國立政治大學資訊科學系

碩士學位論文

衝擊力背心：
透過身上多程度多維度之衝擊力陣列回饋提升提升虛擬實境之互動

ImpactVest:
Rendering Spatio-Temporal Multilevel Impact Force Feedback on Body in VR

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衝擊力背心：

透過身上多程度多維度之衝擊力陣列回饋提升提升虛擬實境之互動

摘要

過去的研究已提出在使用者的手、四肢和頭上產生瞬間且強烈的衝擊力回饋來強化虛擬實境的真實感，但在身體上的衝擊力仍鮮少被討論。身體有著很大的表面積，因此可以在多種虛擬實境應用中呈現更多衝擊力型態，例如：在虛擬實境遊戲中身體被受到射擊、爆炸、拳擊、砍擊。我們提出一個原型能夠呈現在身上的多程度多維度之衝擊力陣列。透過獨立控制在 3×3 陣列的 9 個彈力衝擊器產生在不同強度、位置和時間順序的空間時間組合。我們做了一個最小可覺差實驗來了解使用者在身體上對衝擊力強度的分辨度。以及時間間隔閾值實驗探討兩個衝擊力刺激之間多少的時間間隔作為分辨連續、同時、分散的衝擊力。基於以上實驗結果，我們製作了虛擬實境實驗來驗證我們的原型產生的衝擊力回饋能夠強化虛擬實境的真實度。

關鍵字：衝擊力、力回饋、觸覺回饋、虛擬實境、穿戴式裝置

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ImpactVest:
Rendering Spatio-Temporal Multilevel Impact Force Feedback on Body in VR

ABSTRACT

Rendering instant and intense impact feedback on users' hands, limbs and head to enhance realism in virtual reality (VR) has been proposed in previous works, but impact on body is still less discussed. With a large surface area on body, more impact patterns can be rendered in versatile VR applications, e.g., being shot, blasted, punched or slashed on body in VR games. We propose ImpactVest to render spatio-temporal multilevel impact force feedback on body. By independently controlling nine impactors in a 3×3 layout using elastic force, impact is generated at different levels, positions and time sequences for versatile spatial and temporal combinations. We conducted a just-noticeable difference (JND) study to realize users' impact level distinguishability on body. A time interval threshold study was then performed to understand what time interval thresholds between two impact stimuli are used to distinguish among simultaneous impact, a continuous impact stroke and two discrete impact stimuli. Base on the results, we conducted a VR experience study to verify that impact feedback from ImpactVest enhances VR realism.

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Keywords : Impact, force feedback, haptic feedback, virtual reality, wearable device

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CHAPTER 1

Introduction

Leveraging haptic feedback to enhance virtual reality (VR) realism is widely investigated in recent years. Impact is a common effect in VR, such as being shot by a gun or blasted by a grenade in VR shooting games, or being punched, hit or even slashed in VR fighting games. Such impact force not only applies to users' head, hands and limbs, but also to their body or more precisely torso. Unlike the other body parts, a torso has a larger plane and surface area. By arranging several haptic actuators or impactors on body, users can perceive impact not only at different levels but also with different spatial and temporal combinations or even a continuous impact stroke as slashed by a sword, which enhances VR versatility. Therefore, providing impact on body in VR is required.

Previous works leverage vibrotactile actuation, pneumatic actuation, motor pulling and propeller pulling [1, 3, 4, 9, 10, 13, 16, 18, 26, 34] to render various haptic feedback including impact. Although they generate or simulate good haptic or force feedback, such feedback is still different from rapid and intense impact force, as proven in [20, 33]. To render impact force feedback, electrical muscle stimulation (EMS), airflow jetting and elastic force are used [6, 19, 31, 33, 35] to produce impact on users'

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head, hands and limbs. These methods indeed provide users with realistic impact feedback, but do not focus on impact on body or torso. On the other hand, with a large surface area on body or torso, current methods [3, 4, 10, 11, 13, 18] explore spatio-temporal haptic feedback patterns using vibrotactile and pneumatic actuation. However, although these methods provide good feedback for clear haptic strokes or notifications, the limitations of the actuators prevent them from rendering strong force instantly for realistic impact feedback. Therefore, how realistic impact feedback with spatio-temporal patterns on body affecting uses' VR experiences is still unexplored.

We propose a wearable device, ImpactVest, to render spatio-temporal multilevel impact force feedback on body to enhance users' VR experiences. ImpactVest consists of a 3×3 array of impactors. Each impactor extends an elastic band using a motor and blocks it using a mechanical brake to store impact power. When the brake releases, a rubber ball attached to the band hits the user's body and generates instant impact. By producing impact at different positions, time sequences and levels from the impactors, ImpactVest renders spatio-temporal multilevel impact on body (Figure 1). We conducted a just-noticeable difference (JND) study to understand users' impact force level distinguishability on body. Furthermore, to provide spatio-temporal impact and even achieve a continuous impact stroke, we conducted a time interval threshold study to realize the time interval thresholds between two impact stimuli that users suppose impact feedback as simultaneous impact, a continuous impact stroke or two discrete impact stimuli. Based on the results, we performed a VR experience study to observe how spatio-temporal multilevel impact affects users' VR experiences, and verify whether impact feedback from Impactvest enhances realism in VR applications.

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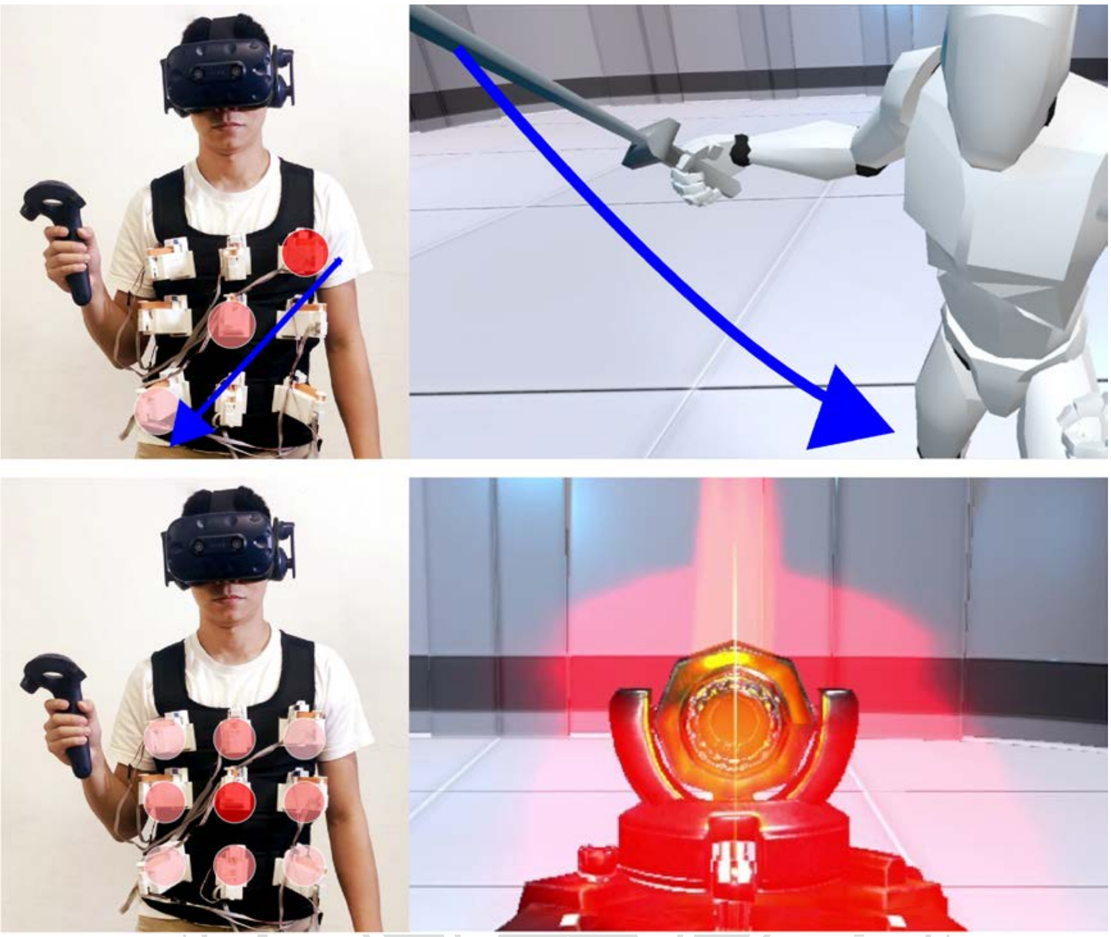

Figure 1. ImpactVest provides spatio-temporal multilevel impact force feedback on body using a 3×3 array of impactors. As being slashed, three impactors sequentially render impact from stronger to weaker (upper). As being blasted, impactors provide stronger impact closer to the center (lower).

