder to distinguish. In addition, 5 participants mentioned that the force stimuli in impact were intenser and more obvious than those in inertia, so these stimuli were more discernible.

We fit a logarithmic function to the Weber fraction versus the aggregated percentage of the data in each condition. We chose the Weber fractions to allow most participants to clearly distinguish the difference in inertia and impact. As a result, 0.325 (83.45% JND on the horizontal axis and 85.69% JND on the vertical axis) and 0.4 (87.97% JND on the horizontal axis and 99.06% JND on the vertical axis) were chosen in inertia and impact, respectively. Based on [5], an increment of 0.325 and 0.4 times the base intensity is required for the next level to be discernible in inertia and impact, respectively. Therefore, we determined that three distinguishable oscillation force levels (1, 2, 3) are (3.5N, 4.64N, 6.15N) in inertia and (4.5N, 6.3N, 8.82N) in impact. The delays of power storing for these levels are (3324ms, 4209ms, 5609ms) in inertia, and (2515ms, 3274ms, 4504ms) in impact.

5 JND STUDY II: ASYMMETRIC OSCILLATION

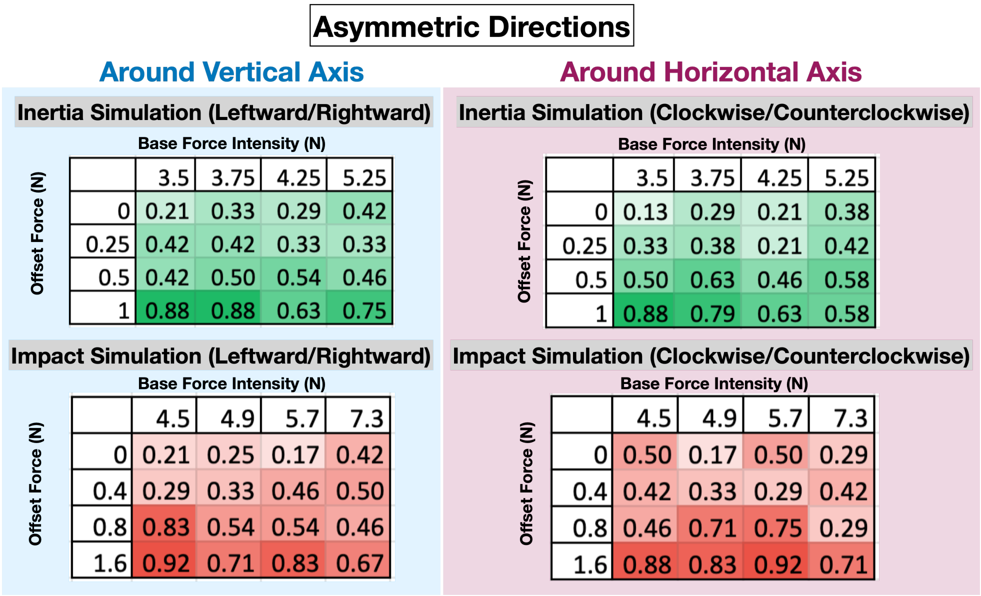
We performed another JND study to observe users' distinguishability of oscillation force levels in asymmetric directions.

5.1 Setup and Procedure

The stimuli's setup, procedure, base, and offset force intensities were the same as the previous JND study. 12 participants (5 female) aged 22-27 (mean: 24.5) were recruited. 9 of them had experienced the previous JND study. The directions we observed in this study differed from those in Study I, so some participants who attended in previous JND study still need to be familiar with experiencing oscillation force in the asymmetric direction provided by OsciHead. By rotating the oscillators in the opposite directions, asymmetric oscillation rotating or twisting the users' heads is rendered in 2D rotation directions. The oscillation forces are around two axes, including the horizontal axis for leaning the head (clockwise/counterclockwise) and the vertical axis for shaking or turning the head (leftward/rightward), examined separately in the oscillation of inertia and impact simulation.

5.2 Results and Discussion

The JND study results of asymmetric oscillation are shown in Figure 9. For inertia, the pairs with offset intensity 1N and base intensities 3.5N and 3.75N are distinguishable between horizontal and vertical axes. For impact, for offset intensity 1.6N, the pairs with base intensities 4.5N, 4.9N, and 5.7N are discernible around the horizontal axis, and with base intensities 4.5N and 5.7N are discriminated around the vertical axis. Compared with the previous JND study results, the force level distinguishability in asymmetric oscillation is generally lower than that in symmetric oscillation in both inertia and impact. This result might be caused by the reason that the asymmetric oscillation rotates or twists the head and interferes with the participants to differentiate the stimuli, as mentioned by some participants. Furthermore, the difference between two axes in asymmetric oscillation seems less obvious than in symmetric oscillation. However, the stimuli are still more distinguishable in impact than those in inertia in asymmetric oscillation. Based on the results, we also fit a logarithmic function to the Weber fraction versus the aggregated percentage of the data in each condition and obtained the Weber fractions with good distinguishability for inertia and impact, respectively. To maintain the consistency between symmetric and asymmetric oscillation, we tried



