彈力 VR: 利用彈性在虛擬實境中提供多個程度的連續力及瞬間力

蔡欣叡
國立台灣大學

曆本純一
東京大學

陳炳宇
國立台灣大學

ABSTRACT

在本篇文章中我們提出了一個輕巧的穿戴式裝置“彈力VR”，對手用者的手提供多個程度的連續力及瞬間力回饋，以提升虛擬實境的沈浸感。我們大略將力回饋分為被動力和主動力。被動力是根據使用者的動作改變而相應被動產生的力 (例如：彈力和阻力)。而主動力則是在使用者觸發某事件後系統主動產生的離散瞬間力 (例如：衝擊力和後座力)。彈力 VR 由彈力帶、伺服馬達和機械鎖所組成。藉由改變機械鎖和馬達去改變彈力帶的長度和延展度，彈力 VR 可以提供多個程度的連續被動力和瞬間主動力。我們透過一個最小可覺差實驗 (JND study) 去觀察使用者的力回饋感知能力，並根據此結果去製作出彈力 VR 的原型。我們也進行了一個 VR 體驗實驗來證明彈力 VR 的力回饋比目前 VR 回饋方式更能提升沈浸感，而最後我們也提出了一些彈力 VR 的應用。

Author Keywords

觸覺回饋; 力回饋; 彈力回饋; 虛擬實境; 穿戴式裝置。

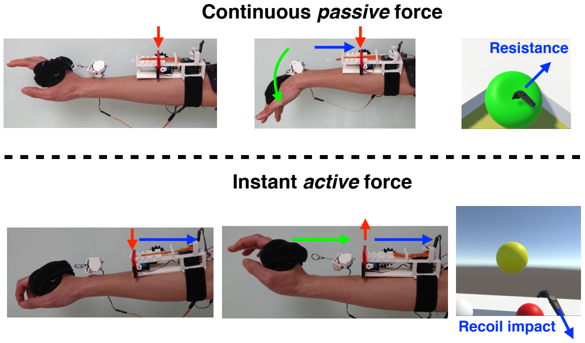


Figure 1: Continuous *passive* force and instant *active* force in ElasticVR. Blue, green and red arrows represent the force of the elastic band, hand movement and mechanical locks, separately.

INTRODUCTION

Force feedback enhances virtual reality (VR) realism and immersion, *e.g.*, continuous resistance when pressing elastic objects or drawing a bow in archery, and quick and strong impact when hit or punched. There are various forces in VR but not all of them can be realistically provided, *e.g.*, continuous force and instant force which are commonly existed in VR applications. Based on the features of how force feedback provided in VR, we generally categorize force feedback into *passive* and *active* forces. *Passive* force is produced passively and continuously changed against users' body part movement. It is dependent to users' movement and usually last in long time, *e.g.*, movement resistance and elasticity (stiffness/softness) as pressing or grasping an object. *Active* force is rendered actively, discretely and instantly stimulate users after triggering the events. It is independent to users' movement and usually last in a short period, *e.g.*, impact when punched and recoil when shooting. Providing continuous *passive* and instant *active* forces enhances realism in VR.

In terms of *passive* forces, Dexmo [8], Wolverine [7] and Grabity [6] restrain the fingers' movement using mechanical brakes to render rigid object shape. Haptic Links [**?**] uses servo motors to control locks and provide various stiffness. Elastic-Arm [1] uses an elastic band to provide *passive* elastic force as users extend the arm in VR. ExoInterfaces [20], CLAW [**?**] and Virtual Walls [12] simulate resistance using impulses from DC motors, a servo motor and electrical muscle stimulation (EMS), respectively. Previous researches generally leverage impulses from discrete control signals to simulate continuous *passive* forces, which limits the realism. Others provide single-level elasticity, which means a rigid object or elastic force with a certain kind of continuous change. Although simulated *passive* force is provided, truly continuous *passive* force with multilevel from a wearable device is not explored. To present *active* forces, Motion Guidance Sleeve [5] stimulates users' arm for guidance. Impulses from motors [20] and EMS [11, 12] are used to stimulate users. EMS presents quick force feedback, but requiring serial calibration steps. Motors need a delay to gradually provide strong force, which is not instant enough (Figure 7).