CHAPTER 2

Related Work

2.1 Devices Rendering Force Feedback

To simulate force feedback in VR, previous researches [4, 10, 13, 18] leverage vibrotactile feedback to generate illusions of force feedback. Force Jacket [3] independently controls the air pressure of 26 airbags in the jacket using an air compressor to compress the users' body and arms to render the various force feedback. Motor pulling/pushing is a common method to generate force feedback implemented in both grounded [21] and ungrounded [22] force devices. Based on the concept, ExoInterfaces [34] and GuideBand [30] use motors pull belts and fishing lines to render force feedback on the forearm. CLAW [2] and PaCaPa [28] use motors to push the hand to render force feedback on controllers. FacePush [1] further uses two motors to make the HMD push on the face. With the development of drones, propeller thrusting is an alternative for force feedback. Pull-Ups [36] contracts pneumatic artificial muscles (PAMs) to pull users hands and even body to simulate impact feedback. Thor's Hammer [9] equips six propellers to generate 3D force feedback on a controller. Similarly, LevioPole [26], Wind-Blaster [16] and Aero-Plane [15] utilize propellers on a pole, worn on a wrist and two sides of a controller to provide force feedback, respectively. These methods perform well for general force feedback. However, since

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impact is intense force feedback, it is quite different from vibrotactile feedback, as proven in [20, 33]. Furthermore, impact occurring instantly is different from force feedback with gradual force increase from motor pulling/pushing and propeller thrusting, as mentioned in [31, 33].

To render instant impact, Jetto [6] emits a lateral air jet to suddenly move and shake the smartwatch in 2D direction. Impacto [19] and Virtual Wall [20] use electrical muscle stimulation (EMS) to stimulate users' hands, arms, and legs to render impact feedback. Impacto further combines EMS and a solenoid to render tactile and force feedback of impact. Tsai et al. propose a series of works [31–33, 35] to exploit the elastic force by extending rubber bands to store impact power and provide instant impact on users' finger, hand and head or between hands. These methods indeed achieve instant impact, but they do not focus on impact feedback on body with spatio-temporal impact patterns.

2.2 On Body Haptic Feedback

Vibrotactile feedback is a very common and simple way to render haptic feedback on body. Slashed [24] attaches several vibration speakers to a belt to provide vibrotactile feedback when being slashed and pierced in VR. Israr and Poupyrev propose a series of works to leverage a 3×4 array of vibration motors on the back to explore how the effect of haptic blur creates illusion of continuous motion [11], investigate stimulus onset asynchrony (SOA) space in apparent tactile motion for continuous moving sensations [12], and explore how to combine apparent tactile motion and phantom tactile sensation in the Tactile Brush algorithm [13]. Furthermore,

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Feel Effects [14] explores the mapping between linguistic phrases and vibrotactile patterns. Choi et al. use vibrotactile actuators on chairs to substitute motion effects for 4D experiences [27] and provide seamless phantom sensation [37]. They also utilize two voice coils on front and back of the vest, respectively, to render penetrating phantom sensations on body [17].

Besides vibrotactile feedback, a commercial product, Teslasuit [29], provides full body tactile feedback using electro- stimulation. Another product, PHANTOMSENSE [5], provides pneumatic haptic feedback on the torso. Force Jacket[3] uses pneumatic actuators to provide force and vibration feedback on body as mentioned above. [23] leverages shape memory alloy (SMA) to control a pin press on the torso on the vest. Therminator [7] uses flowing warm and cold liquid in tubes on abdomen to render thermal feedback. These researches has investigated spatio-temporal haptic patterns on body, especially in vibrotactile feedback, and render good feedback for haptic strokes or as being hugged, slithered or crawled. However, these actuators cannot instantly generate strong force feedback, so the feedback from these methods are different from intense and instant impact feedback. Therefore, how spatio-temporal impact patterns on body affect users' VR experiences still needs to be explored.

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CHAPTER 3

ImpactVest

We propose ImpactVest to provide spatio-temporal multilevel impact force feedback on body. By providing multilevel impact at different positions on body, various spatial impact patterns are rendered. By generating multilevel impact at different time sequences, various temporal impact patterns are achieved. By combining the both factors, ImpactVest provides realistic and versatile impact feedback to enhance users' VR experiences.

3.1 Design Considerations

To achieve the goal, the following design considerations need to be taken into account.

•*Realism.* To render realistic impact feedback, the force increase should be rapid enough, as proven in [33]. Therefore, instead of using motor pulling/pushing or propeller thrusting, we modified and improved the design in [31] using elastic force to render instant impact.

•*Versatility.* ImpactVest presents spatio-temporal multilevel impact feedback and even a continuous impact stroke for versatile VR applications. To achieve these,

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impactors on body must be controlled independently to generate impact at different levels, positions and time sequences. Furthermore, a study should be conducted to understand what time interval thresholds between two impact stimuli make the users feel impact feedback as simultaneous impact, a continuous impact stroke or two discrete impact stimuli.

•*Comfort and Safety.* Impact is intense force feedback. Although stronger impact force feedback could achieve more exciting or even realistic VR experiences, comfort and safety are still the premises. Therefore, a pilot study was conducted to guarantee that the strongest impact feedback provided by ImpactVest does not make the users uncomfortable or even hurt the users. Furthermore, where the nine impact stimuli apply to on body should be carefully chosen to achieve comfort and safety.

•*Mobility.* A major utility of wearable devices is allowing the users to freely move and explore in VR. Therefore, ImpactVest should not be too heavy or bulky to hinder the users' movement.

3.2 Implementation

ImpactVest consists of nine impact devices, also called impactors, in a 3×3 layout on a vest. Each impactor comprises an elastic band, motors, a mechanical brake, a barrel and an impact proxy, as shown in Figure 2. The mechanical brake is made up of a tenon and a mortise. The tenon is controlled by a servo motor (XCSOURCE RC450) to move up and down to release and block one side of the elastic band (width 1cm and length

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8cm) with a knot connected to a wire. The wire is further connected to an impact proxy in a barrel. The other side of the band is connected to another wire further tied on a winding axle (radius: 3.5mm) affixed to a DC motor (Pololu Micro Metal Gearmotor with gear ratio 1000:1) with a rotary encoder (Pololu Magnetic Encoder 12 counts per revolution). When the brake blocks the band using the servo motor, by extending the elastic band using the DC motor in different distances, different impact power is stored in the band. When the brakes releases the band, the band jerks the impact proxy to hit the body around the muzzle of the barrel to render impact feedback. The DC motor then loosens the band back to the origin position. The design concept is modified and improved from ElastImpact [31].

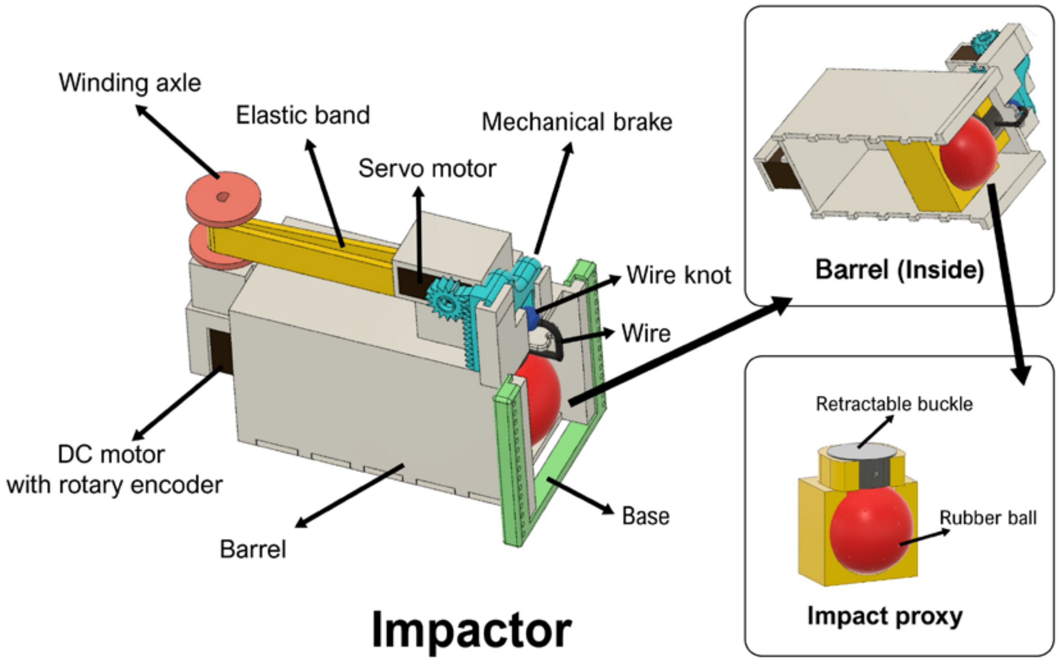

Figure 2. The hardware structure of an impactor of the ImpactVest prototype, including a barrel and an impact proxy.

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The impact proxy consists of a rubber ball and a retractable buckle. Based on [31], the rubber ball is chosen to hit the body since its deformation extends the impact time and provides better impact experiences. The retractable wire is affixed on the end of the barrel to move the impact proxy back to the origin position after it hits the body and the DC motor loosens the band. The length of the barrel is decided in a pilot study which is long enough (about 82mm) to make the impact proxy accelerate to a sufficient velocity for intense impact. Furthermore, to attach the impactors to the vest, a base with tracks is sewed on the vest for each impactor to allow the muzzle of the barrel affixed on the base. Therefore, an impactor can be easily attached to and detached from the vest. A total of nine bases are sewed on the vest in a 3×3 layout.