Asymmetric Directions

Around Vertical Axis

Inertia Simulation (Leftward/Rightward)

Base Force Intensity (N)

Offset Force (N)

	3.5	3.75	4.25	5.25
0	0.21	0.33	0.29	0.42
0.25	0.42	0.42	0.33	0.33
0.5	0.42	0.50	0.54	0.46
1	0.88	0.88	0.63	0.75

Impact Simulation (Leftward/Rightward)

Base Force Intensity (N)

Offset Force (N)

	4.5	4.9	5.7	7.3
0	0.21	0.25	0.17	0.42
0.4	0.29	0.33	0.46	0.50
0.8	0.83	0.54	0.54	0.46
1.6	0.92	0.71	0.83	0.67

Around Horizontal Axis

Inertia Simulation (Clockwise/Counterclockwise)

Base Force Intensity (N)

Offset Force (N)

	3.5	3.75	4.25	5.25
0	0.13	0.29	0.21	0.38
0.25	0.33	0.38	0.21	0.42
0.5	0.50	0.63	0.46	0.58
1	0.88	0.79	0.63	0.58

Impact Simulation (Clockwise/Counterclockwise)

Base Force Intensity (N)

Offset Force (N)

	4.5	4.9	5.7	7.3
0	0.50	0.17	0.50	0.29
0.4	0.42	0.33	0.29	0.42
0.8	0.46	0.71	0.75	0.29
1.6	0.88	0.83	0.92	0.71

Fig. 9. The percentage of responses that judged the two stimuli as different for inertia and impact simulation in asymmetric directions, respectively.

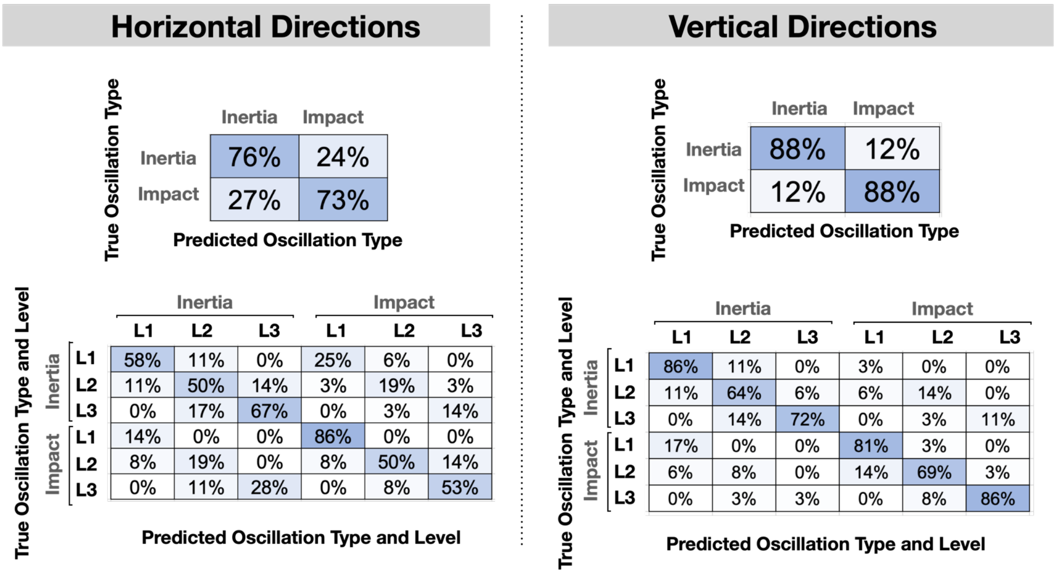
and found that using the same Weber fractions as in symmetric oscillation, 0.325 (79.91% JND around the horizontal axis and 82.78% JND around the vertical axis) and 0.4 (91.72% JND around the horizontal axis and 86.2% JND around the vertical axis) in inertia and impact, respectively, still achieved acceptable distinguishability. Therefore, the force levels are the same in symmetric and asymmetric oscillation.

6 RECOGNITION STUDY

In addition to understanding the distinguishability of oscillation force level from the previous JND studies, we also evaluated oscillation type recognition rates and even combinations of oscillation type and level by performing this recognition study, which followed [20].

6.1 Setup and Procedure

The setup was the same as the previous JND studies, but the pulley system was not used. 12 participants (5 female) aged 23-27 (mean: 24.1) were recruited. 4 of them had experienced the previous JND studies, but more than two weeks elapsed between them. Based on the JND results, oscillation in the three levels of the two types, inertia and impact, were separately compared in horizontal and vertical axes. The participants were familiar with the examining feedback in a training session and then recognized the perceived oscillation feedback. Therefore, a total of 36 (= 2 (types of oscillation) × 3 (force levels) × 2 (axes) × 3 (repetitions)) trials were examined by each participant. Oscillation types and levels were randomized, and the order of the axes was counterbalanced. Half participants examined oscillation in one of two directions on each axis, as in the JND studies. The participants could take a break between sessions. We interviewed the participants after the experiment. The study took about half an hour.