We propose a light-weight, wearable device ElasticVR to provide multilevel *passive* and *active* force feedback to the hand in VR. ElasticVR consists of an elastic band, servo motors and mechanical locks. By changing the elastic band length and fixed by the mechanical lock, it provides continuous *passive* force against the hand movement in multilevel elasticity. By extending the elastic band in different distances using the motor, energy is stored in the band in advance and multilevel *active* force feedback is rendered instantly. We observed users' multilevel force feedback perception in the just-noticeable difference (JND) study. Based on the results, we manufactured the ElasticVR prototype, further compared with current feedback methods in the VR experiences study and demonstrated VR applications using ElasticVR. ElasticVR enhances VR realism using *passive* and *active* force feedback.

RELATED WORK

We discuss researches providing haptic feedback, including cutaneous tactile and kinesthetic force feedback, in VR.

Tactile Feedback in VR

Vibrotactile [3, 10, 13, 18] is a common approach for tactile feedback. Various vibration intensities, duration or patterns are used to simulate touching different parts and textures of objects. By producing ultrasound from a transducer array, UltraHaptics [4] projects points on the users' hand to provide haptic and tactile feedback. NormalTouch and TextureTouch are proposed [2] to augment handheld controllers to render tactile feedback, respectively. By adjusting height and orientation of an adjustable platform on the controller, users perceive shape of virtual objects in NormalTouch. By controlling 4 × 4 array of pins on the controller, TextureTouch presents detailed feedback for texture of virtual objects. By altering orientation of a platform, [16, 17, 19] deform and squeeze the finger tip to provide cutaneous tactile and even force feedback on wearable devices. Tactile feedback methods generally provide detailed texture information of objects in VR to the finger tip. However, without restraining the finger movement, whenever the finger penetrates the virtual objects, the realism and immersion in VR are decreased. Tactile and kinesthetic feedback are complementary. Therefore, they should be combined, as in [11], to provide more realistic haptic feedback in VR.

Force Feedback in VR

Using DC motors to control wires, SPIDAR [14] and [9] provide force feedback in a fixed operating space. SPIDAR-W [15] improves the concept of SIPDAR and implement it on a wearable device. However, these methods are still bulky for wearable devices.

For light-weight devices, Dexmo [8] and Wolverine [7] worn and Grabity [6] hold on the hand, leverage servo or DC motors to control mechanical locks to restrain the users' fingers. Therefore, when grasping a rigid object in VR, the fingers are fixed as the object shape and not able to further penetrate the virtual object. *Passive* force feedback is perceived by the users as grasping. Haptic Links [?] uses servo motors to control friction of the mechanical locks in "chain" and "layer-hinge" forms to provide stiffness in continuous range. Elastic-Arm [1] on the other hand uses an elastic band worn on a shoulder and a hand to provide *passive* force feedback. The elastic force is produced and increased continuously as the hand stretches and extends the elastic band. The feedback is used to simulate extending the arm in VR. Exointerfaces [20], worn on a upper arm, renders *passive* force to the forearm using DC motors and belts. The high frequency impulses produced by the motors provide *passive* force feedback for resistance in VR. CLAW [?] uses a servo motor and force sensor to build a closed-loop force control system. By combining PD control, it simulated different stiffness. EMS impulses are also used to produce *passive* force in VR proposed in [12]. By placing electrodes on shoulders and arms, the force feedback is used to simulate resistance.

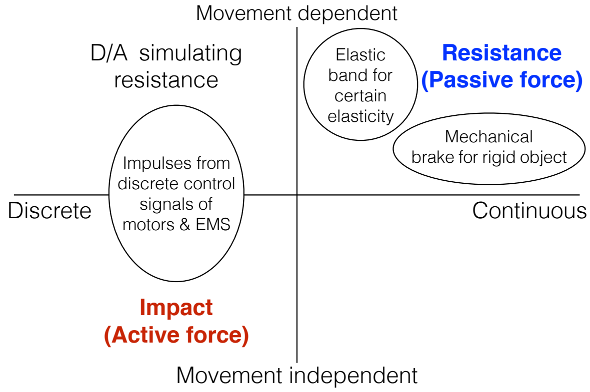


Figure 2: Category of force feedback in VR.

In *active* force feedback, Motion Guidance Sleeve [5], worn a forearm, uses step motors to drag users' arm and provide motion guidance in rotation direction for the arm. Impacto [11] combines kinesthetic feedback from EMS and tactile feedback to provide realistic impact as punched or hit. Exointerfaces [20] and Virtual Walls [12] provide both *passive* and *active* forces using impulses from DC motors and EMS.