We conducted a pilot study to decide the nine positions of the impactors although certainly the middle column of the impactors is on the central line of the body. The positions should not either hurt the users to achieve comfort and safety, or make the users difficult to perceive impact since the impactors are not tightly attached to the uneven body parts. Based on the results, the height of the first row of the impactors is on the upper part of the pectoralis major muscles on the chest. This not only prevents the middle impactor in the first row in the concave between the pectoralis major muscles but also prevents the positions of the impactors easily affected by the body structure differences between males and females. For the second row, the middle impactor position should be around the end of the sternum, also called

breastbone. If its position becomes lower, the impact feedback is rendered on the concave or gap between pectoralis major muscles and abdominal muscles, not covered by the sternum and ribs, which makes the users uncomfortable. At this height, the other

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impactors of the second row provide impact on ribs, which are clearly perceived and do not cause uncomfortable. To maintain the same distance between adjacent rows, the height of the third row is decided by the first two rows, which is on the abdomen (Figure 3).

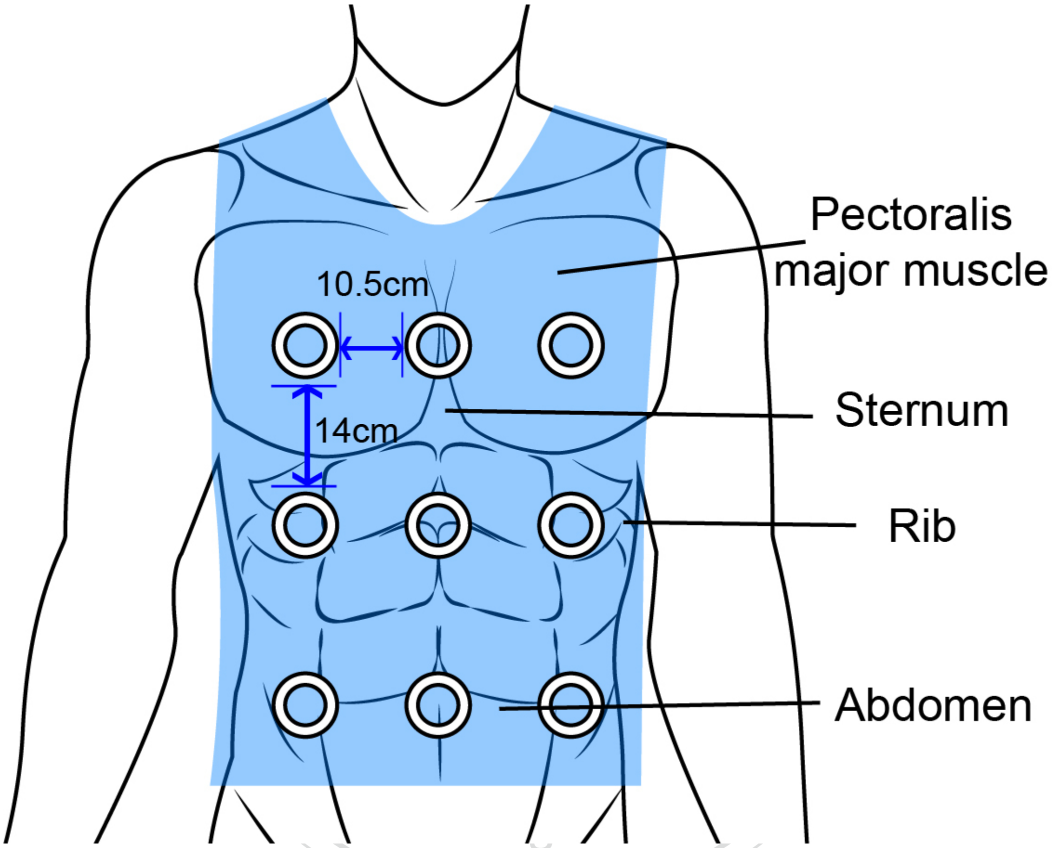

Figure 3. The proper positions of the impactors on body.

To manufacture a free size ImpactVest, we conducted another pilot study to ask users with different heights and genders to attach stickers on the vest to represent the positions of the impactors based on the abovementioned rules. The results show that the distances 14cm between rows and 10.5cm between columns are proper for most users. Furthermore, to allow users to clearly perceive impact feedback, the vest should

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contact with the body as tightly as possible. Therefore, besides sewing three Velcro straps on the vest at the heights of the three rows to fasten the vest, other three Velcro straps are fastened on the body to make the inside of the vest stick on the straps and body.

The vest with bases is 345g and the weight of each impactor is only 93g, which is even lighter than the solenoids providing weaker force. Therefore, the weight of ImpactVest with nine impactors is 1182g (Figure 4). The weight is distributed over the ImpactVest and supported by the body or torso, which does not make users feel heavy. The nine DC motor are connected to five Dual TB6612FNG motor drivers, which are further controlled by two Arduino Mega boards. One of the two signal wires of each rotary encoders is connected to an interrupt pin on the boards to maintain the motor precision. 6V external power is used for the servo motors, and 12V external power is used to supply to the DC motors. About the delay of impact, we describe in the following section when the distinguishable impact levels are chosen.

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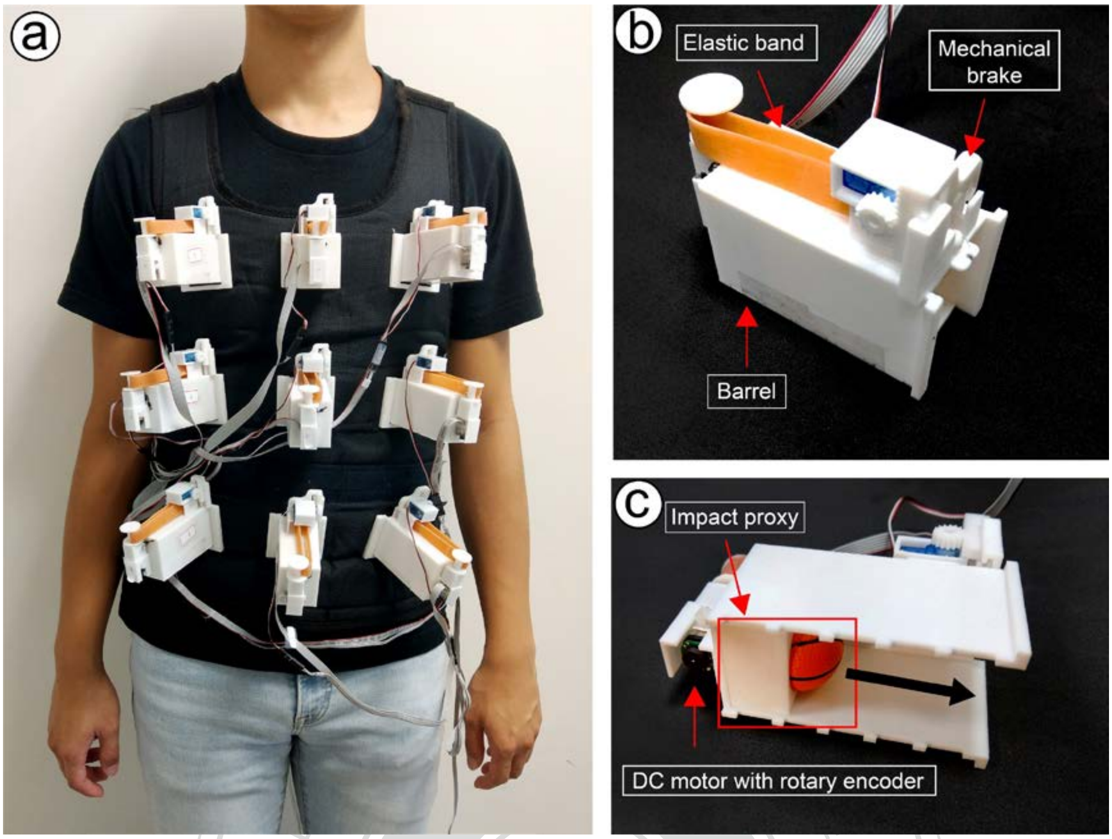

Figure 4. The ImpactVest prototype (a), an impactor (b), and the impact proxy in the impactor (c).

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CHAPTER 4

JUST-NOTICEABLE DIFFERENCE (JND) STUDY - FORCE

ImpactVest are able to provide multilevel impact force feedback on body. We have to understand how many different impact force levels users can distinguish. Therefore, a just-noticeable difference study (JND) using the method of constant stimuli [8, 25, 36] was conducted. The same impact in different positions may be perceived and distinguished differently due to different perception in different body parts, e.g., chest, rib, and abdomen. Furthermore, since the front side of body is not a flat plane, the impactors may contact with body parts in different tightness although we alleviate the differences in choosing impactor positions as mentioned above. This phenomenon is not only between genders or individuals but also within the same user. Therefore, to obtain a general result of impact force level distingiushability on body, we performed a pilot study to find the most and the least sensitive positions of the nine impactors from both genders.

The results show that the most sensitive position is on the upper part of the pectoralis major muscles, which are the positions of the left/right impactors in the first row. The least sensitive position is the position of the middle impactor in the first row due to still on a concave between the upper part of the pectoralis major muscles. By

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performing the JND study in these positions, respectively, we obtained the impact force level distinguishability on body in both best and worst cases. The best case shows the impact level distinguishability on body not interfered by the contact issue. On the other hand, if the impact level difference is larger than that in the worst case, it can be differentiated by all body parts. Although perception in various positions of a body surface could be different, current methods [10, 11, 13] still generally choose uniform discernible intensity of stimuli on body. The worst case results can be used to obtain the uniform impact levels for ImpactVest.