Horizontal Directions

	Inertia	Impact
Inertia	76%	24%
Impact	27%	73%

		Inertia			Impact		
		L1	L2	L3	L1	L2	L3
Inertia	L1	58%	11%	0%	25%	6%	0%
	L2	11%	50%	14%	3%	19%	3%
	L3	0%	17%	67%	0%	3%	14%
Impact	L1	14%	0%	0%	86%	0%	0%
	L2	8%	19%	0%	8%	50%	14%
	L3	0%	11%	28%	0%	8%	53%

Vertical Directions

	Inertia	Impact
Inertia	88%	12%
Impact	12%	88%

		Inertia			Impact		
		L1	L2	L3	L1	L2	L3
Inertia	L1	86%	11%	0%	3%	0%	0%
	L2	11%	64%	6%	6%	14%	0%
	L3	0%	14%	72%	0%	3%	11%
Impact	L1	17%	0%	0%	81%	3%	0%
	L2	6%	8%	0%	14%	69%	3%
	L3	0%	3%	3%	0%	8%	86%

Fig. 10. Four confusion matrices show the recognition rates of oscillation *type* and oscillation *type and level* in horizontal and vertical directions.

6.2 Results and Discussion

The recognition rates of *type*, which means that only the type of the responses is compared regardless of the level, and recognition rates of *type and level*, which means both the type and level of the responses are compared, are shown in Figure 10. For the recognition rates of *type*, the recognition rates of inertia and impact are similar in both axes separately. Duration seemed to be a critical clue in differentiating between inertia and impact. Except for *P3*, *P4*, and *P9*, most participants felt the longer duration from the oscillation of inertia simulation, and 7 participants perceived the shorter period from impact. Furthermore, *P5* and *P11* felt the higher amplitude, and *P12* perceived the less intense oscillation from inertia simulation. For impact simulation, clear shaking (*P9*, *P11*), impact force applying to the HMD (*P5* and *P9*), and intenser force (*P2*, *P5*, *P6*, *P11*) were also mentioned. These comments are consistent with the results of the exploratory study and physical properties evaluated in Figure 7.

For the recognition rates of *type and level*, levels 1 and 3 in both types seemed more recognizable in the vertical directions, and impact level 1 was recognizable in the horizontal directions. The recognition rates in the vertical directions are higher than those in the horizontal directions in the *type* and *type and level* recognition, which 5 participants also mentioned. *P2* supposed that the oscillation duration of the two types was closer in the horizontal directions, which confused them. *P1*, *P5*, and *P12* said that level 1 was less intense, so it was easier to distinguish between both types. On the other hand, *P3*, *P4*, *P9*, and *P12* supposed that due to the stronger force level with the longer oscillation duration, it was easier to distinguish the type in level 3. Besides, we observed that the participants more easily confused the types than the levels, such as inertia level 1 and impact level 3 in horizontal directions and impact level 1 in vertical directions. This result is consistent with the comments of *P6*, *P9*, and *P10* that they believed that they could easily recognize the level if they knew the type. In general, these two oscillation *types* are recognizable to users.

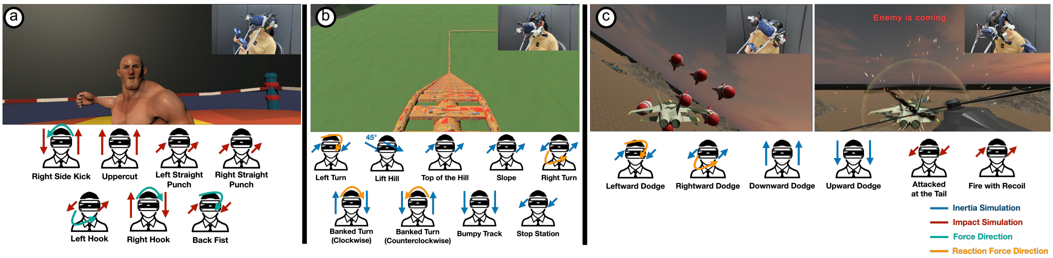


Fig. 11. Fighting Game (left), Roller Coaster Simulation (middle), and Fighter Aircraft Game (right) applications in VR.

However, distinguishing the combination of oscillation *type and level* in the horizontal directions is a bit challenging, but determining the ones in the vertical directions is achievable.

7 VR EXPERIENCE STUDY

To observe how the inertia and impact feedback simulated by oscillation from OsciHead affects users' VR experience and verify whether the simulated inertia and impact feedback enhances realism, we conducted this study with three VR applications.

7.1 Apparatus and Participants

The setup was similar to that in the recognition study. Two, one, or no controllers were needed in these applications. The participants wore earbuds, which played background music to block the noise from the motors. We built three VR scenes for the applications in this study. 12 participants (5 female) aged 20-29 (mean: 24.25) were recruited. They all had experienced VR at least once. Only one attended the previous recognition study, but more than two weeks elapsed between the studies.

