ElasticVR: Providing Multilevel Continuously-Changing Resistive Force and Instant Impact Using Elasticity for VR

Hsin-Ruey Tsai
National Taiwan University
The University of Tokyo
hsnuhrt@gmail.com

Jun Rekimoto
The University of Tokyo
rekimoto@acm.org

Bing-Yu Chen
National Taiwan University
robin@ntu.edu.tw

ABSTRACT

Resistive force (*e.g.*, due to object elasticity) and impact (*e.g.*, due to recoil) are common effects in our daily life. However, resistive force continuously changes due to users' movements while impact instantly occurs when an event triggers it. These feedback are still not realistically provided by current VR haptic methods. In this paper, a wearable device, ElasticVR, which consists of an elastic band, servo motors and mechanical brakes, is proposed to provide the continuously-changing resistive force and instantly-occurring impact upon the user's hand to enhance VR realism. By changing two physical properties, length and extension distance, of the elastic band, ElasticVR provides multilevel resistive force with no delay and impact with little delay, respectively, for realistic and versatile VR applications. A force perception study was performed to observe users' force distinguishability of the resistive force and impact, and the prototype was built based on its results. A VR experience study further proves that the resistive force and impact from ElasticVR both outperform those from current approaches in realism. Applications using ElasticVR are also demonstrated.

CCS CONCEPTS

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

KEYWORDS

Haptic feedback, force feedback, elastic force, resistive force, impact, virtual reality, wearable device

CHI 2019, May 4–9, 2019, Glasgow, Scotland UK

ACM ISBN 978-1-4503-5970-2/19/05…$15.00
https://doi.org/10.1145/3290605.3300450

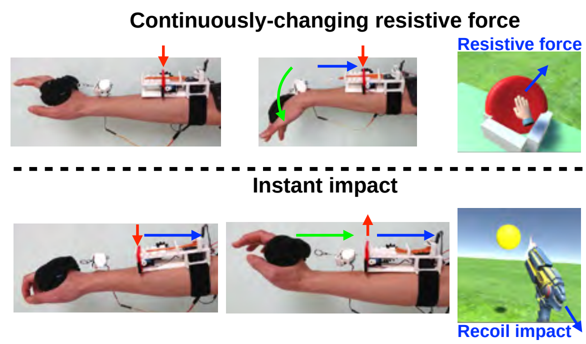

Figure 1: Resistive force and impact from ElasticVR. Blue, green and red arrows indicate the force directions of the band, hand movement and mechanical brakes, respectively.

ACM Reference Format:
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 *CHI Conference on Human Factors in Computing Systems Proceedings (CHI 2019), May 4–9, 2019, Glasgow, Scotland UK*. ACM, New York, NY, USA, 10 pages. https://doi.org/10.1145/3290605.3300450

1 INTRODUCTION

Force feedback indeed enhances the realism and immersion of virtual reality (VR). Resistive force and impact are common force feedback effects, but still not realistically provided in versatile VR applications. For resistive force, users should perceive it continuously changing in opposition to their movement, *e.g.*, when pressing upon elastic objects or pitching. In addition, various resistive force levels are required for versatile VR applications, *e.g.*, pressing objects with different elasticity/stiffness. For impact, users should perceive it instantly occurring (*i.e.*, produced nearly simultaneously) after an event trigger, *e.g.*, a hit or recoil.

To provide resistive force, previous approaches generally leverage either objects with corresponding physical properties [1, 2, 5, 6, 9], *e.g.*, brakes for rigid objects or elastic objects for resistive force, or force simulation [7, 11, 14, 21, 23] by motors, propellers or electrical muscle stimulation (EMS) to provide multilevel resistive force. However, they provide either single-level resistive force, *i.e.*, for rigid or certain elastic objects, using physical properties, or limited continuously-changing resistive force due to delays or cut-off from motors, EMS and propellers using force simulation. To present impact, impulses from motors [4, 23] and EMS [13, 14] are leveraged to stimulate the users. However, EMS requires serial calibration steps and motors need a delay to gradually provide strong force, which is not instant enough (Figure 8).

Hence, we propose a wearable device, ElasticVR, to provide continuously-changing multilevel resistive force and instant multilevel impact upon the hand. ElasticVR consists of an elastic band, servo motors and mechanical brakes. By changing length and extension distance of the elastic band, it provides multilevel resistive force and impact, separately, integrated on one device. By changing the band length using the brake, multilevel resistive force is provided with no delay as in [1, 2]. By extending the band using the motor to store the energy in advance, multilevel impact is rendered instantly as the band is released. Though the delay is in resistive force level switching, it is "prior to" the users' perceiving movement. There is no delay at all "during" the users' movement at a resistive force level. ElasticVR provides resistive force with no delay and impact with little delay to achieve realistic and versatile VR applications. To realize these results, we first observed users' distinguishability of the multilevel resistive force and multilevel impact in a force perception study. Based on the results, we manufactured the ElasticVR prototype and further compared it with current approaches in a VR experience study. The results prove that the resistive force and impact from ElasticVR are significantly more realistic. Finally, some ElasticVR applications are demonstrated.

The paper presents the following contributions:

(1) Providing continuously-changing multilevel resistive force with no delay for realistic and versatile VR applications.
(2) Rendering instantly-occurring multilevel impact with little delay for realistic and versatile VR applications.
(3) Exploring users' force perception distinguishability in regard to resistive force and impact.

2 RELATED WORK

In this section, we discuss the researches providing force feedback for resistive force and impact, respectively, in VR.

Grounded Force Feedback Devices

Using DC motors to control wires, SPIDAR [15] and [12] provide force feedback in a fixed operating space. Some commercial products, *e.g.*, Phantom Premium[1], with complicated mechanical structures and computation also provide resistive force and impact. However, these devices are limited in grounded scenarios. Though SPIDAR-W [16] improves the concept of SIPDAR but its lack of mobility is still a limitation.