The previous researches generally provide single-level *passive* force (*i.e.*, rigid body or certain elasticity). Others leverage discrete control signals to provide impulses from motors or EMS to simulate continuous *passive* force. Although high frequency impulses used, due to the device dead band, continuos *passive* force simulated by discrete impulses has limited realism. While "continuous range" stiffness is provided, *passive* force with "continuous change" force magnitude is hard to be simulated. Furthermore, without bulky but powerful grounded devices, instant *active* force is limited in tiny DC motors, which need a delay to provide strong force. Although EMS provides powerful and quick *active* force, it overwrites the body part movement internally, which is different from *active* force feedback externally applying to the users in usual. Besides, a serial of calibration steps of EMS are demanded. We propose a wearable device ElasticVR to provide continuous *passive* and instant *active* force in multilevel (Figure 2).

DESIGN CONSIDERATIONS

To enhance VR realism using multilevel *passive* and *active* force feedback on a light-weight wearable device, several factors need to be considered.

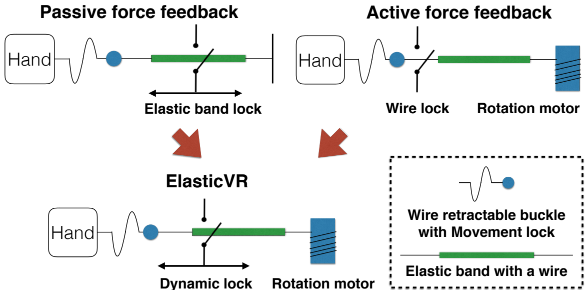


Figure 3: ElasticVR design. Combining functions of providing *passive* and *active* force feedback into one device.

- **Passive force**: Force feedback produced passively and changed continuously against users' movement. *Passive* force increases as moving in the opposite direction to the force direction, and decreases as moving in the same direction. As moving back to the original position, the *passive* force is not further provided. Reaction and elastic forces as pressing or grasping rigid and elastic objects, and resistance are typical *passive* forces. Notably, multilevel *passive* force in this paper does not only mean the force changed depending on the movement but indicates that it is changed in various patterns as grasping different elasticity (stiffness/softness) of objects.
- **Active force**: Force feedback rendered actively, discretely and instantly to stimulate the users as impact while triggering some events in VR. Instant *active* force is usually only lasts for a moment and independent to the users' movement. Impact when punched or hit in action games, recoil when firing in first-person shooting games, and guidance in rhythm or sport games [5] are examples of *active* forces.
- **Realism**: To provide realistic force feedback for immersive VR experiences, truly continuous *passive* force and instant *active* force are required.
- **Light-weight**: Light-weight devices usually demand low computation and power consumption, which are essential for wearable devices. Keeping computing force feedback corresponding to users' movement, and frequently actuating devices to provide various forces increase computation and power consumption, especially for continuous *passive* force feedback, which is undesired.

Providing truly continuous *passive* and instant *active* force feedback in multilevel but avoiding frequently computing force feedback and actuating electronic devices is the goal we would like to achieve.

ELASTICVR

Design

We propose a light-weight, wearable ElasticVR worn on the forearm to provide force feedback to the hand. ElasticVR consists of an elastic band, servo motors and mechanical locks. By altering the band elasticity using servo motors and mechanical locks, ElasticVR provides multilevel *passive* and *active* forces. While not all bands follow Hooke's law as a spring, length and extension distance of an band still maintain non-linear relations to elasticity. For *passive* forces, ElasticVR leverages an movable *elastic band lock* to block the band in different length (Figure 3(left)). For the same band, the shorter the band, the lager the elasticity. Therefore, the shorter the distance between the *elastic band lock* and the hand, the stronger *passive* force provided. As the *elastic band lock* blocks for the certain *passive* force level (or elasticity), the band is extended and the force is increased continuously in the opposite direction to the hand's movement. As releasing and moving the hand back, the band looses and the force is decreased. For *active* forces, ElasticVR extends the band in different extension distances by rotating a *rotation motor* for various *active* force levels. Using a *wire lock* to block between the band and hand, the extension band stores energy in advance and is released to stimulates users instantly as the *wire lock* open (Figure 3(right)).

Using the proposed method to provide force feedback, the hand movement should be restrained as forces delivered, and free as forces not delivered. To achieve such requirements, we leverage a wire retractable buckle with a *movement lock* (Figure 3 (dotted frame)). The retractable wire is connected to the hand, and the buckle with the *movement lock* is connected to the band. While slight retract force felt, it is neglected compared with force feedback from ElasticVR. The retractable buckle provides free hand movement as the *movement lock* open, and blocks the hand movement as the *movement lock* blocks the retractable wire for force delivery. Such design allows users to freely move the hand as ElasticVR stores energy for *active* force.