7.2 Task and Procedure

This study compared two methods, visual-only and OsciHead, using a within-subject design. For the visual-only method, only visual but no haptic feedback was rendered. For OsciHead, both visual and haptic feedback from the OsciHead device were generated. The OsciHead device was worn in both methods. Three applications, including a fighting game, roller coaster simulation, and fighter aircraft game, were experienced by the participants, as shown in Figure 11.

7.2.1 Fighting Game. For the fighting game, seven attacks were performed by the virtual enemy, and impact feedback was experienced in this application. The participants could also punch the enemy using the held controllers. The seven attacks included a right side kick (impact, clockwise, level 3), uppercut (impact, upward, level 2), left straight punch (impact, backward, level 1), right straight punch (impact, backward, level 1), left hook (impact, leftward, level 2), right hook (impact, counterclockwise, level 3) and back fist (impact, rightward, level 3). All three impact levels were simulated by oscillation from OsciHead, and impact simulation with both symmetric (the uppercut and straight punches) and asymmetric (the sidekick, hooks, and back fist) oscillation were rendered in this application (Figure 11 (a)).

7.2.2 Roller Coaster Simulation. For the roller coaster simulation, nine conditions on the track caused nine inertia forces. No controller was needed in this application. Since inertia force prevents users from movement change, the simulated inertia force direction was the opposite of the car movement. In the beginning, the car turned left (inertia, rightward, level 1) and then climbed to a lift hill (inertia, backward and 45° downward, level 2) at a slow speed. When reaching the top of the hill, the car became horizontal again (inertia, backward, level 2). After leaving there, the car moved to a slope and stopped facing downward. After three seconds, it dived from the slope at the maximum speed (inertia, backward, level 3). After a right turn (inertia, leftward, level 1), it encountered a banked turn and caused the car to suddenly incline clockwise and rotate back to the horizontal (inertia, counterclockwise, level 2). Another banked turn in the opposite direction then made it inclining counterclockwise and rotating back (inertia, clockwise, level 2). It then passed through a short bumpy track, which made it bumped along the path (inertia, downward, level 2). Finally, the car braked and stopped (inertia, forward, level 2). Notably, for some conditions consisting of two consecutive inertia forces in the opposite directions, including the two banked turns and the bumpy track, we observed that providing the simulated inertia feedback for the first inertia force caused reasonable and proper feedback in a pilot study. Therefore, the simulated inertia feedback corresponded to the first inertia force. The nine inertia forces were generated by three levels of symmetric/asymmetric oscillation of inertia simulation from OsciHead (Figure 11 (b)).

7.2.3 Fighter Aircraft Game. For the fighter aircraft game, six conditions were caused by inertia and impact forces. The participants used a controller on the dominant hand as the fighter's center stick or control stick. Instead of freely controlling the fighter, the controller was designed to handle the direction of the emergency dodge. By pulling, pushing, tilting left, and tilting right the controller, the fighter dodged upward/downward/leftward/rightward and moved back rapidly. The participants flew the fighter and four 3×3 missile arrays with one missing missile as a gap appeared in the airway. They had to dodge the missile arrays leftward (inertia, rightward, level 2), rightward (inertia, leftward, level 2), downward (inertia, upward, level 2), and upward (inertia, downward, level 2) orderly. If they performed in the wrong direction for the emergency dodge, they failed and got to restart the game. After passing the missile arrays, an enemy helicopter locked on the fighter and fired a missile to hit the tail of the fighter (impact, forward, level 2). The helicopter then flew to the front of the fighter. They had to fire a missile with recoil (impact, backward, level 3) to shoot down the helicopter by pressing the controller's trigger after the loading period. Notably, they were in the third-person view instead of the first-person view since VR flying games could easily cause motion sickness in the first-person view. Furthermore, the third-person view made them clearly see the attack from the tail. Therefore, we chose the third-person view mode in this game and rendered leftward/rightward dodges with rightward/leftward instead of counterclockwise/clockwise inertia simulation. This application demonstrated that versatile force feedback was required in a VR scenario.

After the experimenters briefly introduced the applications, the participants experienced the three VR applications. A total of 6 (= 2 (methods) × 3 (applications)) conditions were experienced by each participant. The methods were counterbalanced. Since we did not compare the VR applications, the applications were experienced orderly. After experiencing each method in an application, they filled out a simulator sickness questionnaire (SSQ) [10] to record the motion sickness and took a break within three minutes. After experiencing both methods in each application, they filled out a questionnaire using a 7-point Likert scale in terms of realism, enjoyment, preference, and distinguishability, allowing decimal scores. After the experiment, an open-ended interview was performed to elicit general comments. The study took about one and a half hours.

