ElastImpact: 2.5D Multilevel Instant Impact Using Elasticity on Head-Mounted Displays

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ABSTRACT
Impact is a common effect in both daily life and virtual reality (VR) experiences, *e.g.*, being punched, hit or bumped. Impact force is instantly produced, which is distinct from other force feedback, *e.g.*, push and pull. We propose ElastImpact to provide 2.5D instant impact on a head-mounted display (HMD) for realistic and versatile VR experiences. ElastImpact consists of three impact devices, also called impactors. Each impactor blocks an elastic band with a mechanical brake using a servo motor and extending it using a DC motor to store the impact power. When releasing the brake, it provides impact instantly. Two impactors are affixed on both sides of the head and connected with the HMD to provide the normal direction impact toward the face (*i.e.*, 0.5D in z-axis). The other impactor is connected with a proxy collider in a barrel in front of the HMD and rotated by a DC motor in the tangential plane of the face to provide 2D impact (*i.e.*, xy-plane). By performing a just-noticeable difference (JND) study, we realize users' impact force perception distinguishability on the heads in the normal direction and tangential plane, separately. Based on the results, we combine normal and tangential impact as 2.5D impact, and performed a VR experience study to verify that the proposed 2.5D impact significantly enhances realism.

Author Keywords
Haptic feedback; force feedback; elastic force; impact; virtual reality; wearable device.

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

INTRODUCTION
Force feedback is commonly leveraged to enhance virtual reality (VR) realism in the recent years. Impact is one of the most common effects in VR applications. Impact is produced instantly when punched, hit or bumped. Such force feedback applies not only to users' hands and limbs but also to their heads. To provide vivid and intense impact effects for versatile applications, multilevel impact force on a head in multiple dimensions is required.

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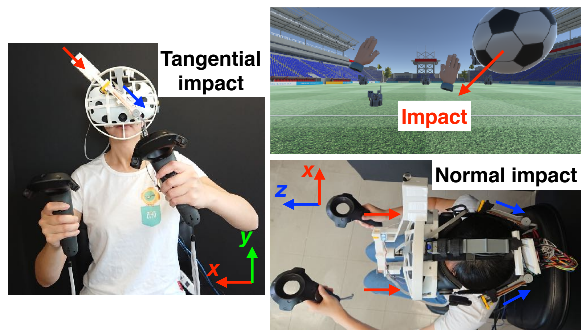

Figure 1. ElastImpact provides 2.5D multilevel impact by combining normal impact (*z*-axis) (right) and tangential impact(*xy*-plane) (left).

Previous researches provide force feedback to users' arms, hands or fingers [2, 3, 7, 8, 15, 17] using motors and propellers to enhance VR realism. They present good force feedback for pushing or pulling body parts, but are not quick enough for instant impact [16]. By jetting an airflow [4], or stimulating muscles using electrical muscle stimulation (EMS) [10, 11], quick impact can be rendered. However, a bulky air compressor or serial calibration steps are required. Using an elastic band and motors on wearable devices, multilevel instant impact in a single direction is provided [16] but on a hand instead of a head. For force feedback on a head, inertia force on a head-mounted display (HMD) is provided when rotating the head using the gyroscopic effect [5]. The effect of a head punched is simulated by producing the hanger reflex phenomenon using balloons [9] and by pushing the face using the HMD and motors [1]. However, these methods are not for instant impact. Instant impact on a head is still not achieved, especially in multidimensional and multilevel.

In this paper, we propose ElastImpact to provide 2.5D multilevel instant impact on a HMD to enhance VR realism (Figure 1). Although 3D force feedback on a head is expected, the force direction from the head to HMD is hard to implement from the HMD. Furthermore, this may result in the HMD departing from the head and affecting VR experience. Therefore, we propose 2.5D impact on a head. ElastImpact consists of three impact devices, also called impactors. Each impactor extends an elastic band using a DC motor and a mechanical brake controlled by a servo motor to store impact power. When the brake releases, multilevel impact is produced. By attaching two impactors on the straps of two sides of the HMD, 0.5D impact in the normal direction from the HMD to head in z-axis is provided. Due to the design of HMD wearing tangential to the head in the xy-plane, producing normal force in x and y axes from a HMD are infeasible. Therefore, we leverage a rotatable impactor connected with a proxy collider and a barrel to produce 2D impact around the HMD in the tangential (xy) plane. We performed a just-noticeable difference (JND) study to understand users' impact force level distinguishability in normal and tangential directions, separately. Based on the results, we combine normal and tangential impact to provide 2.5D multilevel impact. We conducted a VR experience study to compare ElastImpact and the current methods, and prove that impact from ElastImpact significantly enhances realism.

The paper presents the following contributions: (1) Proposing a novel design to combine normal and tangential impact and firstly realize 2.5D impact on a HMD for realistic and versatile VR applications. (2) Observing users' impact force perception on their heads.

RELATED WORK

We discuss previous researches using ungrounded devices to provide force feedback in VR and haptic feedback on the head in VR in this section.