[1] https://www.3dsystems.com/haptics-devices/3d-systems-phantom-premium

Ungrounded Devices for Resistive Force

To provide resistive force, using objects' physical properties and force simulation are two common approaches. Dexmo [9], Wolverine [6] and Grabity [5] leverage servo or DC motors to control mechanical brakes and restrain the users' fingers. Hence, when grasping a rigid object in VR, their fingers are fixed to accommodate the object's shape by the resistive force while not further penetrating the virtual object. Elastic-Arm [1] and FlexiFingers [2] use an elastic band and metal strips worn on the shoulder and hand to provide resistive force as if the hand presses on and/or grasps elastic objects, respectively. Hence, the resistive force is increased continuously as the hand stretches and grasps. Using physical properties, these methods generally provide continuously-changing resistive force but only at a single-level (*i.e.*, rigid body or certain elasticity). The users may need to switch the devices manually to perceive different force levels. Though Shifty [24] uses a stepper motor to change the center of the mass and can provide multilevel force feedback, it focuses on device weight change instead of resistive force.

In force simulation, Exointerfaces [23], worn on the upper arm, renders resistive force on the forearm using high frequency impulses from DC motors with belts. By placing electrodes on shoulders and arms, EMS impulses with a cut-off produce resistive force in [14]. CLAW [7] uses a servo motor and force sensor to build a closed-loop force control system to provide resistive force as grasping different object stiffness. Haptic Links [21] use servo motors to control friction of the mechanical brakes in "chain" and "layer-hinge" forms to provide various resistive force between the hands. Thor's Hammer [11] uses six motors and propellers to produce 3 DoF (degree of freedom) resistive force on a handheld device. However, no matter simulating resistive force using discrete impulses or closed-loop control from motors, EMS or propellers, the delay issue is the common limit. The delays due to deadband and backlash are potential and inevitable limits of control signals and mechanical motors, respectively. Backlash is produced by a gap between gears, which is essential for the gears rotating. The effect of the delay is more obvious when the motors and gears rotate reversely and repeatedly, as in the users' back and forth movement. Such movement however is common when the users feel and explore objects.

Some tactile methods also provide force feedback. By altering orientation of a platform, [17, 19, 20] deform and squeeze the finger tip to provide tactile and even force feedback. However, without restraining the finger movement, whenever the finger penetrates virtual objects, VR realism is decreased.

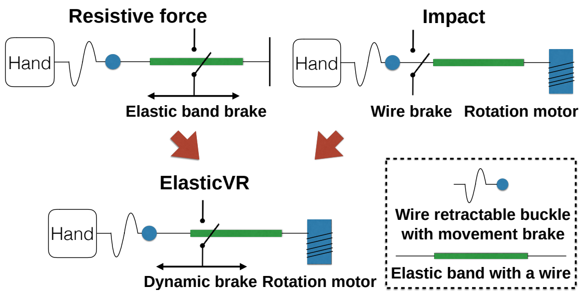

Figure 2: ElasticVR design. Integrating resistive force and impact into one device.

Tactile and force feedback are complementary, and should be combined, as in [13], to provide realistic feedback.

Current resistive force feedback approaches are either single-level or non-continuously-changing. In this paper, ElasticVR provides multilevel continuously-changing resistive force for realistic and versatile VR experiences.

Ungrounded Devices for Impact

Jetto [8] provides 2D lateral impact on a smartwatch by emitting a jet of air. Although the force feedback is ungrounded, it requires a bulky air compressor. Motion Guidance Sleeve [4], worn on the forearm, uses step motors to drag users' arms and provide motion guidance in rotational direction for the arm. Impacto [13] combines force feedback from EMS and tactile feedback from a solenoid to provide realistic impact as if being punched. Exointerfaces [23] and Virtual Walls [14] provide both resistive force and impact using impulses from DC motors and EMS. Without bulky but powerful grounded devices, instant impact is limited to tiny DC motors, which need delays to gradually provide strong force. This restrains the realism. Although EMS provides powerful and quick impact, it overwrites the body part movement internally, which is different from impact externally applied to the users as is usual. In addition, calibration steps of EMS are needed. ElasticVR provides instant impact to enhance VR realism.

3 ELASTICVR

ElasticVR is a wearable device worn on the forearm to provide continuously-changing multilevel resistive force and instant multilevel impact to the hand. Notably, multilevel resistive force does not mean that the force changes depending on the movement but indicates that it changes in various patterns per objects degree of elasticity/stiffness. To provide such realistic force feedback, continuously-changing resistive force with no delay and impact rendered in an extremely short time, *i.e.*, with little delay, are required, as described in Introduction. To accommodate these considerations, we use the object's physical properties instead of force simulation with the potential delay problem as mentioned in Related Work to provide resistive force and impact via ElasticVR.

Hardware

ElasticVR consists of an elastic band, servo motors and mechanical brakes. Using the servo motors and mechanical brakes, ElasticVR alters the elastic band's two physical properties, length and extension distance, to change the band's elasticity. While not all bands follow Hooke's law acting as springs, the length and extension distance of a band still maintain non-linear relation to its elasticity. To provide resistive force, the *elastic band brake* in the ElasticVR design (Figure 2 (left)) blocks different positions of the band to change its length. The shorter the band, the stronger the elasticity, the stronger the resistive force level. When the band is blocked, it is extended and the resistive force is increased continuously in the direction opposite to the hand movement. As the hand releases and moves back, the band is loosed and the resistive force is decreased. Using the elastic band as well as the motors and brakes, ElasticVR provides multilevel resistive force and maintains smoothness of continuously-changing resistive force with no delay, as in [1, 2], for realism. This concept is similar to Shifty [24].

