ElastiLinks: Force Feedback between VR Controllers with Dynamic Points of Application of Force

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ABSTRACT
Force feedback is commonly used to enhance realism in virtual reality (VR). However, current works mainly focus on providing different force types or patterns, but do not investigate how a proper point of application of force (PAF), which means where the resultant force is applied to, affects users' experience. For example, users perceive resistive force without torque when pulling a virtual bow, but with torque when pulling a virtual slingshot. Therefore, we propose a set of handheld controllers, ElastiLinks, to provide force feedback between controllers with dynamic PAFs. A rotatable track on each controller provides a dynamic PAF, and two common types of force feedback, resistive force and impact, are produced by two links, respectively. We performed a force perception study to ascertain users' resistive and impact force level distinguishability between controllers. Based on the results, we conducted another perception study to understand users' distinguishability of PAF offset and rotation differences. Finally, we performed a VR experience study to prove that force feedback with dynamic PAFs enhances VR experience.

Author Keywords
Haptic feedback; force feedback; resistive force; impact; point of application of force; virtual reality

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

INTRODUCTION
Handheld controllers are common devices in virtual reality (VR) interactions. Previous research proposes various force feedback not only on but also between VR controllers. To achieve realistic force feedback between controllers, in addition to force types or patterns, *e.g.*, pulling force, resistive force, impact or inertia force, a proper *point of application of force* (PAF), which means where the resultant force is applied to, is also a critical factor. For example, when pulling a bow in VR, users perceive resistive force without torque on the hand holding the virtual bow since the positions of the PAF and hand are almost the same. However, when pulling a slingshot, users perceive torque of resistive force on the hand holding the virtual slingshot since the PAF is above the hand on the controller (Figure 1). Therefore, to render such force feedback between controllers, a dynamic PAF on each controller is required.

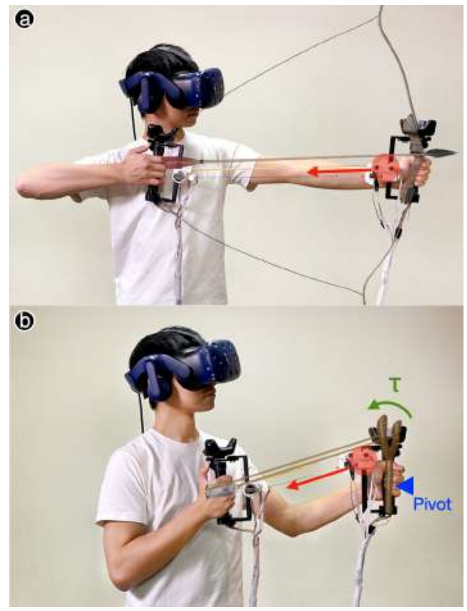

Figure 1. Users perceive resistive force (a) without torque when pulling a virtual bow, and (b) with torque when pulling a slingshot. The translucent red point is the point of application of force (PAF).

Previous works propose various haptic controllers using motors or propellers to provide force feedback [2, 5, 6, 11, 13, 16, 19]. However, these works focus on force feedback on a controller instead of between controllers. For force feedback between controllers, Haptic Links [12] proposes three kinds of mechanical brakes on three links, respectively, between VR controllers to render variable object shapes and stiffness feedback between the two hands or even on one hand with the other controller grounded on the body or in the environment. Nonetheless, where the links connect to the controllers are fixed, so the PAFs are fixed as well. Some other methods [10, 18] use motors to move weights to generate different magni-

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tude of torque on the controllers and achieve weight-changing and shape-changing illusions in VR. Although these methods leverage the property of a dynamic PAF(s) and prove its effect, they focus on weight and shape changing on a controller. How force feedback with dynamic PAFs between controllers affects users' VR experience still waits to be explored.