Force Feedback Devices

To provide ungrounded force feedback, SIPDAR-W [13] implements the concept in SPIDAR G&G [12] on a wearable device. It uses motors to pull proxies held by the user's hands to provide force feedback. ExoInterfaces [17] use two DC motors in opposite directions on the upper arm to pull the user's forearm using belts and achieve one degree of freedom (1DoF) movement. Similarly, Motion Guide Sleeve [2] uses two step motors to pull the user's forearm to provide 1DOF rotation, pronation and supination, hints. CLAW [3] uses a servo motor and a force sensor to form a closed-loop feedback system. CLAW pushes or pulls the user's hand depending on the force s/he applies. One the other hand, Thor's Hammer [7] leverages six motors and propellers in the three axes to provide 3D force feedback to push or pull the user's hand. Similar concept is also used in Wind-Blaster [8] and Leviopole [15] to utilize airflow from propellers to push the user's hand and arm. These methods generally provide good pulling or pushing force feedback. However, to provide impact force, which is produced instantly, they are still not quick enough, as mentioned in [16].

To render impact, Jetto [4] leverages an air compressor to produce a jet of airflow to achieve it on smartwatches. Furthermore, Impacto [10] and Virtual Walls [11] utilize EMS to stimulate the user's arms and hands to provide impact. Impacto further combines tactile feedback from a solenoid and force feedback from EMS to enhance impact effect. Although these methods provide instant impact, a bulky air compressor and a serial calibration steps are necessary. ElasticVR [16] provides resistive force and impact to a hand using motors to change elasticity of an elastic band. By extending the elastic band to store impact power in advance, when releasing the band, multilevel instant impact is provided. However, such device provides impact force only in one direction, and ElasticVR applies impact to a hand instead of a head. Base on the design concept of ElasticVR, we further explore how multidimensional impact on the user's head affects VR experiences.

Haptic Feedback on a Head

Although a lot of researches propose haptic feedback methods, only a few works focus on providing haptic feedback on a head. GyroVR [5] quickly spins disks on the HMD to produce gyroscopic effect and further provide inertia force or resistive force when the user intends to rotate or turn the head. HangerOver [9] leverages two balloons pressing the user's head at the same time to produce hanger reflex phenomenon. Therefore, by combining with VR scenarios, HangerOver makes users turn their head when punched or hit. FacePush [1] proposes to push the HMD on the user's face to render feedback as punched in a boxing game. Two motors are on the both sides of the user's head and connected with the HMD. When the motors pull the HMD, the HMD provides push and press feedback on the face. Even if some of these methods intend to render feedback as punched or hit, the feedback they provide is not impact. Therefore, how impact feedback on a head affecting users still needs to be explored.

ELASTIMPACT

We propose ElastImpact to provide 2.5D multilevel impact on a HMD. The impact direction from the head to the HMD is hard to be produced by the HMD. Furthermore, it may cause the HMD to depart from the head and affect users' VR experience, as mentioned in Introduction. Therefore, providing 2.5D instead of 3D impact is the goal in this paper.

Design Considerations

To render 2.5D impact on a HMD, there are some design considerations we need to take into account, as described in the following.

- *Feedback Realism*. For providing realistic impact feedback, gradual force increase provided by a motor is different from instant impact, as proven in [16]. Therefore, quick enough impact is essential. Hence, instead of stretching the HMD straps as in FacePush [1], we referred the design in ElasticVR [16].
- *Mobility*. To allow users to freely move when exploring VR, mobility is important for VR experience. Hence, bulky devices such as large motors or air compressors are improper, but using elastic bands and tiny motors is a better choice.
- *Safety and Comfort*. For intense impact feedback, safety and comfort are still the premises. Therefore, the impact level, proxy collider material (described in the following), device weight and other potential risks such as using EMS are considered. We therefore performed a pilot study to compare proxy collider materials as in the Hardware subsection.

Hardware

ElastImpact includes three impact devices, also called impactors. Each impactor consists of an elastic band, a DC motor, a servo motor and a mechanical brake, as illustrated in Figure 2 (upper left). The brake is made up of a 3D printed