To provide impact, ElasticVR extends the band to different extension distances for various levels of impact using the *rotation motor* as per the ElasticVR design (Figure 2 (right)). Using the *wire brake* to block the wire between the band and the hand, the extended band stores energy in advance. As the *wire brake* is released, the band is released to instantly stimulate users. The little delay from ElasticVR is much shorter than that directly produced from the same motor (Figure 8).

The force deliveries require restricted hand movement, but hand movements should be free under normal conditions. We leverage the wire retractable buckle with the *movement brake* to achieve such requirements (Figure 2 (dotted frame)). The retractable wire is connected to the hand, and the buckle with the *movement brake* is connected to the band. While a slight retracting force is produced, it is negligible compared with the force feedback from ElasticVR. The retractable buckle provides free hand movement as the *movement brake* is released, and restricts the hand as the *movement brake* blocks the retractable wire for force delivery. The design also allows the free hand movement when storing energy for impact.

To integrate resistive force and impact feedback on a device, we combine the designs and observe that the wire retractable buckle with the *movement brake* can be shared. In addition, the *elastic band brake* and *wire brake* can be combined into one movable *dynamic brake* (Figure 2 (lower)). Thus, ElasticVR consists of an elastic band, two brakes, including the *dynamic brake* and the *movement brake*, and the *rotation motor* (Figure 3 and 4).

Elastic Band. The wider the elastic band, the stronger the elasticity. We chose the proper elastic band in a pilot with the band width 1cm and length 8cm, which provides resistive

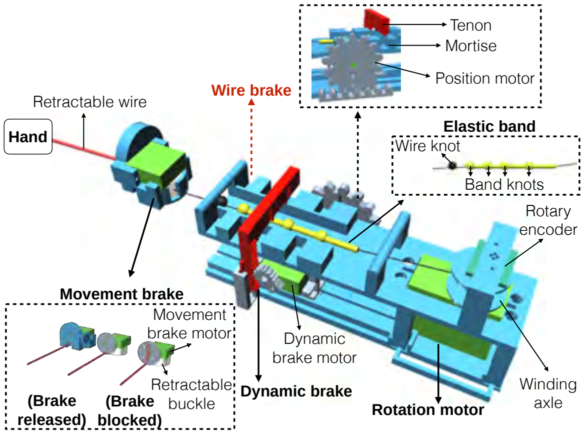

Figure 3: ElasticVR prototype in STL 3D model.

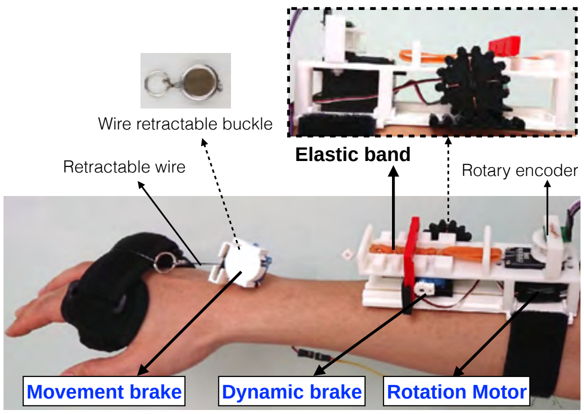

Figure 4: ElasticVR prototype worn on the forearm.

force discriminatively as perceived by the hand. Besides, to firmly block the band using the *dynamic brake*, several tiny rubber bands as *band knots* were tied on the elastic band, and a *wire knot* was tied on the wire (Figure 3 (upper right)). Two fishing lines as wires connect the two sides of the band with the *rotation motor* and the *movement brake*, respectively.

Dynamic Brake. We leveraged mechanical designs, a tenon and mortises, to build the movable *dynamic brake*. Mortises were built, and a tenon is controlled by the *dynamic brake motor* and it is moved by the *position motor* to different mortises' positions (Figure 3 (upper)). The micro servo motors XCSOURCE RC450 (3.7g) are used for the *position* and *dynamic brake motors*. The mortise closest to the hand is used as the *wire brake* (Figure 2). The others are used as the *elastic band brake*. Each *knot* on the band corresponds to a mortise.

Movement Brake. The *movement brake motor* (RC450) is attached to a wire retractable buckle with a diameter of 21mm. It controls a disc with a tiny hole, and the retractable wire is pulled through the hole connected to the hand. Most of the disc is obscured within the case. As the *movement brake*

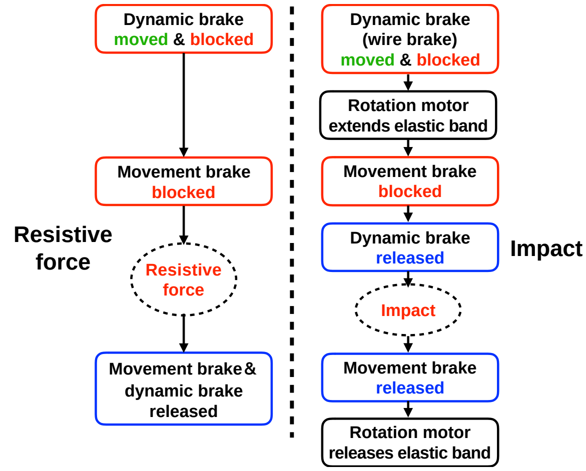

Figure 5: Block diagram of ElasticVR process flow.

blocks, the disc is rotated in the case and the wire is halted by the friction. The hand is restricted (Figure 3 (lower left)).

Rotation Motor. A continuous rotation servo motor GWS S35 STD (41g) and a rotary encoder (Pololu Magnetic Encoder) are used as the *rotation motor*. A winding axle with radius 10mm is attached to it to wind the wire and extend the band.