We propose handheld controllers, ElastiLinks, to provide force feedback with dynamic points of application of force between the controllers. ElastiLinks consist of two controllers, tracks, connectors, and force links. Each controller rotates a track and moves a connector, where the links connect to the controller, on the track. Therefore, the connector becomes a dynamic PAF for the controller, and is able to provide different torque to the controller and hand. Furthermore, ElastiLinks provide two common types of force feedback, resistive force and impact, based on the design concept of ElasticVR [17], on those two links, respectively, between the controllers. With the two types of force feedback and two dynamic PAFs on the two controllers, respectively, ElastiLinks achieve realistic and versatile force feedback between controllers in VR. Although we focus on investigating the dynamic PAF issue in this paper, we must attain distinguishable force levels for resistive force and impact for a proper PAF study design. Therefore, we conducted a perception study to understand users' resistive and impact force level distinguishability between controllers. In additioin, we then performed a second perception study to observe users' distinguishability of PAF offset and rotation differences, which also proves the necessity of requiring dynamic PAFs. Based on the results, we conducted a VR experience study to verify whether force feedback with dynamic PAFs from ElastiLinks enhances VR realism.

This paper presents the following contributions:

1. Providing force feedback between controllers with dynamic points of application of force.
2. Exploring users' resistive and impact force level perception between controllers.
3. Exploring users' distinguishability of PAF offset and rotation differences.
4. Proving that force feedback with dynamic PAFs from ElastiLinks enhances VR realism.

RELATED WORK

Force Feedback on Controllers in Virtual Reality

To enhance VR realism and immersion, previous works propose different haptic controllers to present various force feedback. Thor's Hammer [5] leverages six motors and propellers to generate strong thrusts of air, and provides 3D force feedback on a controller. LevioPole[9] is a stick-like device with multirotors on each side to provide mid-air force feedback. Aero-plane [6] utilizes two miniature jet propellers to simulate weight changes on a 2D plane on a controller. By adjusting the force magnitude of each propeller, illusions of weight shifting and objects with various centers of mass are rendered. Drag:on [19] combines air resistance and weight shifting using a fan-based design to provide dynamic passive haptic feedback on a controller. When rolling and swinging the device, the users perceive multilevel resistive force as the device dynamically changes its surface area and mass distribution. PaCaPa [13] uses two servo motors to control the degrees of two wings on a handheld device which provides dynamically changing pressure to the palm and fingers. This provides the illusion of using a stick to interact with virtual objects in VR. ElastOscillation [16] uses six elastic bands and a proxy to provide 3D force feedback for damped oscillation. The elastic bands' extension distances are controlled by motors to achieve multilevel force feedback. However, the aforementioned works focus on providing force feedback on a single controller instead of between controllers.

For force force feedback between controllers, Haptic Links [12] proposes three kinds of mechanical brakes on three links to provide variable stiffness feedback between controllers. By constraining the specific degree of freedom (DoF) or direction of movement of the controllers, two independent controllers could be used as two-handed tools or weapons. In addition to two-handed tasks, by affixing one of the controllers of Haptic Links on the body or in the environment, force feedback in one-handed tasks can also be provided. This work focuses on stiffness feedback between controllers with fixed PAFs on the controllers. However, the dynamic PAF issue is not discussed in these force feedback controller works.

Dynamic Point of Application of Force in Virtual Reality

To achieve more realistic force feedback, the factors affecting user experience include not only force types or patterns but also the proper PAF. TorqueBAR [14] is a two-handed handheld device, which moves the center of mass in 1DoF to render dynamic inertia feedback. Shifty [18] is a rod-shaped VR controller which dynamically shifts its center of mass to change its lever arm and torque and generate the illusion of shape-changing or weight-changing. Similarly, Transcalibur [10] changes its inertia and center of mass by moving weights on a 2D plane of a controller to render the illusion of 2D shape-changing in VR. SWISH [8] is a weight-shifting interface which dynamically changes the center of gravity of a physical vessel to simulate the weight-shifting of liquid. These methods generate the illusions of shape-changing or weight-changing by shifting a weight(s) and changing the center of mass, which leverages the property of a dynamic PAF(s) of gravity. In addition to the force of gravity, dynamic PAFs for various types of force feedback still waits to be explored.