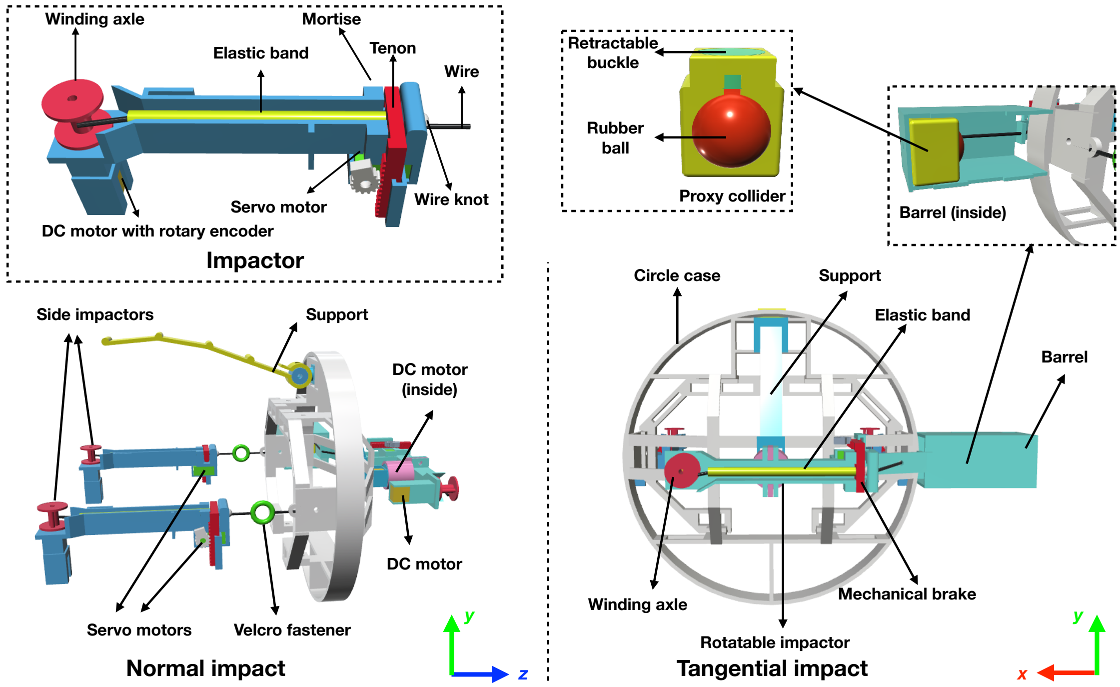

Figure 2. 3D model of the ElastImpact prototype, including two side impactors for normal impact (left) and one rotatable impactor for tangential impact (right). The detailed impactor (upper left) and rotatable impactor (upper right), including a proxy collider and barrel, designs are illustrated.

tenon and mortise. The micro servo motor (XCSOURCE RC450) moves the tenon up and down to release or block elastic band (width 1cm and length 8cm) with a knot on the connected a wire in one side. The other side of the band is extended using the DC motor (Pololu Micro Metal Gearmotor with gear ratio 1000:1) with a winding axle (radius: 6mm) and a rotary encoder (Pololu Magnetic Encoder), as in [16]. By extending the band in different distances, different impact power is stored in the band. When the brake releases the band, multilevel impact force is instantly produced. Two impactors are attached to two sides of the HMD straps to provide impact in the normal direction in z-axis from the HMD to the head. Furthermore, a Velcro fastener is connected between each impactor and the HMD for adjustment (Figure 2 (left)).

For impact in x and y axes, because the HMD is attached to the face by affixing the straps on the head, which is tangential to the head in xy-plane, it provides normal impact in z-axis but is hard to provide normal impact in x and y axes. Therefore, we propose to leverage a *proxy collider* to hit or collide around the HMD and produce impact tangential to the head in xy-plane. To achieve such 2D impact, we 3D printed a circle case for the HMD. The other impactor with a barrel for the proxy collider is then attached to a DC motor (gear ratio 1000:1) with a rotary encoder on the HMD. The DC motor rotates the impactor and barrel in different directions in xy-plane. The rotatable impactor is connected with the proxy collider. Therefore, when the rotatable impactor is actuated, it suddenly pulls the proxy collider to hit the HMD, and the tangential impact force is produced, as shown in Figure 2 (right).

For the proxy collider, we did a pilot study to try two different materials to achieve the design consideration, safety and comfort. The rigid one is made up of PLA and the elastic one has a rubber ball stuck on the surface, as shown in Figure 2 (upper right). We found that the impact from the elastic proxy collider is clearer and more preferred because the rubber ball deforming results in the longer impact time. Therefore, the elastic proxy collider (25g) is used in our prototype in the barrel and connected with the rotatable impactor using a fishing line. To make sure that after the proxy collider hits the HMD, it moves back to the origin position in the barrel, a retractable buckle is used. The retractable buckle is attached to the proxy collider and the retractable wire is affixed on the end of the barrel. Therefore, the wire is pulled out when the proxy collider is jerked to hit the HMD, and is retracted back when the motor in the rotatable impactor loosens the elastic band. The proxy collider is then pulled back to the origin position.

Notably, we tried to affix the rotatable impactor on the HMD in the beginning. However, we found that users perceived the obvious impact effect but hardly distinguished the impact direction in a pilot study. The reason is that when the impact force source and the object that the force applies to are on the same rigid body, the impact force becomes internal force, which makes the HMD shake without direction. To overcome it, a support is built to affix on the HMD strap on the top of the head. The other side of the support passes through the HMD circle case and is connected to the rotatable impactor with the DC motor inside for xy-plane rotation. For the parts of the support contacting with the HMD circle case, a piece of foam is used to absorb the force between them. Furthermore, an

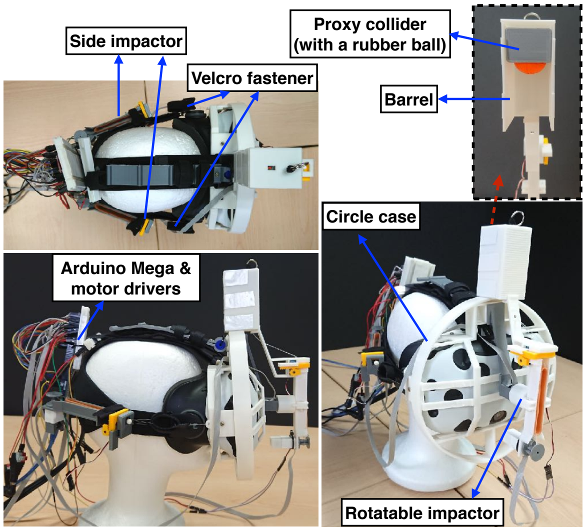

Figure 3. The ElastImpact prototype.