To provide both *passive* and *active* forces from a device, we observe that the wire retractable buckle with the *movement lock* can be shared, and the *elastic band lock* and *wire lock* can be combined into one moveable *dynamic lock* (Figure 3 (lower)). Therefore, ElasticVR consists of an elastic band, two locks, including a *dynamic lock* and a *movement lock*, and a *rotation motor* (Figure 4 and 5).

Prototype Implementation

Elastic band

The wider a elastic band, the larger elasticity and force feedback it provides. We chose the proper elastic band in a pilot with band width 1cm and length 8cm, which was discriminatively perceived as extended by the hand. Furthermore, to make the band firmly blocked by the *dynamic lock*, several *knots* made up of tiny rubber bands were tied on the elastic band, and a *knot* was tied on the wire (Figure 4 (upper right)). Two wires made up of fishing lines were connected two sides of the elastic band with the *rotation motor* and the *movement lock*, respectively. The ElasticVR prototype was shown in Figure 4 and 5.

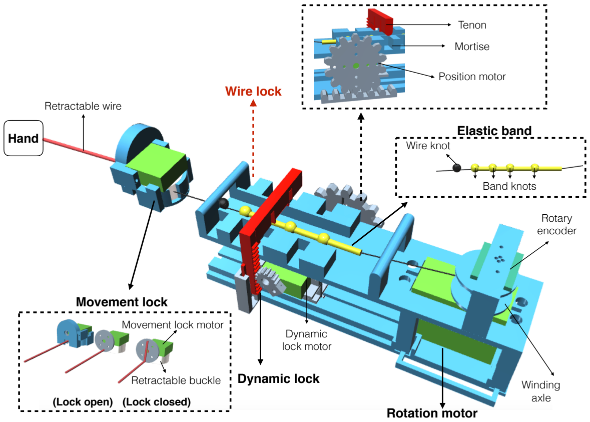


Figure 4: ElasticVR prototype in STL 3D model.

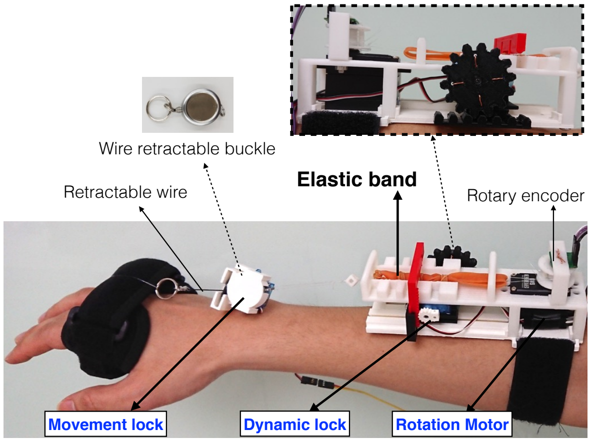


Figure 5: ElasticVR prototype worn on the forearm.

Dynamic Lock

We leveraged mechanical designs to built the movable *dynamic lock*. Mortises were built and a tenon was controlled by a tiny servo motor called *dynamic lock motor* (Figure 4 (upper)). We used another tiny servo motor called *position motor* to make the *dynamic lock* movable, and move the tenon to different mortises positions. XCSOURCE RC450 were used as the *position motor* and *dynamic lock motor*. The one mortise closest to the hand was for the *dynamic lock* used as the *wire lock* (Figure 3) to block the wire. The other mortises were for the *dynamic lock* used as the *elastic band lock* to block the elastic band into different length. Each *knot* on the elastic band was corresponding to mortise in the *dynamic lock*.

Movement Lock

A tiny servo motor (RC450) called *movement lock motor* was attached to a wire retractable buckle. The *movement lock motor* controlled a disc with a tiny hole, and the retractable wire was pulled through the hole connected to the hand. Most part of the disc was in a case. As the *movement lock* closed, the hole with the wire on the disc was rotated in the case, the wire was fixed by friction and the hand movement was blocked (Figure 4 (lower left)).

Rotation Motor

A continuous rotation servo motor (GWS S35 STD) combined with a rotary encoder (Pololu Magnetic Encoder) were used as the *rotation motor* with precise rotation control. A winding axle with radius 1mm was attached to the *rotation motor* to wrap the wire connected to the elastic band.

The *dynamic lock* is moved and closed at first for both force feedback. The *movement lock* is then closed to block hand movement for force delivery in *passive* force and after the band extension using the *rotation motor* in *active* force. The *dynamic lock* and *movement lock* are opened to free hand movement in *passive* force, and deliver force and free the hand in *active* force. In *active* force, we design a 100ms delay between *dynamic lock* and *movement lock* opened to reinforce force feedback, and the *rotation motor* rotates reversely to loose the elastic band at last.