ELASTILINKS

We propose handheld controllers, ElastiLinks, to provide dynamic points of application of force (PAFs) between controllers to enhance VR realism. For a handheld controller, a PAF is where the resultant force is applied to the controller. The same force applied to different PAFs could cause different magnitude and directions of torque on the hand as perceived by the users. For example, when pulling a bow and a slingshot in VR, the hand holding the bow feels resistive force without torque but the hand holding the slingshot perceives both resistive force and torque. This shows how different PAFs affect users' experience. Therefore, a proper PAF is required for VR force feedback devices.

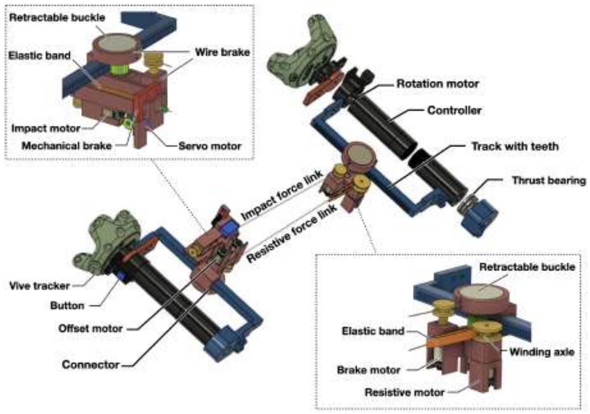

Figure 2. The hardware structure of the ElastiLinks prototype.

Design Considerations

To accomplish our goals, the following design considerations should be taken into account.

- *Realism.* To render force feedback between controllers to enhance the VR experience, it is essential to provide realistic force feedback with proper PAFs for to the corresponding applications. This allows users to perceive not only the proper force magnitude and pattern but also torque on the hands. Therefore, providing dynamic PAFs is our primary consideration.

- *Versatility.* In order to provide force feedback for diverse applications in VR, the versatility of force feedback of the proposed devices is important. Therefore, we implement two types of common force feedback in VR, resistive force and impact, on our devices. To further increase variety for diverse applications, rendering multilevel force feedback is essential.

- *Comfort and Safety.* Comfort and safety are always significant factors that need to be considered for VR haptic devices. Otherwise, users may get injured. To achieve this consideration, the magnitude of force provided by the devices should not be too strong to make users either uncomfortable or even hurt.

- *Mobility.* To allow users to freely explore in VR, the controllers should not be too bulky and heavy, which may hinder the users' movement or tire them easily. If users' physical effort is too much, it may also make the users unwilling to use the devices. Therefore, to achieve mobility in VR, the size and weight of the proposed devices should be considered.

Hardware

The hardware structure of ElastiLinks is shown in Figure 2. ElastiLinks consist of two controllers, tracks, connectors, and force links. The force feedback between the controllers is generated by the force links, and the connectors are at the positions that the links connect to the controllers. Therefore, the two connectors are the PAFs on the controllers, respectively. To provide force feedback with dynamic PAFs, the movement of the connectors on the controllers consists of two kinds of movement, *rotation* and *offset*. The offset is perpendicular to the rotation plane. Each controller rotates the track and moves the connector on the track to achieve the rotation and offset movement, respectively, as shown in Figure 3.

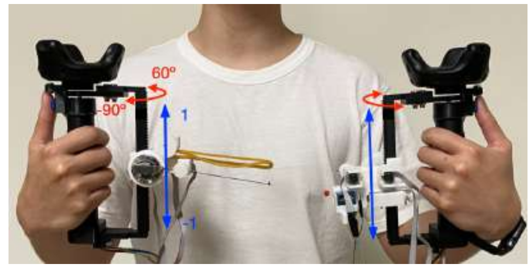

Figure 3. The PAF rotation (red) and offset (blue) movement ranges on the ElastiLinks prototype.