The weight of ElasticVR including its four servo motors is 150g, which is lighter than other force feedback devices [7, 9].

Software

Per the block diagram of process flow shown in Figure 5, the *dynamic brake* is moved and blocked at first for both force feedback. For force delivery, the *movement brake* is then blocked to restrict the hand movement for resistive force, but it is blocked after the band is extended by the *rotation motor* for impact. Resistive force is provided as the hand presses. Impact is provided as the *dynamic brake* is released. The *dynamic* and *movement brakes* for resistive force, and the *movement brake* for impact, are all released to free the hand. For impact, a 100ms delay between *dynamic brake* and *movement brake* release reinforces impact, and the *rotation motor* rotates reversely to loosen the elastic band at last.

Using the motors to change the elastic band's physical properties, ElasticVR provides multilevel resistive force with no delay and impact with little delay to achieve realistic and versatile VR applications. For each resistive force level, ElasticVR constantly actuates the motors five times (Figure 5). However, other resistive force simulation approaches actuate motors depending on the perceiving movement, usually by much more than five times, and this may require more power consumption. In switching resistive force levels, there is a delay, 1160ms (= 800ms + 300ms (move and block the *dynamic brake* in any position) + 60ms (block the *movement brake*). To reduce it, the system can move and block the *dynamic*

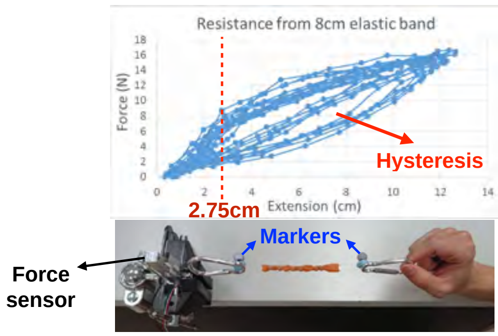

Figure 6: Resistive force stimuli collected by the force sensor and Optitrack markers. Hysteresis could be observed.

brake in advance by inferring the next resistive force level needed by the users. Therefore, only a 60ms delay to block the *movement brake* is required to switch resistive force levels. ElasticVR with no delay "during" but a little delay "prior to" the perceiving movement still provides high VR realism, as proven by our VR study. We report the delay of impact after the following study for realizing more detailed parameters. We have demonstrated the preliminary ElasticVR prototype in [22] and lab open house each for three hours. More than 70 users have experienced the prototype; this guarantees its usability. Most users were surprised with its performance.

Resistive force levels require corresponding numbers and positions of mortises and knots. Impact levels need corresponding revolution numbers from the *rotation motor*. We have observed the parameters in the following study.

4 FORCE PERCEPTION STUDY

To provide proper resistive force and impact parameters for ElasticVR, we observed users' force feedback perception distinguishability in this study. We followed and modified the just-noticeable difference (JND) study in [10, 18].

Apparatus and Participants

Without knowing the appropriate mortise arrangement for resistive force, we built a preliminary ElasticVR prototype as described prior with equidistant mortises to provide only impact in this study. Arduino Uno is used to control the motors in ElasticVR using a USB cable. 4 batteries provided 6V power for the *rotation motor*. In addition, a hand brace worn on the hand connects to an elastic band and the ElasticVR prototype for resistive force and impact perception, separately. An eye mask and earphones were worn to block visual and audio feedback during the study. 12 right-handed participants (5 female) aged 23-33 (mean: 25.25) were recruited.

Stimuli

The resistive force change that depends on users' perceiving movement is different from a general JND stimulus with a certain intensity, so we needed to define the intensity values for resistive force stimuli with dynamic ranges. Hand movement ranges vary among individuals. Therefore, different maximum resistive forces could be perceived as the same resistive force level. We observed that many users repeatedly pressed their hands extending the elastic band to perceive resistive force within a smaller *force perception range*. The mean range of 2.5cm (a band extension between 1.5 to 4cm) was found using a tape measure during the pilot. In addition, due to hysteresis, in the same band extension, the force in the extending procedure is stronger than in the release procedure, as in Figure 6 (upper). Thus, we defined a resistive force level as the force magnitude with 2.75cm band extension (middle of the range) in the band extending procedure.

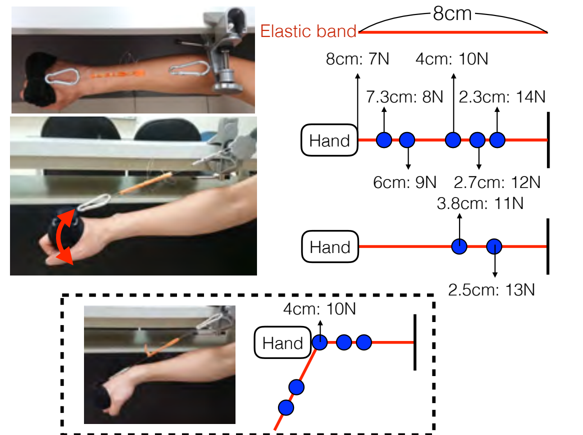

Figure 7: The resistive force apparatus in the force perception study. 7 knots (blue dots) were tied on two elastic bands (right). 10N resistive force was provided (lower).

To obtain the relationship between elastic band force magnitude and extension, we affixed one side of the band with a load cell (TAL220 with HX711 ADC amplifier) and extended it from the opposite side (Figure 6 (lower)). Two markers attached on both sides are tracked by the OptiTrack system. By repeatedly extending the band, we collected the force magnitude and band extension data (Figure 6 (upper)). By averaging the force magnitude in extension 2.75cm with 0.5cm interval (2.5 to 3 cm) in the extending procedure, we obtained the resistive force level. We tied knots on the band to form different band lengths for proper resistive force stimuli (Figure 7). For impact stimuli, we affixed the force sensor and ElasticVR, and measured various impact levels by actuating the *rotation motor* at different revolution numbers. We also used the setup to show the impact difference from a motor impulse and from ElasticVR using the same motor (Figure 8).