Using the *dynamic lock* and *rotation motor*, multilevel *passive* and *active* forces are provided. With the mechanical lock consists of a tenon, mortises in the *dynamic lock* and knots on the elastic band, truly continuous *passive* force and instant *active* force are rendered to enhance VR realism. The mechanical lock is not actuated after closed and provides continuous force depending on the hand movement, which achieves low computation and power consumption. ElasticVR satisfies all design considerations.

Different numbers and magnitude of *passive* force levels require different mortises and knots. Different *passive*

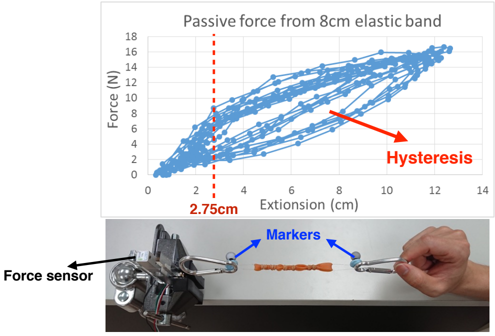


Figure 6: *Passive* force stimuli collection using force sensor and Optitrack markers. Hysteresis caused different forces in the same extension.

force levels need corresponding rotations from the *rotation motor*. We observed the parameters in the following study.

JUST-NOTICEABLE DIFFERENCE (JND) STUDY

To provide proper *passive* and *active* parameters for ElasticVR, we observed users' force feedback perception ability in the just-noticeable difference (JND) study, as in [?, ?]. Different force levels in *active* force provided by a preliminary ElasticVR prototype were examined. However, instead of a certain force magnitude, *passive* force continuously changed depending on users' movement was different from traditional JND stimuli. Therefore, we defined the stimuli specification for *passive* force level.

Apparatus and Participants

Without knowing proper mortise arrangement for *passive* force, we built a preliminary ElasticVR prototype with equidistant mortises to provide only *active* force in the JND study. ElasticVR was described in the previous section. Arduino Uno was used to control the motors in ElasticVR using an USB cable. An eye mask and earphones were worn to block visual and audio feedback. 12 right-handed participants (5 female) aged 23-33 (mean: 25.25) were recruited.

JND Stimuli

The hand movement ranges were various among individuals, so in the same *passive* force level, different maximum forces could be perceived. We observed that users repeatedly pressed the hand and extended the elastic band to perceive *passive* force in a smaller *force perception range*. The mean range 2.5cm (band extension between 1.5 to 4cm) was found using a tape measure in the pilot. Furthermore, due to hysteresis, in the same elastic band extension, the force in band extending procedure is stronger than in loosing procedure Figure 6. Therefore, we defined a *passive* force level as the force magnitude with 2.75cm band extension (middle of the range) in band extending procedure.

We fixed one side of the elastic band with a load cell (TAL220 with HX711 ADC amplifier) and extended it from the other side (Figure 6 (lower)). Two markers attached on the both sides were tracked by the OptiTrack system. By repeatedly extending the band, we collected force and extension data (Figure 6 (upper)). By averaging the force in extension 2.75cm with 0.5cm interval (2.5 to 3 cm) in the extending procedure, we obtained the *passive* force in the current level. By tying knots on the band, we found proper levels for JND stimuli. In *active* force, the same force sensor was used. However, without extending the band manually, we gave different rotation numbers to ElasticVR, which was also fixed, and recorded the *active* force as the *dynamic lock* opened and impact produced. We also used the setup to show the instant *active* force from a motor impulse and from ElasticVR using the same motor in Figure 7.

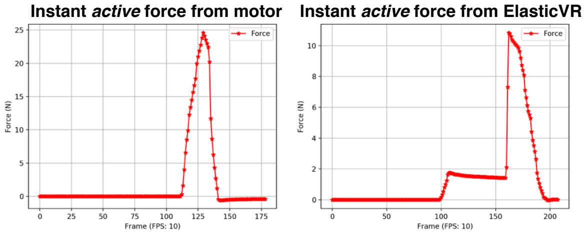


Figure 7: Instant *active* force from a motor impulse and ElasticVR.