To implement a rotatable controller, a DC motor, called a *rotation motor* (Pololu Metal Gearmotor with gear ratio 499:1 and a 48 counts per revolution encoder), is equipped inside the 3D printed cylindrical controller. The shaft of the rotation motor protrudes from one end of the controller. A thrust bearing is attached to the other end of the controller. Therefore, by attaching the track to the both of the ends of the controller, the track is rotated by the motor along the controller. Furthermore, the track is parallel and at some distance from the controller to prevent the track and connector from interfering with the hand holding the controller. The movable connector contains a DC motor, called an *offset motor* (Pololu Micro Metal Gearmotor with gear ratio 298:1), with a gear on its shaft and a rotary encoder (Pololu Magnetic Encoder 12 counts per revolution) to control its offset movement on the track with teeth. Using the rotation and offset movement, the connector can move to any position on the surface of the curved side of the cylinder around the controller, which achieves a dynamic PAF.

To accomplish versatile force feedback, we base on and improve the design concept of ElasticVR [17] and ElastImpact [15] by adjusting elastic bands' length and extension distance to implement a resistive force link and an impact link, respectively. The resistive link consists of an elastic band, made up of two rubber bands (width:1.4mm, length: 13.5cm) in a bundle based on a pilot study, and a DC motor, called a *resistive motor* (gear ratio 1000:1) with a winding axle (radius: 5mm) and a rotary encoder. One end of the elastic band is connected to the winding axle of the resistive motor in a connector. The other end is connected to the other connector on the other controller. The resistive motor changes the elastic band's length by winding the band, which further alters the band's elasticity and resistive force level. The shorter the band is, so the stronger is the resistive force. Therefore, multilevel resistive force can be provided when users extend the band by pulling the controllers apart.

The impact force link consists of an elastic band (width: 1cm, length: 1.3cm), a DC motor, a servo motor and a mechanical brake. The band is wider, shorter and with stronger elasticity than the elastic band in the resistive force link. One end of the band is connected to the DC motor, called an *impact motor* (gear ratio 1000:1), with a winding axle (radius: 10mm) and a rotary encoder on the connector not having the reisitive motor.

The other end of the band with a knot is connected with a fishing line that is further connected to the other connector with the resistive motor on the other controller. The impact motor extends the band to store the impact power when the other end of the band is blocked by the mechanical brake using a tenon and mortise design. When the brake is released by the servo motor (XCSOURCE RC450), the impact is produced and suddenly pulls the other controller toward this one. The longer that the elastic band's extension distance is, so the stronger is the impact force. Therefore, multilevel impact is rendered between the controllers.

ElastiLinks should allow users to freely move the controllers without restriction under normal conditions, and provide force feedback when such feedback is needed, which requires restricting the controllers for force delivery. To achieve this, a *wire brake* with two states, a *free state* and a *locked state*, for each force link is proposed. The wire brake for the resistive force link is integrated into the connector with the impact motor, and vice versa. In fact, the wire brake is where the the force link connects to the other connector on the other controller. The wire brake consists of a retractable buckle and a DC motor, called a *brake motor* (gear ratio 210:1) with a winding axle (radius: 5mm) and a rotary encoder. The retractable wire passes through a small hole on the winding axle and is connected to the elastic band of the resistive force link or the fishing line of the impact link. In the free state, the retractable wire is pulled out smoothly and allows users to freely move the controllers. In the locked state, the brake motor rotates with 2 revolutions to wrap the retractable wire on the winding axle. The wire is halted and the controllers are restricted, which allows force delivery. The retracting force from the buckle is less than 2N, which is negligible compared to that from the force links, as shown in ElasticVR [17].