4.1 Apparatus and Participants

ImpactVest was worn by the participants. Only one impactor in the current examining position was quipped in this study. An eye mask was worn to block the visual feedback. To prevent the noise from the motors, white noise was played on noise-cancelling earbuds. 12 participants (6 females) aged 21-31 (mean: 24.58) with mean height 165.92cm (SD: 6.83cm) were recruited.

4.2 Force Stimuli

To perform the JND study, the stimuli intensity which means the force magnitude should be quantified. We built an aluminum extrusion frame and affixed an impactor and a force sensor (TAL220 with a HX711 amplifier) to measure the impact force (Figure 5 (a)(b)). By extending the elastic band in different distances using different

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motor revolution numbers, the relationship between impact force magnitude and the motor revolution number was obtained. By repeatedly measuring and averaging the force magnitude, the relationship is shown in Figure 5 (c). We found that the maximum impact force the motor can provide was 3.7N in 2.73 revolutions, which was not too strong to cause users uncomfortable. The minimum impact force in this study should be clearly perceived by most users, so 0.4N in 2 revolutions was chosen from a pilot study. Therefore, the force stimuli for the JND study were between the lower bound 0.4N and upper bound 3.7N.

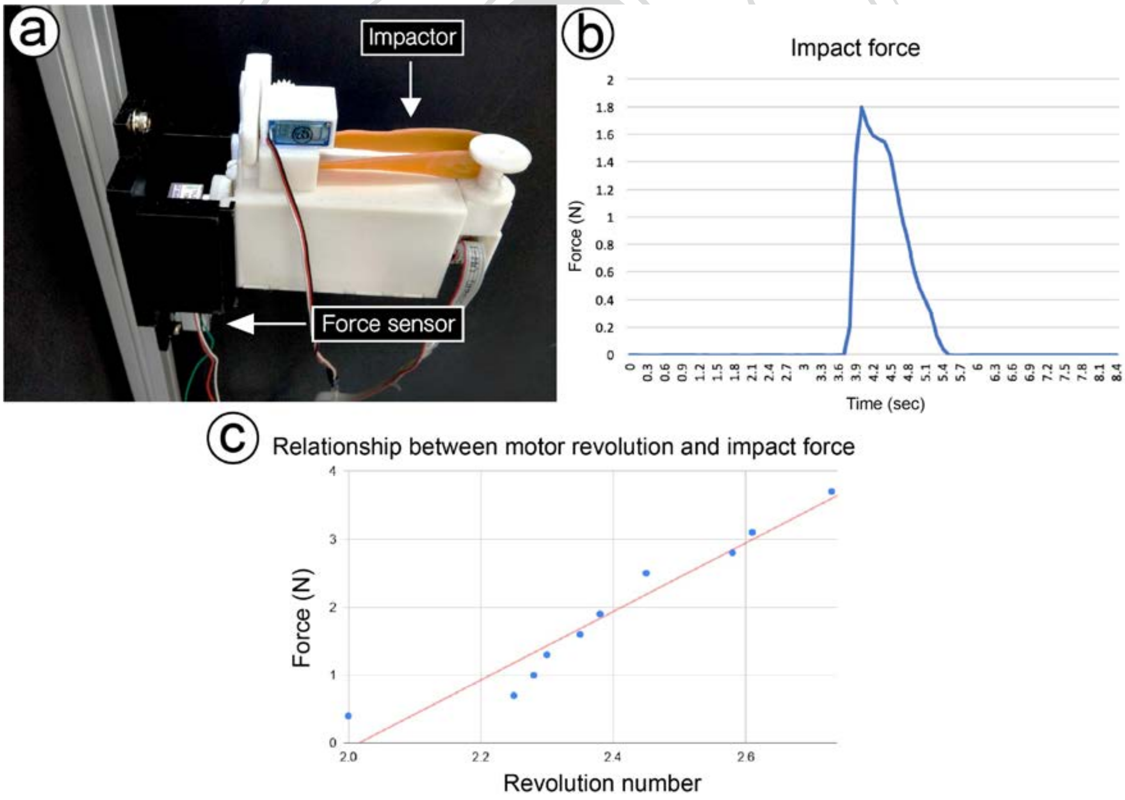

Figure 5. The setup to measure the impact force (a), the impact force measured by the force sensor (b), the relationship between the motor revolution number and impact force (c).

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4.3 Task and Procedure

The participants wore ImpactVest and perceived the impact force stimuli when standing. A pair of impact force stimuli were rendered in a trial. They were asked to respond whether the force levels of the stimuli were same or not. They could ask to play back the stimuli if they were not sure about the answer. Each pair of stimuli consisted of base and offset force intensities (or force levels). To guarantee that the impact stimuli within the upper and lower bounds, four base levels (0.4N 0.7N, 1.3N, 2.5N) and four offset levels (0N, 0.3N, 0.6N, 1.2N) were chosen. The base and offset force levels increased exponentially, which complied with the JND standard [1, 8, 25, 31]. A total of 16 conditions were examined in each position. The order of a pair of stimuli was randomized, and each condition was repeated once. Two positions, including left/right and middle impactors in the first row, were examined, respectively. Therefore, a total of 64 (= 2 (positions) × 16 (conditions) × 2 (repetitions)) were examined by each participant. The conditions were randomized, and positions were counterbalanced. For the position of the left/right impactors in the first row, half participants perceived impact in the left position, and the others perceived it in the right position. We interviewed the participants after the experiment. The study took about an hour.

4.4 Results and Discussion

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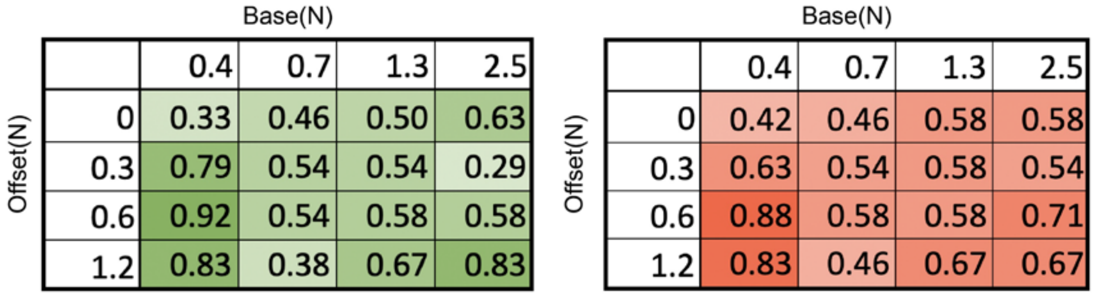
The results of the JND study in each position are shown in Figure 6. The aggregate fractions of responses that the force stimuli in each pair were answered as different impact force levels are shown. For the position of the left/right impactors of the first row (best case), at base level 0.4N, offset level 0.3N achieves almost 80% distinguishability and offset levels 0.6N and 1.2N reach over 80% distinguishability. At base level 2.5N, offset 1.2N also obtains distinguishability over 80%. For the position of the middle impactor of the first row (worst case), at base level 0.4N, offset levels 0.6N and 1.2N achieve the distinguishability over 80%. However, at other base levels, the examining offset levels seem not large enough to be distinguished. The results are loosely consistent with the concept of Weber's law (constant = (offset stimulus intensity) / (base stimulus intensity)) that the larger base levels require the larger offset levels to be distinguished.



	0.4	0.7	1.3	2.5
0	0.33	0.46	0.50	0.63
0.3	0.79	0.54	0.54	0.29
0.6	0.92	0.54	0.58	0.58
1.2	0.83	0.38	0.67	0.83

Impactor in left/right position (best case)

	0.4	0.7	1.3	2.5
0	0.42	0.46	0.58	0.58
0.3	0.63	0.54	0.58	0.54
0.6	0.88	0.58	0.58	0.71
1.2	0.83	0.46	0.67	0.67

Impactor in middle position (worst case)

Figure 6. JND study results of the impactor in the middle and left/right positions. Fractions of responses that the force stimuli in each pair were answered as different impact force levels were shown.

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Comparing between the best and worst cases, stimuli in best case are more distinguishable than those in the worst case. However, to guarantee more robust and uniform distinguishability for ImpactVest, base level 0.4N with offset level at least 0.6N is required in both cases. All participants except P4 and P10 subjectively supposed that the stimuli in the left/right positions were more distinguishable than those in the middle position due to the vest more tightly contacting with the body in the left/right positions. This is consistent with our assumption of the best and worst cases from the pilot study. 6 participants commonly mentioned that the breath states could influence the perception since it changed the tightness between the vest and body. Therefore, some of them maintained the same breath state to more precisely differentiate the stimuli. Furthermore, some other factors were also used as references for distinguishing, such as the stronger impact usually causing deeper muscle depression (P9), the smaller impact range (P5), and longer impact time on body (P12). P6 further described that the stronger impact seemed to penetrate and spread on the body, and the weaker impact seemed to be poked with a shaking sensation.

Based on the results, we chose base level 0.4N and offset level 1.4N, and three impact levels (1, 2, 3) are (0.4N, 1.8N, 3.2N) in ImpactVest. Although this does not completely follow Weber’s law, the larger difference makes users more clearly and easily distinguish. The power-storing delays for these levels are (3500ms, 4600ms, 5400ms), respectively.