Task and Procedure

A pair of force stimuli was examined in a trial. Participants were asked to respond if the force levels were *the same* or

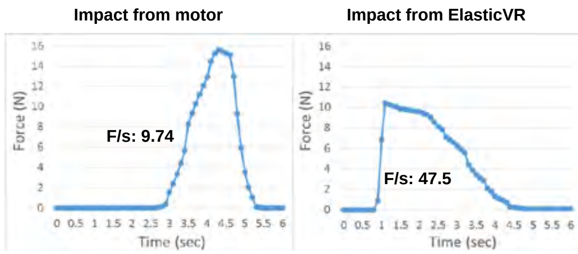

Figure 8: Impact from the motor impulse and ElasticVR. F/s slope is for the force increase as impact produced.

different. Each pair of stimuli included a *base* and *offset* force magnitude. Resistive force stimuli consisted of four base forces (7N, 8N, 9N, 10N) and four offset forces (0N, 1N, 2N, 4N). A total of 7 knots were on the two identical bands to provide resistive force levels from 7N to 14N (Figure 7). The maximum/minimum values of resistive force were depending on the elastic band's elasticity and length. The band we used with the proper resistive force range was unable to provide exponentially increased base and offset values as in a JND study. Therefore, we did not claim that this study is a JND study but a force perception study. Impact stimuli includes four base forces (1N, 2N, 4N, 8N) and four offset forces (0N, 1N, 2,N, 4N), which were also modified for consistency. The revolution numbers of the *rotation motor* are between 0.25 to 2.75 in ElasticVR. A total of 16 conditions were examined in resistive force and impact, respectively. The order of stimuli for each pair was randomized. Each condition was repeated once. Therefore, 64 (= 2 (force feedback) × 16 (conditions) × 2 (repetitions)) trials are examined for each participant.

For resistive force, the experimenters adjusted the force level by affixing the elastic band to the corresponding knot. The participants' arm and hand parallel to the band was then moved to ensure that the band was straight but not extended (Figure 7). The participants were asked strictly to only perceive resistive force using their wrists to guarantee the precision of the study. Participants could ask to play back stimuli in the same pair to confirm the perception and respond to the experimenters. The experimenters unfixed the hand and adjusted to the next force level between stimuli, which guaranteed that the relative hand position was not used to infer a band's length. For impact, the participants wore the preliminary ElasticVR prototype and earphones, blocking motors' sound, and laid their forearm on the desk to perceive the stimuli. The impact levels were adjusted using ElasticVR. The study took approximately an hour.

Results and Discussion

The results of the study on resistive force and impact are shown in Figure 9. The aggregate fractions of responses that participants regarded the stimuli in pair as different force levels are shown. Interestingly, we observed that in resistive

Resistive force

Offset (N) \ Base (N)	7	8	9	10
0	0.38	0.33	0.29	0.21
1	0.50	0.38	0.79	0.67
2	0.46	0.71	0.79	0.92
4	1.00	0.92	0.92	0.92

Impact

Offset (N) \ Base (N)	1	2	4	8
0	0.25	0.17	0.17	0.21
1	0.71	0.71	0.58	0.25
2	0.88	0.96	0.67	0.42
4	1	0.96	0.92	0.83

Figure 9: The force perception study results of resistive force and impact. Fractions of responses that the pair of stimuli were supposed as unequal were shown.

force, the smaller base forces required larger offset forces to be distinguished, which was in contrast to normal JND results as in impact. It consists with the claim that resistive force was not a general JND stimulus. The participants report that it was harder to distinguish the stimuli at lower resistive force levels. However, at higher force levels, they perceived that the resistive force increased quickly, which caused the stimuli to be more distinguished. Thus, we suppose that a more distinct resistive force increase at the same band extension is easier and clearer to perceive and distinguish.

For impact, the results are quite typical, loosely consistent with Weber's law (constant = (offset) / (base)). The stronger base force requires stronger offset force to be distinguished. Although there are unexpected results for resistive force, based on the results in Figure 9, we still obtain proper resistive and impact levels with over 90% distinguishability. For resistive force, five levels (7N, 10N, 12N, 14N, *rigid*) are provided. 7N is the minimum resistive force of the band. *Rigid* is indicated when pressing stiff objects with the strongest force level, so the whole band in ElasticVR is totally blocked by the *wire brake*. For impact, three levels (4N, 8N, 12N) are provided. We chose 4N instead of 2N as the base to make force feedback stronger and easier to be perceived in VR. Based on these results, we manufactured the ElasticVR prototype with proper mortises' and knots' positions, and set corresponding revolution numbers to the control board (Figure 3 and 4).

5 VR EXPERIENCE STUDY

We further observed whether the resistive force and impact from ElasticVR were more realistic than those from conventional feedback methods, and enhanced VR experiences.

Apparatus and Participants

The ElasticVR prototype, a HTC Vive HMD and controller were used in this experiment. Earphones were worn to block audio feedback. We used Unity3D and SteamVR SDK for Vive to build the VR scene. 12 right-handed participants (3 female) aged 20-31 (mean: 24.33) were recruited. One had no VR experience before. Five of them attended to the previous study but about a week elapsed between the two studies.