These eight motors are connected to four Dual TB6612FNG motor drivers, and controlled by two Arduino Mega boards. The wires of the rotary encoders are connected to the interrupt pins on the boards to maintain the motor precision. 6V external power is supplied to the servo motor and the rotation motors, and 12V external power is provided for the other DC motors. A Vive tracker and a button are attached to each controller, not rotating along with the track, for position tracking and input. The weight of ElastiLinks, including eight DC motors and one servo motor, is 750g in total (without the Vive trackers). The weight of one of the controllers is 350g, and the other is 400g.

Software

At initialization, users hold the two controllers and make sure that the thumbs can easily press the buttons on the controllers. The two tracks rotate to the opposite directions of the buttons, which is defined as 0 degrees in the rotation movement for the both controllers. Each connector is at the center of the track, which is defined as 0 for the offset movement. The offset range is between -1 and 1, which means that the connector is at the bottom and on the top of the track, respectively. Both wire brakes are in the free state, so the two ElastiLinks controllers are freely moved by the users at initialization. Although the rotation motor can rotate the track by 360 degrees on each controller, the support for the Vive tracker and the button hinder 120 degrees of the track rotation, which means that the track can only rotate between -120 (outward) and 120 (inward) degrees. Furthermore, during the track rotation, it should not bump the users' wrist or arm. We conducted a pilot study and found that the feasible controller range of rotation for the majority of users is between -90 (outward) and 60 (inward) degrees for the controller. Since the range of the device limitation is smaller than the range of users' physical restriction, the device limitation due to the Vive tracker support does not affect users.

To provide resistive force, the resistive motor winds the elastic band on the winding axle depending on the resistive force level. The rotation and offset motors then simultaneously move the connectors to the corresponding PAF position. At last, the wire brake of the resistive force link come into the locked state, so that the users perceive resistive force when pulling the controllers apart. Notably, the users can only perceive resistive force when pulling the controllers apart or outward instead of pushing the controllers inward due to the hardware design. The resistive motor winding the band before the rotation and offset motors moving the connectors guarantees that the band is precisely wrapped no matter where the connectors are.

To present impact, the servo motor blocks the elastic band using the mechanical brake at first. The impact motor then extends the elastic band to store impact power, and at the same time, the rotation and offset motors move the connectors to the corresponding PAF positions. The wire brake then enters the locked state. The servo motor releases the brake to produce impact, and after a 100ms delay to reinforce impact, the wire brake returns to the free state again. Notably, in the period after the wire brake enters the locked state and before the impact is produced, the users should not move the controllers inward, which may make the fishing line between the controllers become not taut and affect the impact force delivery. These two types of force feedback can not be provided simultaneously, and the wire brakes should not enter the locked state at the same time. The delay for the rotation motor rotating the track by 90 degrees is 1730 ms, and the delay for the offset motor moving the connector from the initial position to each end is 1200ms. The delay for the wire brake actuation is 960ms.

FORCE PERCEPTION STUDY 1 - FORCE LEVEL

To understand users' force level distinguishability of resistive force and impact between controllers, we conducted this force perception study. Although a just-noticeable difference (JND) study is a common method for haptic research [1, 4, 7, 15], a JND stimulus must have a constant intensity. However, the magnitude of resistive force between the controllers depends on the hands' movement. Therefore, we performed a force perception study as in [16, 19] instead of a JND study. Although we focus on exploring PAF in this paper, we must base on the results of this study to obtain the proper resistive and impact force stimuli to further investigate the PAF distinguishability.

Apparatus and Participants

During the study, the ElastiLinks controllers as aforementioned were held by both hands. Users wore a Vive Pro HMD and noise-cancelling earphones which played pink noise to mask the audio feedback from the motors of ElastiLinks. We used Unity3D and SteamVR SDK to build VR scenes for our study. 12 right-handed participants (4 female), aged 22-27 (mean: 23.33) were recruited.