7.3 Results and Discussion

The results are shown in Figure 12. We used a repeated-measures ANOVA and Bonferroni correction to analyze the results statistically. For the fighting game, significant main effects are in all factors, realism ($F_{1,11} = 52.28, p < 0.001$), distinguishability ($F_{1,11} = 42.48, p < 0.001$), enjoyment ($F_{1,11} =$

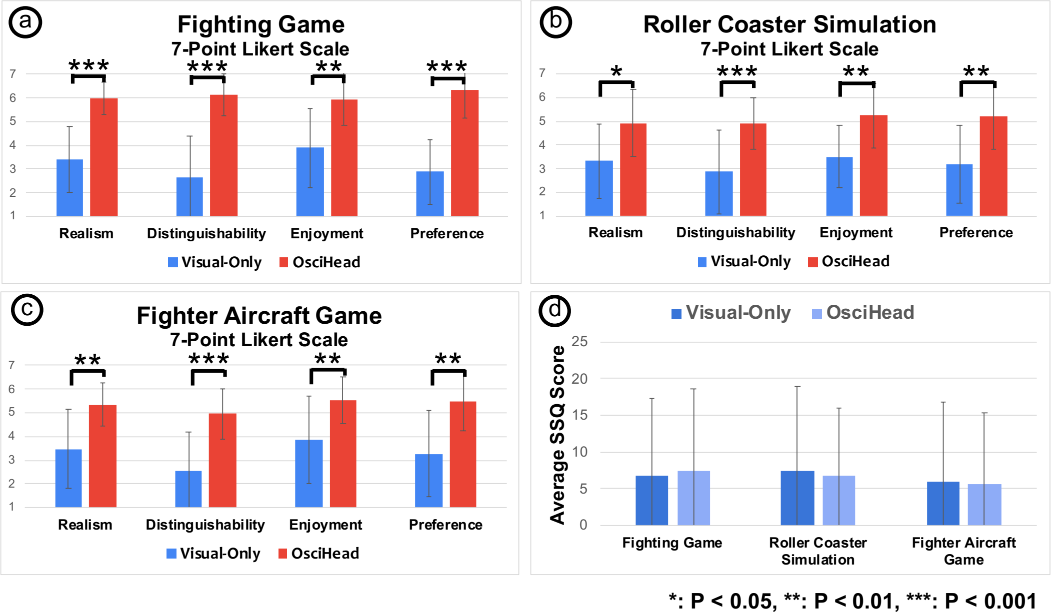


Fig. 12. (a)(b)(c) Subjective results of VR experience study (realism, distinguishability, enjoyment, preference) on a 7-point Likert scale. (d) The comparison of relative SSQ scores in three applications.

11.48, $p < 0.01$) and preference ($F_{1,11} = 34.13, p < 0.001$). For the roller coaster simulation, significant differences are found in all factors, realism ($F_{1,11} = 9.66, p = 0.01$), distinguishability ($F_{1,11} = 26.54, p < 0.001$), enjoyment ($F_{1,11} = 14.56, p < 0.01$) and preference ($F_{1,11} = 11.47, p < 0.01$). For the fighter aircraft game, significant differences are revealed in all factors, realism ($F_{1,11} = 20.24, p = 0.001$), distinguishability ($F_{1,11} = 35.56, p < 0.001$), enjoyment ($F_{1,11} = 17.15, p < 0.01$) and preference ($F_{1,11} = 15.95, p < 0.01$). The results show that the simulated force feedback from OsciHead significantly enhances users' VR experiences. Furthermore, based on [7, 10], we averaged the SSQ scores, as shown in Figure 12 (d). There is no significant effect in the fighting game ($F_{1,11} = 0.31, p = 0.59$), roller coaster simulation ($F_{1,11} = 0.27, p = 0.62$) and fighter aircraft game ($F_{1,11} = 0.19, p = 0.67$). This result means that oscillation feedback from OsciHead does not aggravate motion sickness compared with only the visual feedback.

For the fighting game, 7 of the participants (*P1*, *P3*, *P5*, *P6*, *P7*, *P10*, *P12*) supposed that the impact feedback of the right hook was most realistic since the strong force and proper direction perfectly matched its visual feedback. The feedback on the right sidekick, left/right hooks, and left/right straight punches were also appreciated by 4 or 5 participants. Although level 3 impact was rendered for the sidekick, *P6* expected stronger feedback since a kick was usually more powerful than a punch or hook. For the same reason, *P2* supposed that the feedback of the back fist seemed not very realistic. However, 5 participants (*P2*, *P6*, *P7*, *P10*, and *P12*) still thought the impact force levels matched their imaginations and expectations. Most participants believed that the impact feedback simulated by oscillation was still realistic and could enhance immersion. Interestingly, *P11* mentioned that the feedback in this application was too realistic and even scared them, so they graded higher scores in realism and distinguishability but lower scores in enjoyment and preference for OsciHead. Furthermore, since no participants responded that they felt sick or dizzy from both methods, we suppose that impact simulation from OsciHead enhances realism but does not cause additional motion sickness in the fighting game.