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CHAPTER 5

TIME INTERVAL THRESHOLD STUDY

To render various spatio-temporal impact patterns and even achieve a continuous impact stroke for versatility, the time interval between the two impact stimuli plays an important role. When the interval between impact stimuli is too short, the users perceive simultaneous impact stimuli. When the interval is too long, the users feel two discrete impact stimuli sequentially. When the time interval length is between those for simultaneous and discrete impact feedback, the users may perceive continuous stroke impact. Therefore, we performed this study to find the time interval thresholds to distinguish these three types of impact. The thresholds also represent the time interval upper and lower bounds to generate a continuous stroke impact. We followed the one-up, one-down staircase study design in [13] to conduct this study.

5.1 Apparatus and Participants

The apparatus was similar to that in the previous. ImpactVest, an eye mask and earbuds were worn. However, all nine impactors were equipped on the vest. 12 participants (7 females) aged 22-29 (mean: 24.75) with mean height 168.75cm (SD: 7.74cm) were recruited. 6 of them had attended to the previous study but more than two weeks elapsed between the studies.

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5.2 Task and Procedure

The participants wore ImpactVest and perceived the impact stimuli when standing. Impact force at level 2 (1.8N) based on the result of the previous study was used for the stimuli in this study. The one-up, one-down staircase study design was used to obtain the thresholds of upper and lower bounds, respectively. For the threshold of the upper bound, the initial time interval between two impact stimuli was 120ms, which was large enough for the participants to suppose those as two discrete impact stimuli from a pilot study. The participants were asked whether they felt the “discrete” impact stimuli. If they answered “yes”, the time interval was decreased by a step size. It they responded “no”, the interval was increased by a step size. For the threshold of the lower bound, the initial time interval between impact stimuli was 0ms, so the participants supposed those as simultaneous impact. The participants were asked whether they felt the “simultaneous” impact stimuli. If they answered “yes”, the time interval was decreased by a step size. It they responded “no”, which means that they could distinguish the direction of the impact stroke, the interval was increased by a step size.

At the beginning of the both thresholds, the step size was 8ms. After the first two reversals, which means the change of decreasing to increasing interval, and vice versa, the step size was decreased to 2ms. Each experiment ended after total six reversals, which means eight reversals in total. The average threshold was from the last six reversals, which were at the small step size. Since the distances between rows and columns of the array of impactors on ImpactVest are different, there are five different distances (10.5cm, 14cm, 17.5cm, 25.2cm, 29.9cm) between any two impactors in the

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array (Figure 7). Therefore, the distance also was a factor examined in this study. A total of 10 (= 5 (distances) × 2 (thresholds)) staircase runs were examined for each participant. The distances and order of the thresholds were randomized. For each distance, the positions of the impactor and the direction of the impact stroke were also randomized. The participants could have a break between sessions if they wanted. We interviewed them for some feedback after the experiment. This study took about 3 hours.

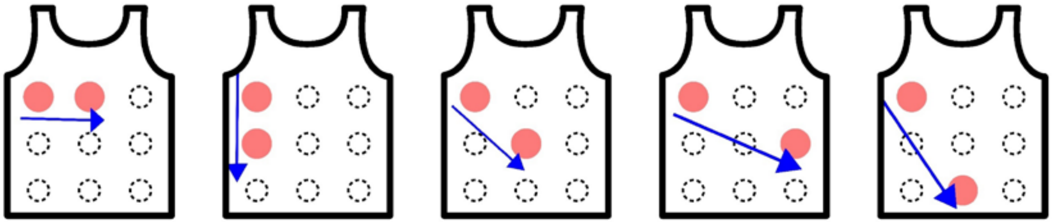

Figure 7. The five different distances between two impactors in the time interval threshold study.

5.3 Results and Discussion

The results are shown in Figure 8. The average threshold of the upper bound is 58.96ms, and the average threshold of the lower bound is 18.94ms. We leveraged a repeated measures ANOVA and Bonferroni correction to statistically analyze the results. A significant difference is found in thresholds ($F1,11 = 31.79$, $p < 0.01$), but not in distances in the threshold of the upper bound ($F4,44 = 0.4$, $p = 0.81$) and the lower bound ($F4,44 = 1$, $p = 0.42$). By further comparing upper and lower bounds in the same distance, the all the thresholds of the upper bounds are significantly higher than the thresholds of the lower bounds ($p < 0.01$ in all pairs), respectively. Therefore,

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we obtain the thresholds of upper bound and lower bound for simultaneous impact, continuous stroke impact and discrete impact. Furthermore, no significant difference between distances indicates that the time interval thresholds are not influenced by distance.

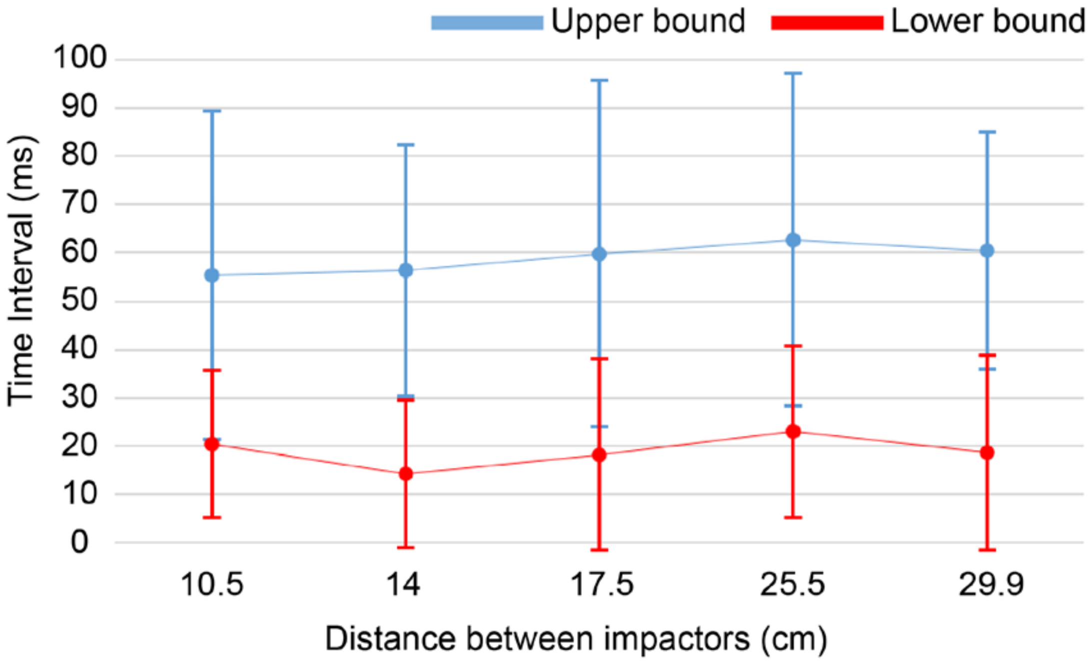

Figure 8. The results of the time interval threshold study. The bars represent the standard deviations.

P2 supposed that the longer distances required the shorter intervals since the intense impact made them clearly perceive that the stimuli were discrete. However, P9 thought that the longer distances needed the longer intervals since an impact stroke took more time to move in a longer distance, which was the phenomenon we expected. Furthermore, most participants mentioned that the space between the vest and body more or less increased the delay of impact applying to the body. Based on the results, 40ms is chosen for a continuous impact stroke.

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CHAPTER 6

VR EXPERIENCE STUDY

Based on the results of the previous studies, we performed this VR experience study to observe how different spatio- temporal multilevel impact patterns affect users' VR experiences, and verify that the impact feedback from ImpactVest is more realistic than the impact feedback simulated by a vibrotactile array as a baseline (Figure 9). Notably, we did not try to prove that haptic feedback from ImpactVest was better than that from the vibrotactile array in all VR scenarios. We only showed that in the scenarios requiring impact feedback, the real impact force from ImpactVest provided more realistic feedback than the simulated impact from vibrotactile actuators due to the different physical properties (Figure 5 (b)). We further envision that these two feedback methods could be combined or integrated in the future.