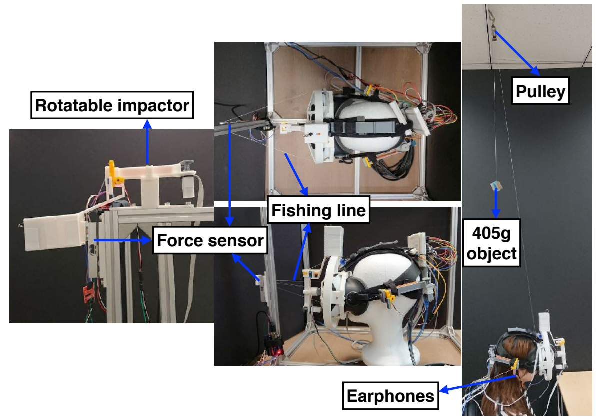

Figure 4. Using a force sensor to measure impact force for JND stimuli in tangential (left) and normal (middle) impact. JND study setup (right).

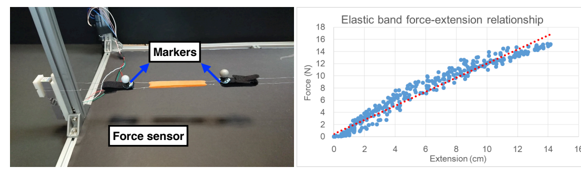

Figure 5. The relationship between the elastic force and the elastic band extension distance (right), which was measured by the force sensor and optical tracker (left).

adjustable design as in a tripod is used to rotate and affix the support on different users' heads.

The four DC motors are controlled by two Dual TB6612FNG motor drivers connected with an Arduino Mega board. The three micro servo motors are controlled by the Mega board connected to a laptop using a USB cable. 12V and 6V power are used for the DC and servo motors, respectively. The weight of the ElastImpact prototype, including three impactors and a HMD, is 960g, which is 405g heavier than the original HMD.

Software

In the beginning, the rotatable impactor stays toward up as the initial position, as shown in Figure 3. The motor rotates it within the revolution number ± 0.5 to provide tangential impact from any direction in xy-plane, which avoids the wires twisted or broken. The mechanical brakes of all three impactors block the elastic bands. The DC motors in the impactors then extend the bands to the corresponding distances. At the same time, the other DC motor rotates the rotatable impactor to the corresponding tangential impact direction. After the these four DC motors all complete the tasks, the three brakes release simultaneously to provide normal and tangential impact. Finally, the three DC motors in the impactors rotate reversely to loosen the elastic bands. We further performed rigorous evaluations for the impact forces from the ElastImpact prototype. This part is described in the following Just-Noticeable Difference (JND) Study section.

JUST-NOTICEABLE DIFFERENCE (JND) STUDY

To observe users' impact force level distinguishability in three axes on the head, respectively, we performed a just-noticeable difference (JND) study.

Apparatus and Participants

ElastImpact as described in the previous section was used to provide the impact force. No visual feedback was shown on the HMD, and brown noise was played on earphones to block motors' audio feedback in the study. Notably, to prevent the additional weight of the ElastImpact prototype affecting the force level distinguishability, we leveraged a pulley system to eliminate the additional weight from the HMD. A pulley was affixed on the ceiling, and a fishing line passed through the pulley. One side of the fishing was attached to the HMD and the other side was tied on a 405g object, consisting of tiny magnets. Therefore, the participants only perceived the HMD weight 555g, same as the original HTC Vive, as shown in Figure 4 (right). 12 participants (6 female) aged 22-31 (mean: 24.83) were recruited.

JND Stimuli

To perform the JND study, we used force sensor to evaluate the impact force stimuli from ElastImpact in different elastic band extension distances in normal and tangential directions, separately. To understand the property of the elastic band used in the ElastImpact prototype, we leveraged an optical tracking system OptiTrack and a force sensor load cell (TAL220 with a HX711 amplifier) to obtain the relationship between the elastic band extension and elastic force. By attaching markers to two sides of the band and affixing one side of the band with the force sensor, the property of elastic band was measured and illustrated as in Figure 5. For normal impact in z-axis, we built an aluminum extrusion frame, and affixed a mannequin head wearing the ElastImpact prototype on the frame. A fishing line was connected between the HMD and the force sensor, which was affixed on another aluminum extrusion bar of the frame. By extending the elastic bands of the side impactors in different distances, different impact levels were measured by the force sensor, as shown in Figure 4 (middle). We found that 3.5N is the maximum impact in the normal direction using those DC motors, and 1.3N impact force can

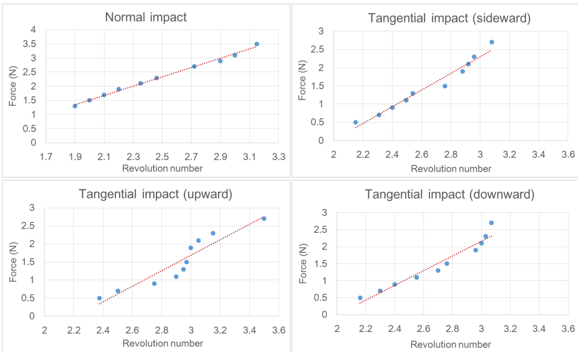

Figure 6. The relationship between impact forces and motor revolution numbers in normal impact and tangential impact (in three directions).