For the roller coaster simulation, 7 participants (*P2*, *P3*, *P4*, *P5*, *P7*, *P10*, *P11*) mentioned that the inertia feedback in sudden left/right turns was the most realistic. They mentioned that it felt like real inertia resistive forces turning the head. The feedback from the slope was also preferred by 6 participants. However, *P4* mentioned that when the car was driven to the end of the slope and became horizontal again, they expected another inertia feedback to be rendered. *P9* and *P11* also commented that they expected the car to drive faster. On the other hand, the feedback in banked turns was not realistic enough for some participants since the timing of the proxies changing the moving directions during oscillation did not perfectly match the suddenly inclining and rotating back movements. Furthermore, 4 participants (*P1*, *P2*, *P6*, and *P8*) proposed that the inertia forces should apply to the whole body instead of only the head. For motion sickness, *P6* mentioned that they felt dizzy when the car turned, especially when it dived fast from the slope in both methods. We believed that the visual feedback instead of OsciHead caused this sickness. Interestingly, *P12* reported that they felt less dizzy when using OsciHead, which is consistent with the case in [31]. We interfere that OsciHead rendering the oscillation feedback matching the shaking or rapidly moving visual feedback might reduce the sickness.

For the fighter aircraft game, more than half participants mentioned that the feedback in downward/upward dodges and attacks at the tail was the most realistic. Furthermore, half of the participants appreciated the feedback on the fire with recoil. They thought the force levels in these conditions matched their imaginations. *P2*, *P7* and *P12* commented that the recoil was really realistic. However, 5 participants supposed that the leftward/rightward dodges feedback was not consistent with their thoughts due to too strong oscillation and oscillation directions in leftward/rightward instead of clockwise/counterclockwise. We believe that the third-person view instead of the first-person perspective more or less affects immersion and realism. Still, it also reduces motion sickness, and no participants felt dizzy in this application.

Comparing the oscillation of inertia and impact simulation, most participants except *P9* and *P11* believed they could distinguish the difference between these two types of oscillation. For inertia, *P2* and *P10* mentioned that they perceived clear back and forth shaking due to the lower oscillation frequency. *P4* and *P12* supposed that the directions of inertia forces were obvious, which might be caused by a longer duration in inertia simulation. *P4* mentioned that s/he seemed to feel the inertia force during acceleration. For impact, 4 participants (*P1*, *P2*, *P4*, *P10*) thought that they felt intenser oscillation. *P8* recognized that faster oscillation with a shorter duration was in impact simulation. *P7* and *P12* supposed that the inertia simulation was appropriate for suddenly turning left/right, and the impact simulation was proper for recoil feedback.

In general, the results show that the simulated inertia and impact from OsciHead significantly enhance VR realism and achieve versatility. Furthermore, it does not cause additional motion sickness when shaking the head. These two types of oscillation are discernible and match their simulated force feedback, respectively, which achieves our goal.

8 LIMITATION AND FUTURE WORK

Although the feedback from OsciHead enhances VR realism and versatility and is appreciated by users, the current prototype still has some limitations. The device's weight is a bit heavy, which may cause the HMD to tilt forward slightly. If our design is built-in in the future HMD, it could be smaller and lighter. Furthermore, the current design provides oscillation in 2D translation and 2D rotation directions. We envision achieving oscillation in 3D translation and 3D rotation directions, including in toward/away and nodding directions of the HMD, in the future. Although there was no delay within the oscillatory behaviors generated by OsciHead, the loading time to prepare oscillation feedback is inevitable.

The JND studies took about 2.5 hours and 1.5 hours to conduct the experiments separately, which might cause the participants' fatigue. To avoid this problem, we let the participants take a break between sessions to ensure they have enough energy to finish the following experiment. In each session, the participants took about 30 minutes to experience 32 trials (= 16 (conditions) × 2 (repetitions)), and then they would take a break about 10 to 15 minutes before the next session. In addition, we counterbalanced the order of the oscillation types and axes to reduce the basis of the participants' getting used to the ahead sessions. A similar procedure was also proposed in [26].

The current prototype used the proxy weight of 60g to provide clear oscillation feedback when users wear the HMD. If the present concept is designed as a module in the future, it could provide oscillation feedback on not only heads but also other parts of bodies (e.g., hands, feet, etc.). According to mounting on different aspects of bodies, the weight of the OsciHead prototype and the proxy could be adjusted to provide proper oscillation feedback, such as generating oscillation force on heads to simulate inertia force for liquids with a smaller and lighter device [30]. Therefore, the weight of the OsciHead prototype and the proxy could be reduced by modular design. It is similar to putting vibration motor modules on different parts of bodies, but oscillation feedback could provide more sophisticated simulation feedback than vibration feedback.

By rotating the oscillators and moving the proxies to extend the bands simultaneously after adjusting the band's elasticity, the loading time could be further reduced. Furthermore, rendering proper animations in the load time [18, 24, 32] could also mitigate the delay issue for real-time interactions. Although we take inertia and impact as examples to prove the concept in this paper, some other scenarios for different types of oscillation were proposed in the exploratory study. Therefore, we will further explore how to map more oscillation types to versatile force feedback in the future.