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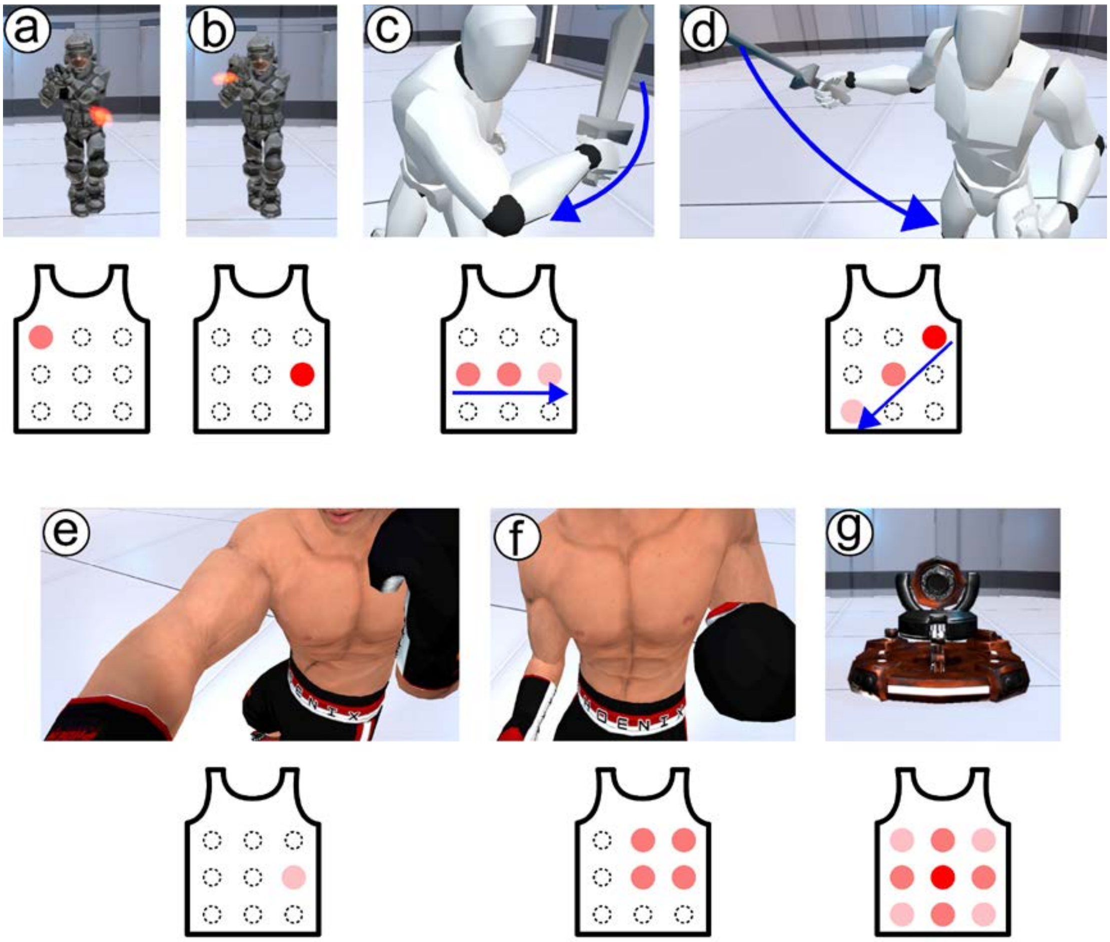

Figure 9. Seven enemies attack with different impact feedback from ImpactVest in the VR experience study. Two solders shoot with a pistol (a) and a rifle (b). Two swordmen slash in two trajectories (c) and (d). Two boxers throw an upper-cut (e) and a jab (f). A cannon fires to blast (g).

6.1 Apparatus and Participants

ImpactVest was worn for the impact feedback as in the previous study. Furthermore, delays from different impact levels of each impactor may affect the designed impact patterns for the VR applications, especially for complicated patterns involving several impactors. Therefore, we measured and compensated the delays among levels and also impactors by attaching the nine impactors on an acrylic board with force sensitive resistor (FSR) sensors for calibration (Figure 10 (left)). Furthermore, since vibrotactile feedback was compared as a baseline in this study, nine eccentric rotating mass (ERM) vibration motors were worn on the same positions as where the impact feedback produced from ImpactVest via three Velcro straps, as shown in Figure 10 (right). A Vive Pro HMD was worn and a controller was held on the dominant hand. To isolate the noise from the devices and environment, background music was played on noise-cancelling earbuds. 12 participants (7 female) aged 21-30 (mean: 23.91) with mean height 169.56cm (SD: 7.29cm) were recruited. All of them had not attended to the previous studies but had VR experiences.

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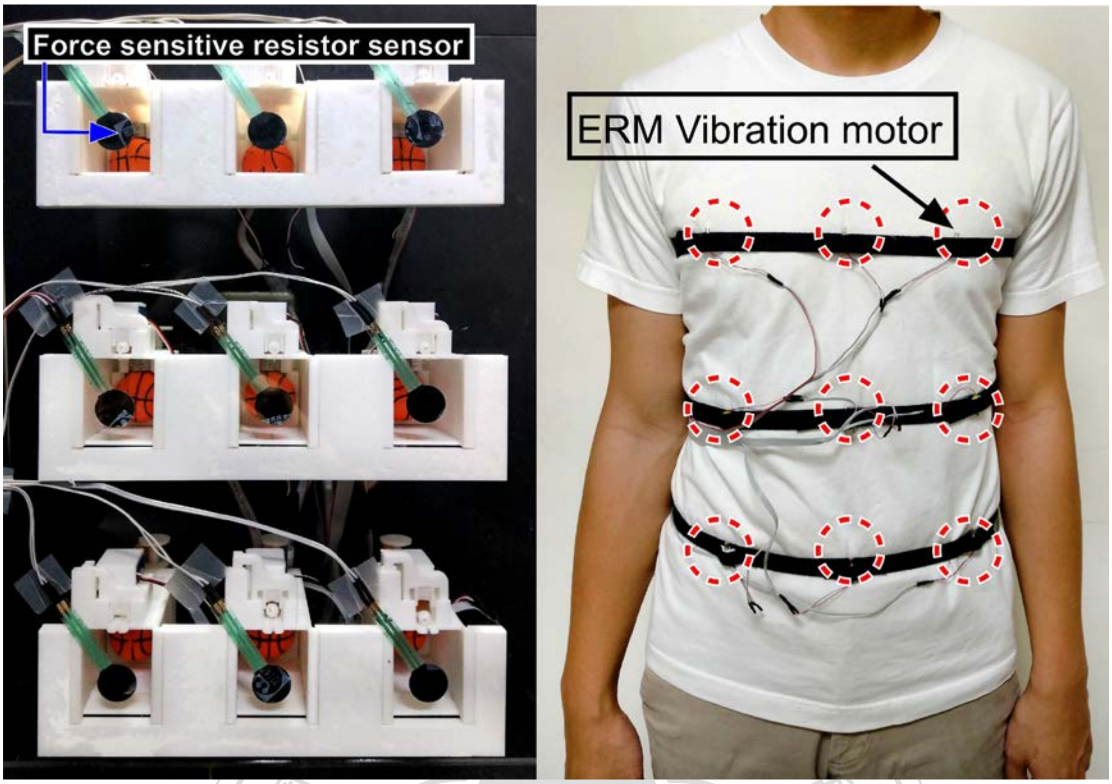

Figure 10. The setup to measure delays among impact levels and also impactors (left). Vibrotactile feedback from the vibration motors (right).

6.2 Task and Procedure

We built a VR scene that participants were in a room initially, and seven enemies, including two soldiers, two swordman, two boxers, and a cannon, appeared and attacked the participants sequentially by shooting, slashing, punching and blasting. The soldiers fired a shot with a pistol and a rifle at impact level 2 and 3, respectively, in random order. The swordman slashed with a sword in two trajectories in random order. By defining the impactor or vibration motor on the upper-right part of the chest as position (1, 1), which means the upper-left point in Figure 9, one trajectory was from the participants' right to left in the middle in positions ((2, 1), (2, 2), (2, 3)) with impact levels (2, 2, 1) sequentially. The other was from their left chest to right abdomen in

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positions ((1, 3), (2, 2), (3, 1)) with impact levels (3, 2, 1) sequentially. Based on the previous study result, the impact time intervals were 40ms to form continuous impact strokes. The boxers threw a jab and an upper-cut, respectively. A jab was a quick but weak punch with impact level 1 at position (2, 3), and an uppercut was a strong punch and applying to a larger surface area with impact level 2 at positions ((1, 2), (1, 3), (2, 2), (2, 3)) simultaneously. The cannon fired one time on the whole body with impact level 3 in the center (2, 2), level 1 at the corners ((1, 1), (1, 3), (3, 1), (3, 3)), and level 2 in the rest positions ((1, 2), (2, 1), (2, 3), (3, 2)) simultaneously. These VR applications included impact feedback at different levels, positions and time sequences.

Initially, we introduced the devices and applications to the participants. Two feedback methods, vibrotatile feedback (V) and impact feedback from ImpactVest (I), were compared in this study, and the order was counterbalanced. After the participants wore the corresponding feedback device and HMD, they held the controller in their dominant hand and stood in the VR scene and held a virtual riffle. Each enemy appeared sequentially. The participants were free to shoot the enemy by pressing the trigger on the controller. After the enemy performed one attack, they perceived the feedback on the body, and they could defeat the enemy. After the enemy was down and disappeared, the next enemy showed up. When all the seven enemies were beaten, the VR experience ended. After the participants experienced both feedback methods and completed the experiment, they were asked to fill out a questionnaire with a 7-point Likert scale, allowing decimal scores, in realism, distinguishability and enjoyment for the four types of the attacks, including shot, slash, punch and explosion. They were then encouraged to provide open-ended feedback in the interviews. The study took about an hour.

6.3 Results and Discussion

The results are shown in Figure 11. Repeated measures ANOVA and Bonferroni correction were used to analyze the feedback.