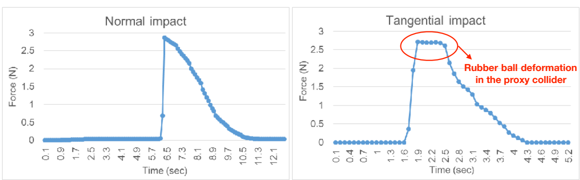

Figure 7. Normal and tangential impact measured by the force sensor. Deformation of the rubber ball in the proxy collider prolonging the impact time is observable (right).

Backward

Offset \ Base	1.3	1.5	1.9	2.7
0	0.29	0.33	0.33	0.42
0.2	0.46	0.38	0.67	0.38
0.4	0.58	0.67	0.79	0.54
0.8	0.96	0.92	0.96	0.67

Upward/downward

Offset \ Base	0.5	0.7	1.1	1.9
0	0.21	0.21	0.38	0.38
0.2	0.38	0.38	0.33	0.58
0.4	0.79	0.79	0.63	0.67
0.8	0.92	0.96	0.96	0.75

Leftward/rightward

Offset \ Base	0.5	0.7	1.1	1.9
0	0.25	0.33	0.42	0.50
0.2	0.42	0.38	0.46	0.42
0.4	0.63	0.63	0.75	0.67
0.8	0.92	0.92	0.92	0.96

Figure 8. JND study results of normal impact (upper) and tangential impact in two axes (lower). Fractions of responses that the pair of stimuli were supposed as unequal were shown.

be clearly perceived by users in a pilot study. Therefore, we repeatedly measured the impact force between 1.3N to 3.5N in different elastic band extension distances (in motor revolution numbers), and averaged them to obtain normal impact stimuli. The relationship between normal impact forces and motor revolution numbers is illustrated in the Figure 6.

For tangential impact, we examined *x* and *y* axes, respectively. Furthermore, due to symmetric perception on each axis, impact from two directions on each axis were randomly tested for the participants. We found that the rotatable impactor produces different impact forces when it is rotated in different angles to the vertical axis. Although the proxy collider is only 25g, the tangential impact force produced by the proxy collider is still slightly affected by the gravity. Therefore, to guarantee that JND stimuli of tangential impact are equal in four directions in *x* and *y* axes, we measured the impact force in three directions, upward, sideward, downward, separately. By affixing the rotatable impactor and force sensor on the aluminum extrusion frame, and rotating the whole aluminum extrusion frame in different directions, we measured the impact force in these three directions, respectively, as shown in Figure 4 (left). The maximum upward impact force is 2.7N, and 0.5N impact was found to be clearly perceived by the participants in a pilot study. Therefore, the JND stimuli of tangential impact levels are between 0.5N to 2.7N. More power is needed to be stored in the elastic band for the upward impact, which means that more motor revolution number is needed. The impact in downward and sideward requires storing similar power in the band, as shown in Figure 6.

Notably, normal impact applies to the user's face and tangential impact applies to the HMD. These two types of impact have different properties and are produced and measured in different approaches. Therefore, we did not examine the same impact levels for normal and tangential impact in the JND study. In addition, we would discuss how to combine normal and tangential impact based on the JND study results to provide 2.5D impact in the following section. Furthermore, we leveraged the abovementioned setting to illustrate the properties of normal and tangential impact, separately, in Figure 7. The deformation of the rubber ball in the proxy collider prolonging the tangential impact time is shown in Figure 7 (right). Although the force stimuli were produced by our prototype, they were measured by the force sensor to obtain the objective quantitative data. Therefore, for other methods producing impact on the head using HMD in the future, they can repeat and generalize the results by applying the same impact force.

Task and Procedure

The participants wore the ElastImpact prototype on the heads to perceive the impact. For each trial, the participants were stimulated by a pair of impact. They then responded that the impact levels of the stimuli were the same or different. If they felt unclear to the stimuli or uncertain to the answer, they could ask the experimenter to play back the stimuli. Each pair of stimuli consisted of *base* and *offset* force intensity (or levels). For the stimuli range examined in the study, the upper bounds were the forces less than the maximum forces from the motors, and the lower bounds were those can be obviously perceived. For normal impact, four base force levels were (0.5N, 0.7N, 1.1N, 1.9N) and offset force levels were (0N, 0.2N, 0.4N, 0.8N). For tangential impact, four base force levels were (1.3N, 1.5N, 1.9N, 2.7N) and offset force levels were (0N, 0.2N, 0.4N, 0.8N). The base and offset force levels increased exponentially, which complied with the JND standard, as in [1, 6, 14, 16]. Impact in three axes were examined, separately. Each participant randomly was assigned only one of two directions in *x* and *y* axes, respectively, for the study. A total of 16 conditions for each axis, respectively. The order of each stimuli pair was randomized, and each condition was repeated once. Therefore, a total of 96 (= 3 (axes) $\times$ 16 (conditions) $\times$ 2 (repetitions)) trials were examined by a participant in the JND study. We asked the participants for some feedback after the experiment. The study took about one and a half hours.