9 CONCLUSION

We propose OsciHead to simulate versatile force feedback by rendering different types of oscillation caused by those forces on a head. By controlling the elasticity and stored power of the bands and the oscillators' directions, multiple types, levels, and dimensions of oscillation are rendered for versatile force feedback. We performed an exploratory study to obtain versatile scenarios for different types of oscillation and take oscillation with a lower frequency and longer duration for inertia simulation and oscillation with higher frequency and shorter duration for impact simulation as examples. We then conducted two JND studies to obtain three different oscillation levels for inertia (3.5N, 4.64N, 6.15N) and impact (4.5N, 6.3N, 8.82N) simulation for symmetric and asymmetric oscillation. We also showed the recognition rates of these two oscillation types in the recognition study. Finally, we performed a VR study to verify that simulated inertia and impact feedback from OsciHead significantly enhance VR realism, achieve versatility, and demonstrate three applications involving inertia and impact feedback.

ACKNOWLEDGMENTS

Removed for review.

REFERENCES

[1] Tomohiro Amemiya, Hideyuki Ando, and Taro Maeda. 2008. Lead-Me Interface for a Pulling Sensation from Hand-Held Devices. *ACM Trans. Appl. Percept.* 5, 3, Article 15 (Sept. 2008), 17 pages. https://doi.org/10.1145/1402236.1402239

[2] Hong-Yu Chang, Wen-Jie Tseng, Chia-En Tsai, Hsin-Yu Chen, Roshan Lalintha Peiris, and Liwei Chan. 2018. FacePush: Introducing Normal Force on Face with Head-Mounted Displays. In *Proceedings of the 31st Annual ACM Symposium on*

User Interface Software and Technology (Berlin, Germany) *(UIST '18)*. Association for Computing Machinery, New York, NY, USA, 927–935. https://doi.org/10.1145/3242587.3242588

[3] Chih-Hao Cheng, Chia-Chi Chang, Ying-Hsuan Chen, Ying-Li Lin, Jing-Yuan Huang, Ping-Hsuan Han, Ju-Chun Ko, and Lai-Chung Lee. 2018. GravityCup: A Liquid-Based Haptics for Simulating Dynamic Weight in Virtual Reality. In *Proceedings of the 24th ACM Symposium on Virtual Reality Software and Technology* (Tokyo, Japan) *(VRST '18)*. Association for Computing Machinery, New York, NY, USA, Article 51, 2 pages. https://doi.org/10.1145/3281505.3281569

[4] 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* (Québec City, QC, Canada) *(UIST '17)*. Association for Computing Machinery, New York, NY, USA, 119–130. https://doi.org/10.1145/3126594.3126599

[5] Gescheider. 2013. *Psychophysics.* Psychology Press. https://doi.org/10.4324/9780203774458

[6] Jun Gong, Da-Yuan Huang, Teddy Seyed, Te Lin, Tao Hou, Xin Liu, Molin Yang, Boyu Yang, Yuhan Zhang, and Xing-Dong Yang. 2018. Jetto: Using Lateral Force Feedback for Smartwatch Interactions. 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, 1–14. https://doi.org/10.1145/3173574.3174000

[7] Jan Gugenheimer, Dennis Wolf, Eythor R. Eiriksson, Pattie Maes, and Enrico Rukzio. 2016. GyroVR: Simulating Inertia in Virtual Reality Using Head Worn Flywheels. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology* (Tokyo, Japan) *(UIST '16)*. Association for Computing Machinery, New York, NY, USA, 227–232. https://doi.org/10.1145/2984511.2984535

[8] 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* (New Orleans, LA, USA) *(UIST '19)*. Association for Computing Machinery, New York, NY, USA, 763–775. https://doi.org/10.1145/3332165.3347926

[9] Seungwoo Je, Hyelip Lee, Myung Jin Kim, and Andrea Bianchi. 2018. Wind-Blaster: A Wearable Propeller-Based Prototype That Provides Ungrounded Force-Feedback. In *ACM SIGGRAPH 2018 Emerging Technologies* (Vancouver, British Columbia, Canada) *(SIGGRAPH '18)*. Association for Computing Machinery, New York, NY, USA, Article 23, 2 pages. https://doi.org/10.1145/3214907.3214915

[10] Robert S. Kennedy, Norman E. Lane, Kevin S. Berbaum, and Michael G. Lilienthal. 1993. Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness. *The International Journal of Aviation Psychology* 3, 3 (July 1993), 203–220. https://doi.org/10.1207/s15327108ijap0303_3

[11] Shi-Hong Liu, Pai-Chien Yen, Yi-Hsuan Mao, Yu-Hsin Lin, Erick Chandra, and Mike Y. Chen. 2020. HeadBlaster: A Wearable Approach to Simulating Motion Perception Using Head-Mounted Air Propulsion Jets. *ACM Trans. Graph.* 39, 4, Article 84 (July 2020), 12 pages. https://doi.org/10.1145/3386569.3392482

[12] 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 amp; Technology* (Charlotte, NC, USA) *(UIST '15)*. Association for Computing Machinery, New York, NY, USA, 11–19. https://doi.org/10.1145/2807442.2807443