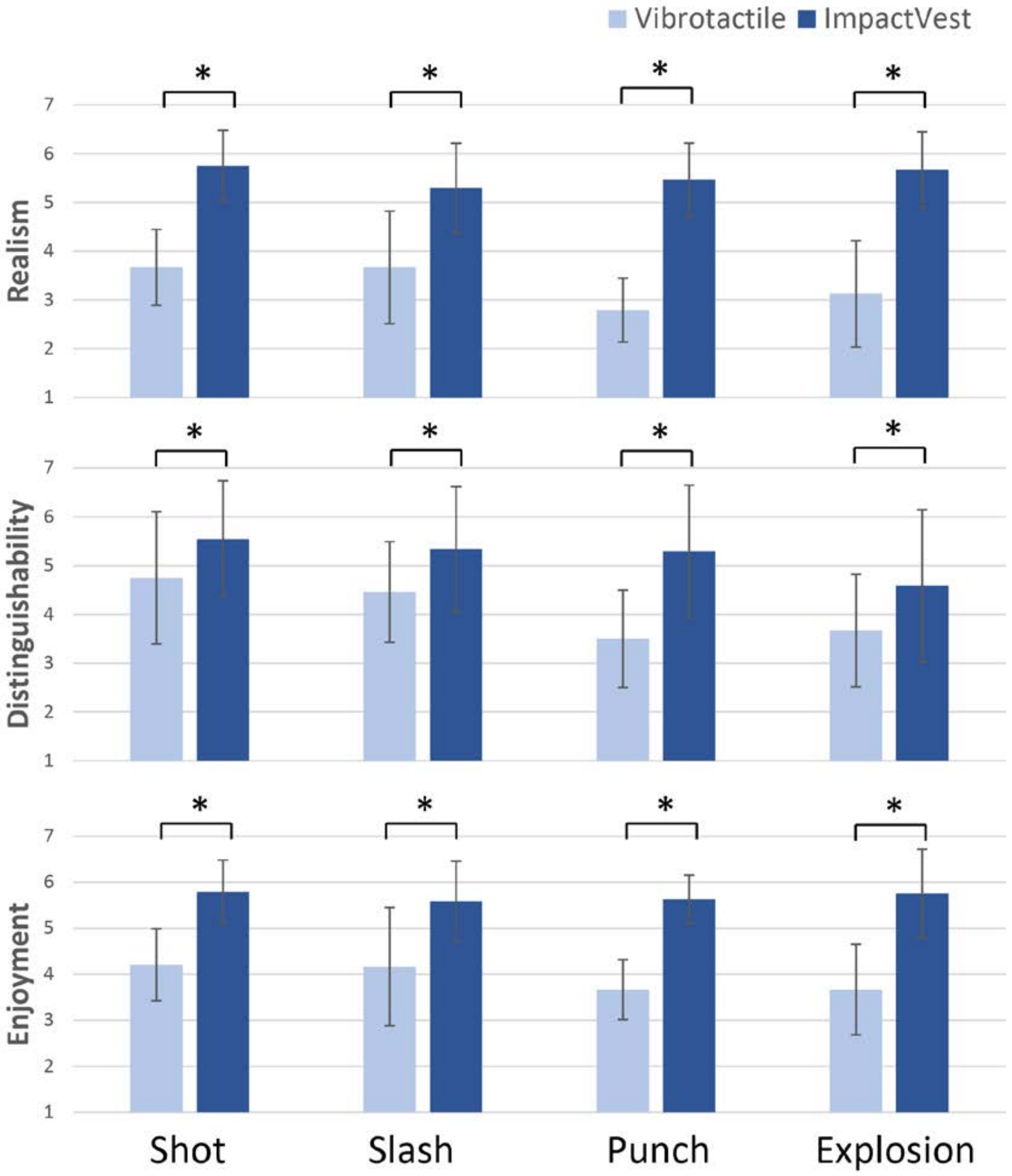

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Figure 11. The results of the VR experience study in regard to realism, distinguishability and enjoyment in a 7-point Likert scale.

Significant differences are found in all types of the attacks, including for shot in realism ($F1{,}11 = 50.18$, $p < 0.01$), distinguishability ($F1{,}11 = 17.49$, $p < 0.01$), and enjoyment ($F1{,}11 = 44.62$, $p < 0.01$), for slash in realism ($F1{,}11 = 11.41$, $p < 0.01$), distinguishability ($F1{,}11 = 5.04$, $p = 0.046$) and enjoyment ($F1{,}11 = 7.81$, $p = 0.02$), for punch in in realism ($F1{,}11 = 71.29$, $p < 0.01$), distinguishability ($F1{,}11 = 17.86$, $p < 0.01$) and enjoyment ($F1{,}11 = 52.03$, $p < 0.01$) and for explosion in realism ($F1{,}11 = 57.89$, $p < 0.01$), distinguishability ($F1{,}11 = 5.30$, $p = 0.04$) and enjoyment ($F1{,}11 = 22.99$, $p < 0.01$). Therefore, the impact feedback from ImpactVest significantly outperforms the simulated impact feedback from vibrotactile actuators.

For shot, 10 participants could not clearly differentiate between impact levels 2 and 3 in (I). This might be caused by two reasons. Instead of standing steadily, the participants moved their body and hand to shoot the solders in VR, which could make ImpactVest not contact with the body tightly all the time. Furthermore, due to the animations in VR, the time between two stimuli was longer than that in the JND study, which could make the participants more difficult to distinguish impact levels. However, feedback in (I) was still significantly more distinguishable than that in (V), which was supposed similar among all levels. Moreover, all participants discriminated the different positions of the two shots.

In regard to slash, 7 participants (P2, P3, P4, P5, P7, P8, P11) mentioned that they could perceive the trajectories of the impact strokes distinctly in (I). P3 and P5 highly

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appreciated the realistic impact feedback from (I), which perfectly matched with the visual feedback as they expected. However, some participants felt feedback of slashes slightly noncontinuous in (I). P6 and P10 said that "Since the impact feedback from ImpactVest was too strong, the impact strokes felt noncontinuous in the places between impactors on the trajectories. This was not obviously perceived in vibrotactile feedback." P6 further mentioned that "I perceived three separate impact points obviously." P9 also commented that "I supposed that a shorter time interval between impactors or more impactors equipped on ImpactVest could provide better feedback for continuous impact strokes." Although the strong intensity of (I) seemed a drawback for rendering continuous impact strokes, and (V) was supposed to provide better continuity of the feedback by most participants except P2, (I) with intenser feedback still generated more realistic feedback in slash VR experiences.

In terms of punch, the jab with only an impactor or vibration motor actuated was similar to the shots. P2, P3 and P10 observed that the surface area punched by the uppercut was larger than that punched by the jab in (I). However, P4 and P9 said that they perceived multiple impact points from (I) for the uppercut. This was caused by the similar reason as mentioned prior that the impact from (I) was too strong and obvious for the participants to regard the feedback from the four impactors as integrated feedback of an uppercut. Moreover, P9 indicated that s/he somehow perceived a trajectory from down to up for the uppercut. This might be because of the time errors among the impactors to render impact simultaneously. Interestingly, P5 and P8 reported that the punch position of the uppercut was around the middle point of the four impactors. We supposed that this phenomenon was similar to a phantom point produced

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when multiple haptic points are actuated [13]. 8 participants (P2, P3, P4, P5, P7, P8, P10, P11) mentioned that they could distinguish the impact levels from (I).

For explosion, 5 participants (P2, P5, P7, P11, P12) reported that they could clearly perceive the impact level gradation from the center with stronger impact to the corners with weaker impact. Furthermore, P2, P5 and P12 said that they felt as being struck by a sphere. All participants considered that feedback from (I) had better realism than that from (V) for explosion simulation. However, P8 indicated that “Both feedback from vibration motors and ImpactVest felt like nine discrete haptic feedback points instead of whole integrated large impact. Furthermore, it was more difficult to simulate this using intense and distinct feedback from the impactors than using vague feedback from vibration motors although ImpactVest provided better feedback experiences.” P9 also mentioned that “Too many impactors actuated at the same time, I could not distinguish the impact levels.”

Although some comments were mentioned that the intense and distinct feedback from ImpactVest might reduce continuity of impact strokes and integration in combinations of simultaneous multiple impact points, it still significantly outperformed vibrotactile feedback in realism, distinguishability and enjoyment. Therefore, this study verified that spatio-temperal multilevel impact from ImpactVest enhances VR experiences.

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CHAPTER 7

LIMITATIONS AND FUTURE WORK

Although feedback from ImpactVest is generally appreciated, there are still some limitations. Since the impact power- storing duration is not short enough, generating consecutive impact stimuli from the same impactor is infeasible. Furthermore, smaller impactors in a denser layout are needed to prevent the noncontinuous issue between impactors in impact strokes, as mentioned in the VR experience study. Although impact feedback simulated by vibrotactile actuators is not as realistic as feedback from real impact forces in ImpactVest, vibrotactile actuators still simualte different types of haptic sensations well. Therefore, we envision that impactors and vibrotactile actuators can be combined and complement each other to render more realistic and versatile feedback in the future. Interestingly, the concept of phantom sensation is mentioned in the VR experience study. We believe that the phantom sensation of impact feedback is an issue worth to investigate in the future. While the studies were performed by the proposed impactors, since we measured and quantified the impact feedback in this paper, future works can base on the results of the studies to further investigate advanced topics by generating impact using other devices.

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CHAPTER 8

CONCLUSION

We proposed a wearable device, ImpactVest, to render spatio-temporal multilevel impact force feedback on body using a 3×3 array of impactors. Each impactor stores power in the extended elastic band to instantly generate strong impact and remains lightweight. We conducted a JND study to obtain three distinguishable impact levels (0.4N, 1.8N, 3.2N) for the whole front part of the torso. We then performed a study to realize that the time interval thresholds for rendering continuous impact strokes are between 18.94ms and 58.96ms, and we choose 40ms time interval for continuous impact strokes. Furthermore, we conducted a VR study to verify that the feedback from ImpactVest significantly enhances VR realism, and proposed some VR applications requiring impact patterns involving different levels, positions and time sequences.