Force Stimuli

To obtain the proper resistive and impact force levels examined in the study, respectively, we conducted a pilot study using ElastiLinks. For resistive force, when the whole length of the elastic band was extended, the lowest force level was provided. By gradually increasing the revolution number of the resistive motor to wind the band and repeatedly pulling the controllers to perceive resistive force, three resistive force levels were chosen for the perception study. The highest force level was the upper bound of force that users were willing to exert in the VR experience. For impact force, the lowest force level was the impact clear enough for most users to perceive even if they did not pay much attention. By gradually increasing the extension distance of the elastic band and repeatedly perceiving impact, three impact levels were chosen for the perception study. The highest force level was the impact that could be provided by the current elastic band and impact motor.

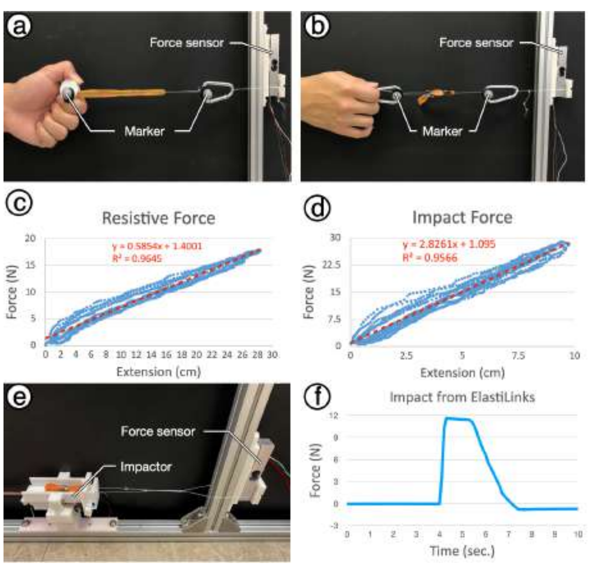

Figure 4. The setup to measure the relationship between elastic force and band extension distance for the elastic bands in the (a) resistive force and (b) impact links. The relationship for bands in the (c) resistive force and (d) impact links. The setup to measure impact (e) and the recorded impact force data (f).

To quantify these resistive and impact force stimuli, we built an aluminum extrusion frame and affixed a force sensor (TAL220 with a HX711 amplifier) on it. For resistive force, we measured the relationship between the resistive force magnitude and extension distance of the elastic band in the three chosen resistive force levels, respectively. We affixed one end of the band on the force sensor and extended it from the opposite end by using a fishing line (Figure 4 (a)). Two markers attached to both ends were tracked by the OptiTrack system. By repeatedly extending and releasing the band, we collected the data of the relationship (Figure 4 (c)). We then computed the regression line of the data and used the slope of it to quantify each resistive force level, which was similar to the elastic coefficient in Hook's law for a spring. The resistive force stimuli level (1, 2, 3) have coefficients (0.59, 0.76, 1.56), respectively. For impact, we firstly used the same setting to measure the relationship of the elastic band on the impact link to understand its property (Figure 4 (b)(d)). To measure each impact force level, the impact motor with a case was affixed to the aluminum extrusion frame. The band was then connected between the impact motor and the force sensor with fishing lines. By repeatedly producing the chosen three impact levels using the recorded revolution numbers for the impact motor, we measured and averaged the force sensor values and obtained the results indicating that the impact force stimuli level (1, 2, 3) are (3.2N, 8.1N, 11.5N), respectively (Figure 4 (e)(f)).

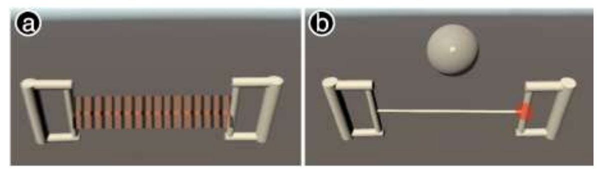

Figure 5. Two VR scenes were built for (a) resistive force and (b) impact tasks, respectively. The opaque and smaller elastic band and ball are the visual feedback at initialization. The translucent and larger band and ball are the visual feedback with the maximum scale. The translucent red point is the position that the ball hits on the controller.