Task and Procedure

A pair of force stimuli were provided in a trial in the JND study. Instead of distinguishing which force is stronger, participants only needed to respond that the force levels were the *same* or *different*. Each pair of stimuli included a *base* and *offset* force magnitude. *Passive* 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 two band with the same width and length to provide *passive* force level from 7N to 14N (Figure 8). *Active* force stimuli included four base forces (1N, 2N, 4N, 8N) and four offset forces (0N, 1N, 2,N, 4N). The rotation numbers were between 0.25 to 2.75 full rotations of the *rotation motor* in ElasticVR. *Passive* and *active* force feedback were examined separately. Usually, the base and offset values were increased exponentially in a JND study. However, the force magnitude range of *passive* force is depending on the elastic band, which did not provide such wide range forces. Therefore, the base forces were increased linearly in *passive* force. A total of 16 conditions for *passive* and *active* force, respectively. The order of stimuli in each pair was randomized. Each condition was repeated once. Thus, 64 (= 2 (force feedback) × 16 (conditions) × 2 (repetitions)) trials were examined by a participant from both force feedback in the JND study.

During the experiment of *passive* force, instead of wearing ElasticVR, we directly fixed one side of the elastic band and the other was connected to the hand brace

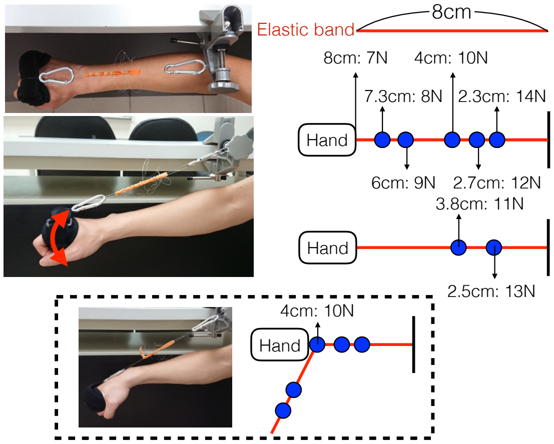
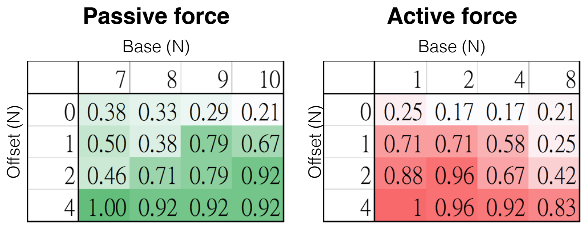


Figure 8: *Passive* force JND study apparatus. 7 knots (blue dots) were tied on 2 elastic bands (right). 10N *passive* force was provided (lower).

worn on the hand. The participants also wore a eye mask to eliminate visual feedback. The experimenter adjusted the force level by fixing the band at the corresponding knot, moved the participants' arm and hand to where the band was straight but not extended, and made sure the band is parallel to the arm for proper force direction. The participants then pressed the hand repeatedly to perceive the force, and tried the other stimulus force in the pair. They could ask to play back stimuli to confirm the perception and responded the answer. The experimenter unfixed the band to free hand and adjust to next force level between stimuli, which made sure the participants could not use the relative hand position to infer the band length. In *active* force, the participants wore the preliminary ElasticVR prototype, eye mask and earphones, blocking motors' sound, and laid the forearm on the desk to perceive stimuli. The experimenter adjusted the force levels by sending control signal with corresponding rotation numbers to ElasticVR. The study took about an hour.

Results and Discussion

The results of the JND study in *passive* and *active* force feedback were shown in Figure 9. The fractions of responses that participants regarded the stimuli in pair as the same force level were shown. Interestingly, we observed that in *passive* force, the smaller base forces required larger offset forces to be distinguished, which was contrast to normal JND results as in *active* force. Due to *passive* forces with continuous force change, which was quite different from traditional JND stimuli, this might cause the unique JND results. The participants responded that it was harder to distinguish whether the stimuli were the same in lower *passive* force levels with weaker resistance. However, in higher *passive* force levels, they perceived that the resistance increased quickly, which caused the stimuli more discriminative. Therefore, we supposed that more distinct force increase as the same band extension was clearer to be perceived and distinguished.



Passive 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

Active force

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: JND study results of *passive* and *active* forces. Fractions of responses that the pair of stimuli were supposed as equal were shown.