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References

[1] 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

[2] Inrak Choi, Eyal Ofek, Hrvoje Benko, Mike Sinclair, and Christian Holz. 2018. CLAW: A Multifunctional Handheld Haptic Controller for Grasping, Touching, and Triggering in Virtual Reality. In Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (Montreal QC, Canada) (CHI ’18). Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3173574.3174228

[3] Alexandra Delazio, Ken Nakagaki, Roberta L. Klatzky, Scott E. Hudson, Jill Fain Lehman, and Alanson P. Sample. 2018. Force Jacket: Pneumatically-Actuated Jacket for Embodied Haptic Experiences. In Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (Montreal QC, Canada) (CHI ’18). Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3173574.3173894

[4] Taichi Furukawa, Nobuhisa Hanamitsu, Yoichi Kamiyama, Hideaki Nii, Charalampos Krekoukiotis, Kouta Minamizawa, Akihito Noda, Junko Yamada, Keiichi Kitamura, Daisuke Niwa, Yoshiaki Hirano, and Tetsuya Mizuguchi. 2019. Synesthesia Wear: Full-Body Haptic Clothing Interface Based on Two-Dimensional

Signal Transmission. In SIGGRAPH Asia 2019 Emerging Technologies. Association for Computing Machinery, New York, NY, USA, 48–50. https://doi.org/10.1145/3355049.3360524

[5] TN Games. 2021. PHANTOMSENSE. https://tngames.com/

[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] Sebastian Günther, Florian Müller, Dominik Schön, Omar Elmoghazy, Max Mühlhäuser, and Martin Schmitz. 2020. Therminator: Understanding the Interdependency of Visual and On-Body Thermal Feedback in Virtual Reality. 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, 1–14. https://doi.org/10.1145/3313831.3376195

[8] Aakar Gupta, Antony Albert Raj Irudayaraj, and Ravin Balakrishnan. 2017. HapticClench: Investigating Squeeze Sensations Using Memory Alloys. 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, 109–117. https://doi.org/10.1145/3126594.3126598

[9] Seongkook Heo, Christina Chung, Geehyuk Lee, and Daniel Wigdor. 2018. Thor’s Hammer: An Ungrounded Force Feedback Device Utilizing Propeller-Induced Propulsive Force. In Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (Montreal QC, Canada) (CHI ’ 18). Association for Computing Machinery, New York, NY, USA, 1–11. https://doi.org/10.1145/3173574.3174099

[10] Ali Israr, Seung-Chan Kim, Jan Stec, and Ivan Poupyrev. 2012. Surround Haptics: Tactile Feedback for Immersive Gaming Experiences. In CHI ’12 Extended Abstracts on Human Factors in Computing Systems. Association for Computing Machinery, New York, NY, USA, 1087–1090. https://doi.org/10.1145/2212776.2212392

[11] Ali Israr and Ivan Poupyrev. 2010. Exploring Surround Haptics Displays. In CHI ’10 Extended Abstracts on Human Factors in Computing Systems. Association for Computing Machinery, New York, NY, USA, 4171–4176. https://doi.org/10.1145/1753846.1754121

[12] A. Israr and I. Poupyrev. 2011. Control space of apparent haptic motion. In 2011 IEEE World Haptics Conference. 457–462.

[13] Ali Israr and Ivan Poupyrev. 2011. Tactile Brush: Drawing on Skin with a Tactile Grid Display. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (Vancouver, BC, Canada) (CHI ’11). Association for Computing Machinery, New York, NY, USA, 2019–2028. https://doi.org/10.1145/1978942.1979235

[14] Ali Israr, Siyan Zhao, Kaitlyn Schwalje, Roberta Klatzky, and Jill Lehman. 2014. Feel Effects: Enriching Storytelling with Haptic Feedback. ACM Trans. Appl. Percept. 11, 3, Article 11 (Sept. 2014), 17 pages. https://doi.org/10.1145/2641570

[15] Seungwoo Je, Myung Jin Kim, Woojin Lee, Byungjoo Lee, Xing-Dong Yang, Pedro Lopes, and Andrea Bianchi. 2019. Aero-Plane: A Handheld Force-Feedback Device That Renders Weight Motion Illusion on a Virtual 2D Plane. In Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology (New Orleans, LA, USA) (UIST '19). Association for Computing Machinery, New York, NY, USA, 763–775. https://doi.org/10.1145/3332165.3347926

[16] Seungwoo Je, Hyelip Lee, Myung Jin Kim, and Andrea Bianchi. 2018. Wind-Blaster: AWearable 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

[17] Jinsoo Kim, Seungjae Oh, Chaeyong Park, and Seungmoon Choi. 2020. Body-Penetrating Tactile Phantom Sensations. 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, 1–13. https://doi.org/10.1145/3313831.3376619

[18] Yukari Konishi, Nobuhisa Hanamitsu, Kouta Minamizawa, Ayahiko Sato, and Tetsuya Mizuguchi. 2016. Synesthesia Suit: The Full Body Immersive Experience. In ACM SIGGRAPH 2016 Posters. Association for Computing Machinery, New York, NY, USA. https://doi.org/10.1145/2945078.2945149

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

[20] Pedro Lopes, Sijing You, Lung-Pan Cheng, Sebastian Marwecki, and Patrick Baudisch. 2017. Providing Haptics to Walls Heavy Objects in Virtual Reality by Means of Electrical Muscle Stimulation. In Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (Denver, Colorado, USA) (CHI ’17). Association for Computing Machinery, New York, NY, USA, 1471–1482. https://doi.org/10.1145/3025453.3025600

[21] Jun Murayama, Laroussi Bougrila, YanLin Luo, Katsuhito Akahane, Shoichi Hasegawa, Béat Hirsbrunner, and Makoto Sato. 2004. SPIDAR G&G: a two-handed haptic interface for bimanual VR interaction. In Proceedings of EuroHaptics, Vol. 2004. 138–146.

[22] Kazuki Nagai, Soma Tanoue, Katsuhito Akahane, and Makoto Sato. 2015. Wearable 6-DoF Wrist Haptic Device “SPIDAR-W”. In SIGGRAPH Asia 2015 Haptic Media And Contents Design (Kobe, Japan) (SA ’15). Association for Computing Machinery, New York, NY, USA, Article 19, 2 pages. https://doi.org/10.1145/2818384.2818403

[23] M. Nakamura and L. Jones. 2003. An actuator for the tactile vest - a torso-based haptic device. In 11th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2003. HAPTICS 2003. Proceedings. 333–339.

[24] Sayaka Ooshima, Yasushi Fukuzawa, Yuki Hashimoto, Hideyuki Ando, Junji Watanabe, and Hiroyuki Kajimoto. 2008. /Ed (Slashed): Gut Feelings When Being Cut and Pierced. In ACM SIGGRAPH 2008 New Tech Demos (Los Angeles, California) (SIGGRAPH '08). Association for Computing Machinery, New York, NY, USA, Article 14, 1 pages. https://doi.org/10.1145/1401615.1401629

[25] Henning Pohl, Peter Brandes, Hung Ngo Quang, and Michael Rohs. 2017. Squeezeback: Pneumatic Compression for Notifications. 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, 5318–5330. https://doi.org/10.1145/3025453.3025526

[26] Tomoya Sasaki, Richard Sahala Hartanto, Kao-Hua Liu, Keitarou Tsuchiya, Atsushi Hiyama, and Masahiko Inami. 2018. Leviopole: Mid-Air Haptic Interactions Using Multirotor. In ACM SIGGRAPH 2018 Emerging Technologies (Vancouver, British Columbia, Canada) (SIGGRAPH '18). Association for Computing Machinery, New York, NY, USA, Article 12, 2 pages. https://doi.org/10.1145/3214907.3214913

[27] Jongman Seo, Sunung Mun, Jaebong Lee, and Seungmoon Choi. 2018. Substituting Motion Effects with Vibrotactile Effects for 4D Experiences. Association for Computing Machinery, New York, NY, USA, 1–6. https://doi.org/10.1145/3173574.3174002

[28] Yuqian Sun, Shigeo Yoshida, Takuji Narumi, and Michitaka Hirose. 2019. PaCaPa: A Handheld VR Device for Rendering Size, Shape, and Stiffness of Virtual Objects in Tool-Based Interactions. In Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (Glasgow, Scotland Uk) (CHI '19).

DOI:10.6814/NCCU202101281

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

[29] Teslasuit. 2021. Teslasuit. https://teslasuit.io/

[30] Hsin-Ruey Tsai, Yuan-Chia Chang, Tzu-Yun Wei, Chih-An Tsao, Xander Koo, Hao-Chuan Wang, and Bing-Yu Chen. 2021. GuideBand: Intuitive 3D Multilevel Force Guidance on a Wristband in Virtual Reality. In Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems. 1–13.

[31] 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

[32] Hsin-Ruey Tsai and Jun Rekimoto. 2018. ElasticVR: Providing Multi-Level Active and Passive Force Feedback in Virtual Reality Using Elasticity. In Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems (Montreal QC, Canada) (CHI EA '18). Association for Computing Machinery, New York, NY, USA, 1–4. https://doi.org/10.1145/3170427.3186540

[33] 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

[34] 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

[35] 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 33nd Annual ACM Symposium on User Interface Software and Technology.

[36] 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

[37] G. Yun, S. Oh, and S. Choi. 2019. Seamless Phantom Sensation Moving Across a Wide Range of Body. In 2019 IEEE World Haptics Conference (WHC). 616–621.

DOI:10.6814/NCCU202101281