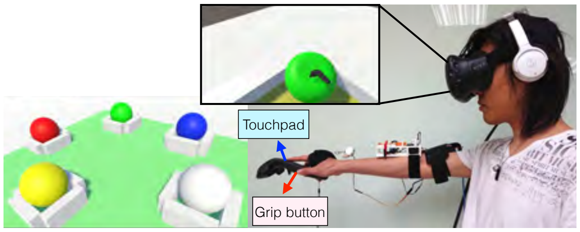

Figure 10: The apparatus and VR scene of the VR study.

Task and Procedure

Five balls with different colors and elasticity/stiffness were placed in the VR scene (Figure 10). The participants could freely press and fire (or shoot) the balls to experience resistive force from the elastic balls and impact from the recoil with three fire power levels, respectively. Three feedback methods were examined, including vibration (V) from the off-the-shelves controller, general force feedback method (F) using impulses from a motor as a baseline, and force feedback from ElasticVR (E). Notably, the motor in (F) was the same as in (E), which compares our (E) and the previous (F) design concepts using the same hardware. Two force feedback, resistive force and impact, with 5 and 3 levels were experienced, separately. Therefore, a total of 6 (= 3 (force feedback methods) × 2 (kinds of force feedback)) conditions were experienced. Feedback methods were counterbalanced. Each method was experienced for about 5 to 10 minutes. The participants could experience different force feedback at various levels freely at will. Force distinguishability is examined in the previous study, so it is not examined but only observed using the subjective scale in this study.

The participants held a Vive controller in the dominant hand on the study. For resistive force in (V), based on the study in [14], the system provides stronger vibrations when pressing harder balls using SteamVR SDK for Vive, and vice versa. For (F), by replacing the band with a fishing line and disabling the *dynamic brake* in ElasticVR, motor impulses are used to simulate resistive force. When pressing the balls, impulse magnitude increases as shorter distance between the controller and ball center (*i.e.*, pressing deeper) and the increment is sharper for harder balls, and vice versa. For (E), the system infers that the ball would be pressed in a free exploration by computing which ball is closest to the controller, so only a 60ms delay to block the *movement brake* is required as mentioned in the ElasticVR section. The participants were asked to press the balls only using the wrist in (E). Besides, different deformation levels of the balls in visual feedback were provided as pressing in all feedback methods.

For impact, the participants randomly picked up a ball by pressing the grip button with their thumb and *fired* it by pressing the touch pad with their index finger on the controller (Figure 10). After a short period to store fire power, the ball is ejected. The three fire power levels depend on the fire sequence. The stronger power, the longer power storing period. The periods were the same for all feedback methods. Stronger vibration and impulse were provided for stronger recoil in (V) and (F), separately, and vice versa. In (E), ElasticVR stores power by actuating the *rotation motor* at level 1 (4N, 1940ms), 2 (8N, 3920ms), and 3 (12N, 6000ms). As power is stored in advance, only a 360ms delay (60ms to block the *movement brake* and 300ms to release the *dynamic brake*) is required for impact. When firing and recoil is produced, the various firing speeds and distances of the balls are provided as visual feedback. After the experiment, the participants filled out a questionnaire with a 7-point Likert scale, allowing decimal scores, and were encouraged to give open-ended feedback in an interview. The study took a half an hour.

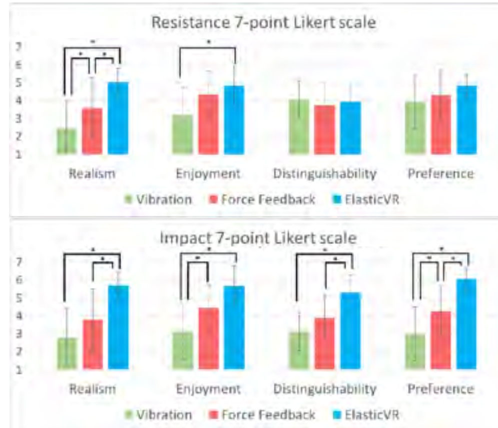

Figure 11: 7 Likert-scale of the VR experience study.

Results and Discussion

The scores on 7-point Likert scale are shown in Figure 11. Repeated measures ANOVA and Bonferroni correction for post-hoc pairwise tests are used for the further analyses. We did not try to compare with resistive force and impact, so the analyses were only within the same force feedback.

For resistive force, significant main effects are found in realism ($F_{2,22} = 32.64, p < 0.01$) and enjoyment ($F_{2,22} = 10.43, p < 0.01$), but not in distinguishability ($p = 0.83$) and preference ($p = 0.15$). Post-hoc pairwise tests show that there are significant differences among all pairs in regard to realism and only between (V, E) in enjoyment. Therefore, resistive force from (E) is significantly more realistic than that from (V) and (F). Resistive force from (E) and (F) has a similar enjoyment level. For impact, significant main effects are revealed in all factors ($p < 0.01$ in all). Post-hoc pairwise tests show that there are significant differences in (V, E) and (F, E) in realism and distinguishability, in (V, F) and (V, E) in enjoyment, and among all pairs in preference. Therefore, impact from (E) is significantly more realistic, distinguishable and preferred than that from (V) and (F). Impact from (E) and (F) has a similar enjoyment level.

For resistive force, all participants respond that the resistive force provided by (E) is more realistic. *P3, P9, P10, P11, P12* commonly mention that they clearly perceived the continuously-changing force magnitude as moving the hand, which made it realistic. *P9* comments that when pressing the balls, it seemed that a "buffer" absorbed the force she applied, and it gradually resisted the hand movement. The smooth and gradual force change caused the resistive force from (E) realistic. Although the force change is also in (F), the change of patterns from (E) and (F) are quite different. *P5, P12* suppose that force feedback from (F) with a delay when pressing the balls was not similar to elastic force. These results prove our claim that continuously-changing resistive force with no delay from (E) is significantly more realistic, although there exists a little delay in force level switching. Most participants suppose that (V) is not realistic at all in VR but a distinguishable hint, which is consistent with vibrotactile research. For (E), some participants comment that the lower and higher force levels are distinct, especially the *rigid* one. However, the middle levels are a bit unclear.