In terms of the *active* force, the results were quite typical, loosely consistent with Weber's law (constant = (offset) / (base)). The stronger base force required stronger offset force to be distinguished. Although the unexpected results in *passive* force, based on the results in Figure 9, we still could obtained proper *passive* and *active* force perception levels over 90% JND. In *passive* force, five levels (7N, 10N, 12N, 14N, *rigid*) were provided. 7N was the minimum passive force provided by the band. *Rigid* indicated as pressing stiff object with strongest elasticity or resistance. The elastic band length was 0 in ElasticVR and totally blocked by the *wire lock*. In *active*, three *active* levels (4N, 8N, 12N) were provided. We chose 4N instead of 2N as the base to make force feedback stronger and more easier to be perceived in VR applications. Based on the results, we manufactured the ElasticVR prototype with proper mortises' and knots' positions, and set corresponding rotation numbers (Figure 4 and 5).

VR EXPERIENCES STUDY

We further observed whether the continuous *passive* force and instant *active* force from ElasticVR were more realistic than those from conventional feedback methods, and enhanced VR experiences.

Apparatus and Participants

ElasticVR made based on the JND study, a HTC Vive HMD and controller were used in this experiment. Earphones were worn to block audio feedback. 12 right-handed participants (3 female) aged 20-31 (mean: 24.33) were recruited. One did not experience VR before. Five of them attended to the JND study but approximately a week elapsed between the two studies.

Task and Procedure

Three feedback methods were examined, including vibration feedback (V) from the off-the-shelves controller, general force feedback method (F) using impulses from discrete control signals of a motor, and force feedback from ElasticVR (V+F). Two force feedback, *passive* and *active* forces with 5 and 3 levels were experienced, separately. Therefore, a total of 6 (= 3 (methods) × 2

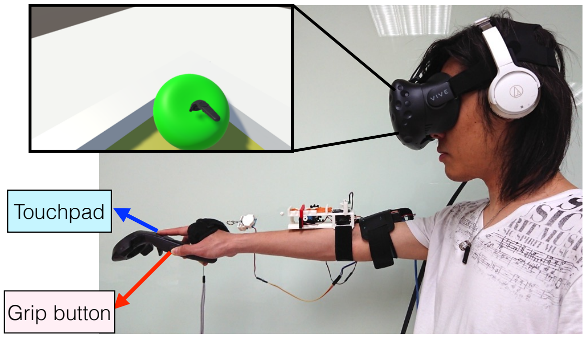


Figure 10: Apparatus and VR scene of the VR experience study.

(force feedback)) conditions were experienced. Feedback methods were counterbalanced. Each method was experienced for about 5 to 10 minutes. Distinguishability of force levels were examined in the JND study, so it was not the examined factor in the study, but observed it only using the subjective scale.

We built a VR scene and allowed the participants to freely press and shoot (or fire) virtual objects to experience continuous resistance from elastic objects and instant impact from recoil in *passive* and *active* forces. There were five balls with different colors and elasticity (Figure 10). The participants held a Vive controllerlightweight in the dominant hand and freely explored the VR scene by pressing the balls. To reduce the delay from mechanical operations in ElasticVR, as the controller approached a ball, *dynamic lock* was moved to the corresponding position and closed. Therefore, ElasticVR only needed to close the *movement lock* to provide *passive* force. By replacing the elastic band with a fishing line and disabling dynamic lock, the same ElasticVR device was used to provide motor impulses. Different deformation levels of the balls, vibration periods from the controller (V), motor rotation speeds (F) and *passive* force levels from ElasticVR (E) were provided as pressing the balls.

In firing or shooting, the participants randomly picked a ball by pressing the grip button with thumb and *fire* it by pressing the touch pad with the index finger on the controller (Figure 10). After a short period to store the fire power, the ball was ejected. Three different levels of fire power were presented. The fire power levels were depending on the fire sequence instead of the ball color. The stronger fire power, the longer power storing period. The periods were the same in all feedback methods. The speeds and distances the balls flew, vibration periods (V), motor rotation speeds (F) and *active* force levels from Elastic (E) were provided as firing and recoil produced. After the experiment, the participants filled out a questionnaire with a 7-point Likert scale, decimal scores were allowed, and encouraged to have some open-ended feedback in the interview. The experiment took approximately an half hour.

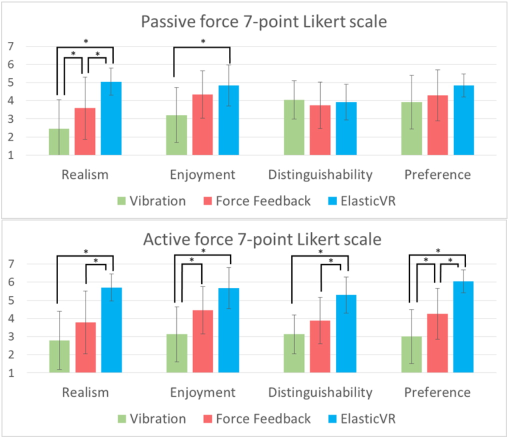


Figure 11: 7 Likert-scale of the VR experience study.