Task

Two VR scenes were built for the resistive force and impact (Figure 5), respectively. Based on the study design in [16, 19], the participants matched the visual feedback to the perceived force feedback. For resistive force, we rendered virtual ElastiLinks controllers connected by an elastic band instead of rendering the physical force links. A striped pattern was shown on the virtual band to provide better visual feedback of elasticity during band extension (Figure 5 (a)). The participants repeatedly pulled the controllers apart and moved them back to perceive the resistive force. They then freely adjusted the width of the virtual band in VR until it best matched the perceived force feedback. The wider that the elastic band is, the stronger is the resistive force.

For impact, the same virtual controllers were rendered, but instead of the elastic band, a solid cylinder was connected between the controllers at the points where the connectors were on the tracks, which made the participants regard the controllers as a rigid device to prevent them from moving the controllers and affecting the impact perception. The participants saw a virtual ball flying approach and hitting where the connector was at on the controller with the wire brake of the impact link. The ball was then shown on the HMD, and they freely adjusted the size of the ball to match the magnitude of the impact force best (Figure 5 (b)). The larger that the ball is, the stronger is the impact. For the both of the force perception tasks, the participants could try and perceive the force stimuli as many times as they wanted until the best-matching scale was determined. The study design allowed the participants to map the perceived force stimuli to the desired visual feedback scale. By analyzing the data, we could understand the force level distinguishability.

Procedure

Initially, the participants sat on a chair and were introduced to the manner by which they could pull the controllers in the resistive force task and how to maintain a holding pose for the impact task. They were then shown the range of the visual feedback in VR and force feedback from the ElastiLinks devices for each force task. Therefore, they could gain a idea of how to match the visual and force feedback for each task. For the resistive force task, the participants pulled the device apart, perceived the force, and adjusted the width of the virtual band to their estimation of the best-matching scale by telling the experimenter what they wanted (wider/narrower). The range of the virtual band width scale was between 1 to 8 based on a pilot study, and the initial scale for each trial was 1. The participants could scale up or down by 0.1 scale, and the experimenter could adjust the scale continuously until the participants asked to stop. The best-matching scale for each trial was then recorded. For the impact task, there was a similar procedure. The range of the virtual ball size scale was between 1 to 5 based on a pilot study, and the participants could scale up or down by 0.1 scale. After each task, the participants were then asked to fill out a questionnaire.

Since impact was mostly provided on the controller with the wire brake of the impact link where the virtual ball hit, half of the participants held this controller using the dominant hand as the counterbalance. A total of 30 (= 2 (force feedback types) $\times$ 3 (force levels) $\times$ 5 (repetitions)) trials were examined by each participant. Force feedback types and levels were counterbalanced. To obtain the force level distinguishability independent to the PAF position, we divided the PAF rotation and offset ranges into five regions, respectively. For both force tasks, the PAF was changed only on the controller with the wire brake of the impact link since resistive force was equally perceived on both controllers but impact was mostly perceived on this controller. To decide the PAF for each repetition, one of the PAF rotation and offset regions was randomly but not repeatedly chosen, and within that chosen region, the PAF position was randomly selected. Notably, in each repetition, the PAF position for all three force levels of each force type were the same. We expected that such a design could obtain the force level distinguishability results for most PAF positions. After the experiment, we performed an interview to obtain some additional feedback. The study took about an hour.

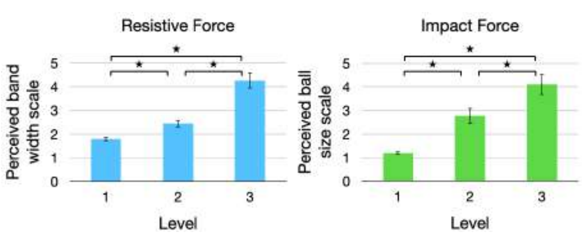

Figure 6. The results of the force perception study 1.