For impact, most participants mention that the impact instantly provided by (E) results in better realism. Compared with the impact from (E), that from (F) is not provided fast enough, which reduces the realism. These results also verify our claim that (E) providing impact instantly is significantly more realistic. More powerful motors or grounded devices might solve the problem, but those could make the wearable device bulky. Interestingly, only *P4* supposes that (V) is more realistic. *P4* comments that the recoil includes vibration and force feedback. The vibration from (V) is similar to the recoil feedback in video games using controllers, but the force feedback from both (E) and (F) are not realistic enough. He felt the hand pulled back instead of pushed, which limited the realism using (E). This could be further improved by combining tactile and force feedback as in [13]. Generally, ElasticVR provides better performance in both continuously-changing resistive force and instant impact, which indeed enhances VR experiences.

6 ELASTICVR APPLICATIONS

In addition to pressing balls and firing recoil, we propose another two ElasticVR applications, surgery training and baseball game, also shown in the demo video.

In the surgery training, ElasticVR provides resistive force for palpations and impact for electric shocks from defibrillation (Figure 12). For palpations, we provide two body parts, the chest and abdomen, of the patient in both healthy and unhealthy conditions. In the healthy condition, a chest with ribs inside is usually harder than an abdomen, so, resistive force level 4 and 2 are for the chest and abdomen, respectively. In

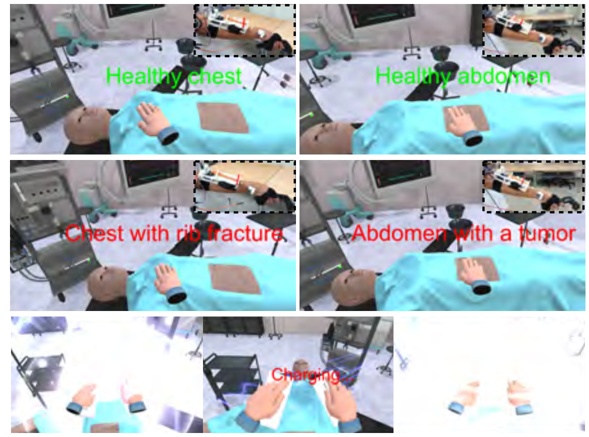

Figure 12: Surgery training. Palpation (upper) with 4 resistive force levels. Defibrillation (lower) with strong (lower-right) and weak (lower-left) electric shock.

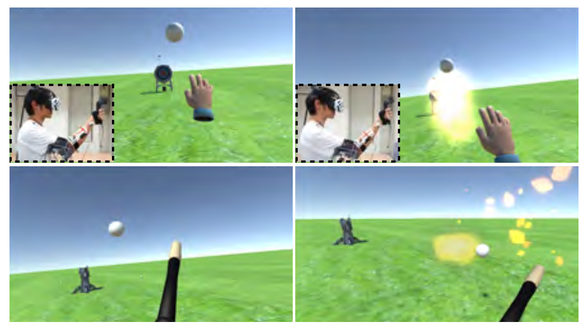

Figure 13: Baseball game. 2 resistive force levels in pitching (upper) and 2 impact levels in batting (lower).

an unhealthy condition, we provide stronger resistive force level 5 and 3 for a chest with a rib fractured and abdomen with a possible tumor, separately. With multilevel resistive force from ElasticVR, the users can learn to diagnose whether a patient is healthy in palpation training. For defibrillation, two electric shock levels are provided. After setting the electric shock level, the users press the grip button on the Vive controller to charge the defibrillator, and ElasticVR stores the impact power. When the charging is done, they press the grip button to defibrillate the patient, and ElasticVR provides the impact for the electric shock. We expect that the users experience surgery in VR before in the real surgery room.

In the baseball game, ElasticVR provides resistive force for pitching and impact for batting (Figure 13). For pitching, the users pitch at two power levels. They feel the stronger resistive force as pitching at faster speed and stronger power (fireball), and vice versa. They press and hold the grip button on the Vive controller to grasp the ball. When pressing the hand during pitching, the resistive force is gradually increased. When releasing the grip button, the ball is released and thrown, and ElasticVR releases the *movement* and *dynamic brakes* so the resistive force suddenly disappears. The inertia makes the hand suddenly move faster as the ball leaves the hand, which is similar to real pitching. In batting, the balls are ejected at two speeds. The faster ball speed, the stronger impact (fireball). After setting the ball speed, the users press the grip button, the pitching machine reloads, and ElasticVR stores the impact power. As the pitching machine ejects the ball, the users swing the bat. If hit, ElasticVR produces the impact. If missed, ElasticVR releases the *movement brake* and turns the *rotation motor* in reverse to release the stored power. Force feedback provided by ElasticVR makes the VR games and experiences more interesting and realistic.

7 LIMITATIONS AND FUTURE WORK

Some limitations exist in the current ElasticVR prototype. ElasticVR cannot provide resistive force if the users press with the arm instead of the wrist. It is a common limit for partial body devices [2, 3, 9, 20]. Such devices must be worn on all joints, e.g., wrist, elbow, shoulder [1], to provide complete force feedback. We envision downsizing ElasticVR and wearing it on all joints of the entire arm in a future version. By replacing the large servo motor with the micro gearmotor for the *rotation motor*, ElasticVR can be smaller and lighter but provide stronger torque. We also desire to miniaturize the device, so users can wear it on the fingers and perceive force feedback from each finger independently. However, how to provide the force normal to the fingers is still a problem. In addition, when pressing rigid objects, ElasticVR uses the *movement brake* to restrict the hand. It is strong enough since the users did not exert all strength to break the device when perceiving an object that is rigid. However, it can be further improved using advanced brakes as in [21]. Another limit of ElasticVR is time needed to store power for impact, so a quickly consecutive impact is improper. However, batting, electric shock with charging and shooting with weapon reloading are good applications.