[13] Pedro Lopes, Sijing You, Lung-Pan Cheng, Sebastian Marwecki, and Patrick Baudisch. 2017. Providing Haptics to Walls amp; 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. https://doi.org/10.1145/3025453.3025600

[14] 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* (San Diego, California) *(SIGGRAPH '07)*. Association for Computing Machinery, New York, NY, USA, 8–es. https://doi.org/10.1145/1278280.1278289

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

[16] Neung Ryu, Woojin Lee, Myung Jin Kim, and Andrea Bianchi. 2020. ElaStick: A Handheld Variable Stiffness Display for Rendering Dynamic Haptic Response of Flexible Object. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '20)*. Association for Computing Machinery, New York, NY, USA, 1035–1045. https://doi.org/10.1145/3379337.3415862

[17] 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* (New Orleans, LA, USA) *(UIST '19)*. Association for Computing Machinery, New York, NY, USA, 751–761. https://doi.org/10.1145/3332165.3347870

[18] 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.* Association for Computing Machinery, New York, NY, USA, 1–11. https://doi.org/10.1145/3290605.3300241

[19] Shuntaro Shimizu, Takeru Hashimoto, Shigeo Yoshida, Reo Matsumura, Takuji Narumi, and Hideaki Kuzuoka. 2021. Unident: Providing Impact Sensations on Handheld Objects via High-Speed Change of the Rotational Inertia. In *2021 IEEE Virtual Reality and 3D User Interfaces (VR).* IEEE, 11–20.

[20] 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.* Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3290605.3300682

[21] Colin Swindells, Alex Unden, and Tao Sang. 2003. TorqueBAR: An Ungrounded Haptic Feedback Device. In *Proceedings of the 5th International Conference on Multimodal Interfaces* (Vancouver, British Columbia, Canada) *(ICMI '03).* Association for Computing Machinery, New York, NY, USA, 52–59. https://doi.org/10.1145/958432.958445

[22] Hsin-Ruey Tsai and Bing-Yu Chen. 2019. ElastImpact: 2.5D Multilevel Instant Impact Using Elasticity on Head-Mounted Displays. 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, 429–437. https://doi.org/10.1145/3332165.3347931

[23] 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* (Honolulu, HI, USA) *(CHI '20).* Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3313831.3376408

[24] Hsin-Ruey Tsai, Jun Rekimoto, and Bing-Yu Chen. 2019. ElasticVR: Providing Multilevel Continuously-Changing Resistive Force and Instant Impact Using Elasticity for VR. 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, 1–10. https://doi.org/10.1145/3290605.3300450

[25] Dzmitry Tsetserukou, Katsunari Sato, and Susumu Tachi. 2010. ExoInterfaces: Novel Exosceleton Haptic Interfaces for Virtual Reality, Augmented Sport and Rehabilitation. In *Proceedings of the 1st Augmented Human International Conference* (Megève, France) *(AH '10).* Association for Computing Machinery, New York, NY, USA, Article 1, 6 pages. https://doi.org/10.1145/1785455.1785456

[26] Chi Wang, Da-Yuan Huang, Shuo-Wen Hsu, Cheng-Lung Lin, Yeu-Luen Chiu, Chu-En Hou, and Bing-Yu Chen. 2020. *Gaiters: Exploring Skin Stretch Feedback on Legs for Enhancing Virtual Reality Experiences.* Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3313831.3376865

[27] Tzu-Yun Wei, Hsin-Ruey Tsai, Yu-So Liao, Chieh Tsai, Yi-Shan Chen, Chi Wang, and Bing-Yu Chen. 2020. ElastiLinks: Force Feedback between VR Controllers with Dynamic Points of Application of Force. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '20).* Association for Computing Machinery, New York, NY, USA, 1023–1034. https://doi.org/10.1145/3379337.3415836

[28] Kyle N Winfree, Jamie Gewirtz, Thomas Mather, Jonathan Fiene, and Katherine J Kuchenbecker. 2009. A high fidelity ungrounded torque feedback device: The iTorqU 2.0. In *World Haptics 2009-Third Joint EuroHaptics conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems.* IEEE, 261–266.

[29] Takeshi Yamamoto and Koichi Hirota. 2015. Recognition of weight through shaking interaction. In *2015 IEEE World Haptics Conference (WHC).* IEEE, 451–456.

[30] Humphrey Yang, Tate Johnson, Ke Zhong, Dinesh Patel, Gina Olson, Carmel Majidi, Mohammad Islam, and Lining Yao. 2022. ReCompFig: Designing Dynamically Reconfigurable Kinematic Devices Using Compliant Mechanisms and Tensioning Cables. In *CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22).* Association for Computing Machinery, New York, NY, USA, Article 170, 14 pages. https://doi.org/10.1145/3491102.3502065

[31] Yuan-Syun Ye, Hsin-Yu Chen, and Liwei Chan. 2019. Pull-Ups: Enhancing Suspension Activities in Virtual Reality with Body-Scale Kinesthetic 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, 791–801. https://doi.org/10.1145/3332165.3347874

[32] 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.