Results and Discussion

The impact JND study results of three axes are shown in Figure 8. The aggregate fractions of responses that the stimuli in each pair were supposed as different impact levels are shown. For normal impact, we observed that the participants clearly distinguished impact levels in offset level 0.8N and base levels 1.3N, 1.5N and 1.9N. However, in base level 2.7N, offset level 0.8N seems not clear enough for most participants to distinguish the difference. This result is loosely consistent with the concept of Weber' law (constant = (offset stimulus intensity) / (base stimulus intensity)) that the larger base level requires the larger offset level to be distinguished. We chose 1.3N as base level and 0.8N as offset level. Therefore, three impact levels 1.3N, 2.1N and 2.9N are for normal impact. The power-storing duration of these normal impact levels are 3460ms, 4330ms and 5330ms, separately.

For tangential impact, the participants achieved about 80% recognition rate at offset level 0.4N and base levels 0.5N and 0.7N in *y*-axis (up/down directions), but these are still not robust enough. At offset level 0.8N and base levels 0.5N, 0.7N and 1.1N, over 90% impact force distinguishability is guaranteed. In *x*-axis (left/right directions), the distinguishability is over 90% at offset level 0.8 N and all base levels. For tangential impact, the common base and offset levels from *x* and *y* axes, that the participants clearly distinguished the differences, should be chosen. However, to provide more intense impact to enhance VR realism, we chose 1.1N as base level and 0.8N as offset level. Therefore, three impact levels 1.1N, 1.9N and 2.7N are for tangential impact. Although the weight of the proxy collider causes that the same power stored in the elastic band produces different impact forces in different directions, as mentioned above, such effect is quit slight, especially between downward and sideward impact. Therefore, we ignored it and used the motor revolution numbers in sideward impact for that in tangential impact in the following VR study. The power-storing duration of these tangential impact levels are 4480ms, 5160ms and 5660ms, respectively.

Most (10 of 12) participants subjectively suppose that normal impact is easier to distinguish than tangential impact. 6 of them mention that larger impact stimuli in the normal impact JND study are more distinguishable. Interestingly, this is opposite to the Weber's law. However, this is consistent with the normal impact result in Figure 8 that the distinguishability of offset levels 0.2N and 0.4N and base level 1.9N are higher than those at base levels 1.3N and 1.5N. Furthermore, some participants comment that the normal impact was directly produced from the HMD, so it was clearer to distinguish than the tangential impact indirectly from the proxy collider to the HMD. A few participants mention that normal impact sometimes seemed not from the HMD to the head, but from the both sides of the side impactors or even without clear direction. This may result from the reacting force of the side impactors, which makes the strap press to the head. To alleviate such side effect, we combined the visual feedback in the VR study.

For tangential impact, there is no consensus that impact in *x* or *y* axis is easier to distinguish. However, in the upward impact condition, some participants comment that they felt downward impact or even impact from the HMD to the head. To further investigate the phenomenon, we performed a pilot study and found that such effect also exists when using a grounded device to produce upward impact to the HMD. We realize that such effect results from the HMD wearing design, which consists of a strap above and two straps on the both sides of the head. Due to no strap below the head, when upward impact happens, users do not feel that the HMD moves up. However, while the HMD moves down to the original position, they feel downward impact instead. This is the potential limit due to the current HMD wearing design. We reduced the effect by combining visual feedback in the VR experience study.

Figure 9. The boxing game (upper) and goalkeeping game (lower) VR scenes in the VR experience study.

To provide 2.5D impact, we need to further combine normal and tangential impact. The impact forces in the current normal and tangential impact levels are similar but still different. Furthermore, normal and tangential impact are produced and measured in different approaches, as mentioned above. Therefore, we have to normalize the impact levels based on their own base and offset levels, separately, to produce combined 2.5D impact. For example, to provide level 1 impact from lower front to upper rear, 45 degrees to the vertical, normal and tangential impact need to provide level 1 impact forces, 1.3N and 1.1N, separately. We verified the performance of such combination in the following VR experience study.

VR EXPERIENCE STUDY

To observe how the impact from ElastImpact affects users in VR interactions, and compared with other methods, whether the impact from ElastImpact enhances VR realism, we performed this VR experience study.

Apparatus and Participants

The ElastImpact prototype was used in this study. There was no pulley system used. The Arduino Mega board and the breadboard with the motor drivers were attached to the back strap of the HMD. Although these might increase the HMD weight, they balanced the torque from the weight of the ElastImpact prototype in the front of the HMD. Earphones were worn to block the motors' noise. We built two VR scenes for the VR experience study using Unity3D and SteamVR SDK for Vive.