8 CONCLUSION

In this paper, we propose a wearable device, ElasticVR, to provide continuously-changing multilevel resistive force and instant multilevel impact to enhance VR realism. Using servo motors and mechanical brakes to alter an elastic band's physical properties, length and extension distance, ElasticVR provides multilevel resistive force with no delay and impact with little delay for realistic and versatile VR applications. By performing a force perception study, we understand that 5 and 3 levels in resistive force and impact, respectively, are discriminative by users. Based on these results, we built the ElasticVR prototype and compare it with other feedback methods in the VR experience study. The results prove that resistive force and impact from ElasticVR are significantly more realistic. Finally, some ElasticVR applications are proposed.

ACKNOWLEDGMENTS

This research was partly supported by Ministry of Science and Technology of Taiwan (MOST106-2917-I-002-014, 107-2218-E-002-038, 107-2218-E-011-016, 106-2923-E-002-013-MY3), National Taiwan University (NTU-107L2033-03) and JST CREST Grant Number JPMJCR17A3, Japan.

REFERENCES

[1] Merwan Achibet, Adrien Girard, Anthony Talvas, Maud Marchal, and Anatole Lécuyer. 2015. Elastic-Arm: Human-scale passive haptic feedback for augmenting interaction and perception in virtual environments. In *Virtual Reality (VR), 2015 IEEE*. IEEE, 63–68.

[2] Merwan Achibet, Benoît Le Gouis, Maud Marchal, Pierre-Alexandre Leziart, Ferran Argelaguet, Adrien Girard, Anatole Lécuyer, and Hiroyuki Kajimoto. 2017. FlexiFingers: multi-finger interaction in VR combining passive haptics and pseudo-haptics. In *3D User Interfaces (3DUI), 2017 IEEE Symposium on*. IEEE, 103–106.

[3] Hrvoje Benko, Christian Holz, Mike Sinclair, and Eyal Ofek. 2016. Normaltouch and texturetouch: High-fidelity 3d haptic shape rendering on handheld virtual reality controllers. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. ACM, 717–728.

[4] Chia-Yu Chen, Yen-Yu Chen, Yi-Ju Chung, and Neng-Hao Yu. 2016. Motion guidance sleeve: Guiding the forearm rotation through external artificial muscles. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. ACM, 3272–3276.

[5] Inrak Choi, Heather Culbertson, Mark R Miller, Alex Olwal, and Sean Follmer. 2017. Grabity: A Wearable Haptic Interface for Simulating Weight and Grasping in Virtual Reality. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology*. ACM, 119–130.

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

[7] Inrak Choi, Eyal Ofek, Hrvoje Benko, Mike Sinclair, and Christian Holz. 2018. CLAW: A Multifunctional Handheld Haptic Controller for Grasping, Touching, and Triggering in Virtual Reality. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, 654.

[8] 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*. ACM, 426.

[9] Xiaochi Gu, Yifei Zhang, Weize Sun, Yuanzhe Bian, Dao Zhou, and Per Ola Kristensson. 2016. Dexmo: An inexpensive and lightweight mechanical exoskeleton for motion capture and force feedback in VR. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. ACM, 1991–1995.

[10] 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*. ACM, 109–117.

[11] Seongkook Heo, Christina Chung, Geehyuk Lee, and Daniel Wigdor. 2018. Thor's Hammer: An Ungrounded Force Feedback Device Utilizing Propeller-Induced Propulsive Force. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, 525.

[12] Seungzoo Jeong, Naoki Hashimoto, and Sato Makoto. 2004. A novel interaction system with force feedback between real-and virtual human: an entertainment system: virtual catch ball. In *Proceedings of the*

2004 ACM SIGCHI International Conference on Advances in computer entertainment technology. ACM, 61–66.

[13] 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*. ACM, 11–19.

[14] 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*. ACM, 1471–1482.

[15] 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.

[16] 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*. ACM, 19.

[17] Alvaro G Perez, Daniel Lobo, Francesco Chinello, Gabriel Cirio, Monica Malvezzi, José San Martín, Domenico Prattichizzo, and Miguel A Otaduy. 2015. Soft finger tactile rendering for wearable haptics. In *World Haptics Conference (WHC), 2015 IEEE*. IEEE, 327–332.

[18] 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*. ACM, 5318–5330.

[19] Domenico Prattichizzo, Francesco Chinello, Claudio Pacchierotti, and Monica Malvezzi. 2013. Towards wearability in fingertip haptics: a 3-dof wearable device for cutaneous force feedback. *IEEE Transactions on Haptics* 6, 4 (2013), 506–516.

[20] Samuel B Schorr and Allison M Okamura. 2017. Fingertip Tactile Devices for Virtual Object Manipulation and Exploration. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM, 3115–3119.

[21] Evan Strasnick, Christian Holz, Eyal Ofek, Mike Sinclair, and Hrvoje Benko. 2018. Haptic Links: Bimanual Haptics for Virtual Reality Using Variable Stiffness Actuation. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, 644.

[22] 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*. ACM, D300.

[23] 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*. ACM, 1.

[24] Andre Zenner and Antonio Krüger. 2017. Shifty: A Weight-Shifting Dynamic Passive Haptic Proxy to Enhance Object Perception in Virtual Reality. *IEEE Transactions on Visualization and Computer Graphics* 23, 4 (2017), 1285–1294.