Results and Discussion

The scores in subjective 7-point Likert scale were shown in Figure 11. Repeated measures ANONVA and Bonferroni correction for post-hoc pairwise tests were leveraged for the further analyses. We did not try to compare with *passive* and *active*, so the analyses were only within in the same force feedback.

In *passive* force, significant main effects were 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 showed that significant differences were among all pairs in realism and only between (V, E) in enjoyment. Therefore, *passive* force feedback from (E) was significantly more realistic than that from (V) and (F). *Passive* force feedback from (E) and (F) had similar enjoyment level. In *active* force, significant main effects were revealed in all factors ($p < 0.01$ in all). Post-hoc pairwise tests showed that significant differences were in (V, E) and (F, E) in realism and distinguishability, in (V, F) and (V, E) in enjoyment, and among all pairs in preference. Thus, *active* force from (E) was significantly more realistic, distinguishable and preferred than that from (V) and (F). *Active* force feedback from (E) and (F) had similar enjoyment level.

In *passive* force, all participants responded that the force provided by (E) was more realistic. *P3, P9, P10, P11, P12* commonly mentioned that they clearly perceived the force change as the hand movement, which made it realistic. *P9* commented that as pressing the balls, it seemed a "buffer" to absorb the force she applied and gradually resisted the hand movement. The smooth and gradual force change caused the force from (E) realistic. Although the force change also existed in (F), the change patterns from (E) and (F) were quite different. *P5, P12* supposed that they perceived force feedback from the impulses for (F) pulling the hand and releasing, but the discrete force impulses were not similar to elastic force. Certainly, with high sample rate controller or PID controller and motors, the force change could be smoother and more continuous. However, higher computation and power consumption were required as well. It showed that (E) could provide more realistic *passive* force than (F) using the same light-weight device. (V) was generally supposed not realistic but only providing a hint. However, some participants supposed (V) was more distinguishable, due to used to vibration controller in video games (*P11*). In (E), some participants commented that the lower and higher force levels were distinct, especially the *rigid* one. However, the middle levels were a little bit unclear.

In *active* force, most participants mentioned that the impact force provided instantly by (E) resulted in better realism. Compared with the force from (E), the force from (F) was not provided fast enough, and reduced the realism. Again, more powerful motors could solve the problem, but this violated the light-weight design consideration. Interestingly, *P4* was the only participant supposing that (V) was more realistic in shooting or firing. *P4* commented that the recoil consisted of vibration and force feedback. The vibration from (V) was similar to the recoil feedback in video games using controllers, and the force feedback from both (E) and (F) were not realistic enough. However, generally ElasticVR was shown to provide better performance in both *passive* and *active* force feedback. Continuous and instant forces provided by ElasticVR indeed enhance VR experiences.

LIMITATIONS AND FUTURE WORK

Some limitations exist in current ElasticVR prototype. As shown in Figure 2, the continuous/movement independent category is still not provided. By combining a force sensor and PID control in ElasticVR as in CLAW [**?**], ElasticVR is possible to provide the force feedback. Furthermore, the current *passive* force level specification defined in this paper seems not precise enough in the JND study. We suppose that taking the relation between force increase and extension may be more proper. We also envision some ElasticVR applications using continuous and instant forces. In baseball games, ElasticVR provides continuous *passive* force in pitching and releases as the ball thrown, so the pitcher feels the stronger resistance as pitching in faster speed. Instant *active* force can be used in batting as well. In surgery training, students touch different body parts of the patient to diagnose whether it is normal based on the elasticity, which can be provided by continuous *passive* force. They could experience the impact as using defibrillator to cure patients simulated by instant *active* force. We will improve the ElasticVR device and implement more novel VR applications in the future.

CONCLUSION

We propose a wearable device ElasticVR to provide continuous *passive* force and instant *active* force feedback in multilevel. By leveraging a elastic band, servo motors and mechanical locks, the light-weight ElasticVR device alters the band elasticity and provides truly continuous force and instant force. By performing the JND study, we obtain that 5 and 3 levels in *passive* and *active* forces, respectively, are discriminative from users and proper to be provided by ElasticVR. Based on the results, the ElasticVR prototype is build and further used to compare with other feedback methods in the VR experiences study. The results show that continuous resistance and instant impact provided by ElasticVR are more realistic than that from other methods. ElasticVR enhances VR realism.

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