Two vive controllers were held in the study. 12 participants (4 female) aged 21-27 (mean: 24) were recruited. Three participants had attended to the JND study but more than one week elapsed between the two studies.

Task and Procedure

Two VR applications, boxing and goalkeeping games, were experienced in this study. For the boxing game, a virtual boxer threw three types of punches, a jab, a hook and an uppercut. A jab is a quick but light punch normal to the face. Therefore, normal impact in level 2 and tangential impact in level 1, level (n2, t1), was provided by ElastImpact. A hook is a heavy punch to the side of the head. Therefore, level (n1, t3) was rendered. An uppercut is also a heavy punch but to the jaw, so level (n2, t3) was provided. To provide tangential impact in the corresponding directions, the motor rotated the rotatable impactor in left/right directions for left/right jabs and hooks, and in lower left/right directions for left/right uppercuts. The punch types were presented in random order and in random hands of the virtual boxer. The participants could also punch the boxer using the controllers. After the three types were all experienced by the participants, they could punched and knocked out the virtual boxer.

For the goalkeeping game, five cannons in different positions and directions, left, down, middle, up, right, ejected balls to the participants, as shown in Figure 9. The left, middle and right cannons ejected soccer balls in the faster, normal and slower speeds, respectively, which were provided by ElastImpact in levels (n2, t3), (n3) and (n1, t2) in three directions, respectively. No tangential impact was provided when the middle cannon ejected. The down cannon ejected a beach ball in a slower speed, which was provided by ElastImpact in level (n1, t1) with the tangential impact from the lower left direction. The up cannon ejected a basketball in a normal speed, which was provided by ElastImpact in level (n3, t3) with the tangential impact from the upper right direction. The ball ejection order was randomized. Although the participants could use the controllers to wave virtual hands blocking the balls. However, to guarantee that all participants experienced all impact, we disabled the colliders of the hands in Unity during the experiment. After experiencing impact by five balls, the participants finished the goalkeeping game.

In this study, impact from three force feedback methods were examined and compared, including 1D push (P), 1D impact (I) and 2.5D ElastImpact (E). All three methods were implemented using the ElastImpact prototype. In 1D push, instead of storing power in the elastic bands in advance, the motors in the side impactors directly pulling the HMD made the HMD push the face in normal direction as in [1]. In 1D impact, the tangential impact from ElastImpact was disabled, so only normal impact was provided. In 2.5D ElastImpact, the complete 2.5D impact from ElastImpact was rendered. We compared (P) with (I) to observe how push and impact feedback affected users' VR experience, and compared (I) and (E) to understand whether combining tangential and normal impact further enhanced VR realism. Although these methods were all rendered from our prototype and the device weight might affect the experiences, it guaranteed that the study was under the

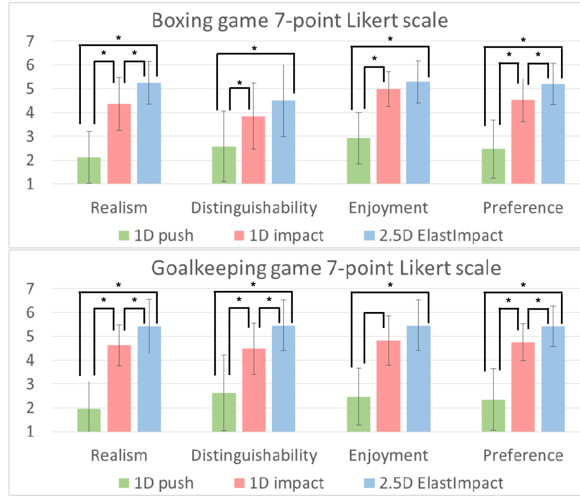

Figure 10. Subjective results of VR experience study in 7 Likert-scale.

same condition with the same device weight. Furthermore, [1] proves that 1D push outperforms visual feedback (no haptic stimulus) in realism, and [11, 16] observe that vibration feedback interferes realism in VR. Therefore, although we did not reproduce the device in [1], we followed the design concept to render 1D push, and further investigated advanced factors. A total of 6 (= 2 (VR applications) × 3 (force feedback methods)) conditions were experienced. The VR applications were experienced in the order, the boxing game and then the goalkeeping game. The three force feedback methods were counterbalanced. After the experiment, the participants gave scores on a questionnaire in 7-point Likert scale, allowing decimal scores. The experimenter then interviewed them for some open-ended feedback. The study took about half an hour.

Results and Discussion

The subjective scores of the questionnaire in 7-point Likert scale are shown in Figure 10. We leveraged repeated measures ANOVA for significant differences analyses and Bonferroni correction for post-hoc pairwise tests. We did not try to compare between the two VR applications, but focused on the effects among the three force feedback methods.

For the boxing game, significant main effects are found in all factors, realism ($F_{2,22} = 56.59, p < 0.01$), distinguishability ($F_{1.26,13.84} = 9.63, p < 0.01$), enjoyment ($F_{2,22} = 38.07, p < 0.01$) and preference ($F_{2,22} = 33.71, p < 0.01$). Post-hoc pairwise tests reveal that significant differences are among all pairs in realism and preference, and between (P, I) and (P, E) pairs in distinguishability and enjoyment. Therefore, 2.5D impact is significantly more realistic and preferred than 1D impact and 1D push. Although 2.5D impact and 1D impact have similar distinguishability and enjoyment levels, it is still significantly more distinguishable and enjoyable than 1D push. Furthermore, 1D impact is significantly better than 1D push in all factors. For the goalkeeping game, significant main effects are found in all factors, realism ($F_{1.31,14.31} = 98.16, p < 0.01$), distinguishability ($F_{1.19,13.1} = 24.79, p < 0.01$), enjoyment ($F_{2,22} = 50.42, p < 0.01$) and preference ($F_{1.29,14.24} = 69.48, p < 0.01$). Post-hoc pairwise tests show that significant differences are among all pairs in all factors, except between(I, E) in enjoyment. Thus, 2.5D impact is significantly more realistic, distinguishable and preferred than 1D impact and 1D push. Even if 2.5D impact and 1D impact have similar enjoyment level, 2.5D impact is still more significantly enjoyable than 1D push. In addition, 1D impact is significantly better than 1D push in all factors.

For both games, all participants mention that (P) gradually increasing force by pushing the HMD is not realistic enough for impact feedback. This comment and the statistical analysis result verify that instant impact on HMD is more realistic than push on HMD due to its delay, which is consistent with the results in [16]. Such reason also affects the enjoyment and preference for VR impact effects. Although larger motors with faster speeds and similar torque may reduce the delay, they may greatly increase the HMD weight, which is not proper for a head wearing device. Interestingly, even though (P) has the lowest distinguishability, *P11* supposes that 1D push with longer force increase periods made him more clearly distinguish the force levels. Therefore, he gave higher scores for distinguishability in (P) in both games. However, 1D push with single force direction still gets lower distinguishability scores from most participants. Based on the results, we suppose that 1D push in (P) may be good feedback for other VR scenarios, but it is improper to be used as haptic feedback for VR impact effects, *e.g.*, in boxing and goalkeeping games.

Comparing between (I) and (E), most participants comment that 2.5D impact from (E) with multiple directions is more realistic. Although five participants suppose that tangential impact is not obvious enough, two of them still believe that combining tangential impact in (E) more or less enhances realism compared with (I). Interestingly, five participants also mention that except the multiple directions, (E) providing stronger impact force by combining both normal and tangential impact, enhances realism, which is consistent with the result in [1]. Furthermore, *P1* and *P9* commonly mention that they felt the whole HMD shaking in (E), which reinforces the impact effect. Especially, when the basketball hit the head in the goalkeeping game, *P9* supposes that strong impact from (E) completely simulated the effect of hit by a heavy basketball. A few participants mention that sometimes the visual feedback direction and impact direction in (E) were not thoroughly matching. However, they also comment that such minor differences were hard to notice especially when experiencing VR. Therefore, they still suppose that (E) enhanced VR realism, which is consistent with the concept in [5] that not necessarily realistic but comprehensible force feedback enhances realism. This also supports that we did not render strong impact as a real punch for a perfect match due to safety, but enhanced realism with safe and proper impact.

Generally, the participants suppose that feedback from impact is significantly better than that from push in all aspects. 2.5D impact further enhances and diversifies the impact effects in VR. Therefore, the study proves that 2.5D impact from ElastiImpact indeed enhances VR experience.

LIMITATIONS AND FUTURE WORK

There are still some limitations in the current ElastImpact prototype needed to be solved in the future. The current prototype provides normal impact only in one direction in z-axis. We envision that by further improving the HMD design, it is possible to render normal impact also in xy-plane. Due to the current HMD wearing design, users are hard to perceive upward impact, but falsely distinguish such impact as downward impact. It may be improved by adding a strap wearing on the user's chin in the future. The current prototype weight is still a little bit heavy for users because we 3D printed the extra circle case for the HMD. Therefore, if the current prototype is built in the HMD in manufacture, many support parts for affixing may be reduced to lighten and downsize the device. Using a flexible shaft may further reduce the torque on the HMD. ElastImpact rotates the rotatable impactor within a half revolution in clockwise and counterclockwise. This limit may be eliminated by using a rotary connector in the future.

CONCLUSION

We propose ElastImpact on HMD to provide 2.5D multilevel impact to enhance VR experiences. Two side impactors provide normal impact in z-axis from the HMD to the head. A rotatable impactor with a proxy collider and a barrel is rotated in xy-plane to provide tangential impact. Combining the normal impact (0.5D) and tangential impact (2D), ElastImpact provides 2.5D impact. We performed a JND study to understand that 3 levels are distinguishable in normal impact (1.3N, 2.1N, 2.9N) and tangential impact (1.1N, 1.9N, 2.7N), respectively. We further combined the two types of impact and performed a VR experience study to verify that compared with 1D push and 1D impact, 2.5D impact from ElastImpact significantly enhances VR experiences.

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