Results and Discussion

The study results for each force type are shown in Figure 6. Since we focused on the distinguishability within each force type, we did not compare the differences between them. Repeated measures ANOVA and Bonferroni correction were used for statistical analyses in this study. Significant main effects are found in both resistive force ($F_{2,22} = 14.16, p < 0.01$) and impact ($F_{1.33,14.63} = 39.36, p < 0.01$). Post-hoc pairwise tests indicate significant differences among all pairs for both force types. Therefore, the participants could clearly distinguish all three levels for both resistive force and impact.

For resistive force, the participants claimed that they distinguished the force levels using the extension distance, force magnitude they applied to pull, and difficulty of pulling the controllers apart. 6 participants (*P1*, *P2*, *P4*, *P5*, *P8*, *P9*) stated that the virtual elastic band with the extended texture looked realistic. *P8* mentioned that the farther s/he pulled the controllers apart, the more easily s/he could distinguish the force level. If s/he pulled them to a short extension distance, s/he only felt small differences between the resistive force levels. For impact, most of the participants (*P2*, *P3*, *P4*, *P5*, *P7*, *P8*, *P9*, *P12*) felt that the impact force provided by ElastiLinks was similar to what would happen if a real ball hit the controllers. However, they also claimed that the lowest impact level was too weak to be matched with this scenario. Therefore, we decided not to use the lowest impact level to simulate the feedback of being hit in VR although it was distinguishable. 5 participants (*P1*, *P2*, *P5*, *P8*, *P10*) reported that they perceived the impact on the controller with the impact motor, which was not the controller intended as designed for providing impact. Based on this phenomenon, we inferred that both the impact force and its reaction force which were applied to the different controllers could be used to distinguish the impact force levels.

In the follow-up interview, we asked the participants whether the PAF rotation and offset influenced their distinguishability of force level. All participants reported that they perceived larger force magnitude when the PAF with a larger rotation angle to the initial position, especially for resistive force. However, the aforementioned situation did not affect the difficulty for most participants to distinguish the force levels in the same PAF. For resistive force, *P1* stated that for those PAFs with larger the rotation angles, s/he could more easily distinguish the force level because s/he could perceive the force more obviously. On the contrary, *P6* and *P10* supposed that it was more difficult to distinguish force levels for the PAFs with different rotation angles, because they used how hard they pulled the controllers to distinguish force levels for all of the examined PAFs. Although the participants might perceived different influences from the PAF rotation, they could still distinguish the three resistive levels as shown in the results. For impact, 2 participants (*P5*, *P12*) stated that because the impact force only lasted for a moment, it was difficult to distinguish the direction of the force caused by the PAF change. Therefore, the PAF did not influence the users to distinguish impact force levels.

Based on the results, three resistive force levels (1, 2, 3) with coefficients (0.59, 0.76, 1.56) are distinguishable, and have device delays (236ms, 2575ms, 4427ms) from ElastiLinks. For impact, three levels (1, 2, 3) with force magnitude (3.2N, 8.1N, 11.5N) are distinguishable, and have device delays (1421ms, 2193ms, 2964ms) from ElastiLinks. Furthermore, the impact level 1 is recommended not to be used in VR applications due to its weak magnitude.

FORCE PERCEPTION STUDY 2 - ROTATION AND OFFSET

To understand users' distinguishability of the PAF rotation and offset differences for resistive force and impact, respectively, we conducted this force perception study. The study design was similar to the previously conducted force perception study but focused on distinguishability of the PAF instead of force level. On the other hand, proving that users could distinguish different PAFs in this study also showed the necessity of providing proper PAFs in this paper.

Apparatus and Participants

The apparatus and VR scenes were the same as in the previous study. 12 participants (6 female, 1 left-handed), aged 21-29 (mean: 24) were recruited. Although four of them had attended to the previous force perception study, more than 10 days had elapsed between the two studies.

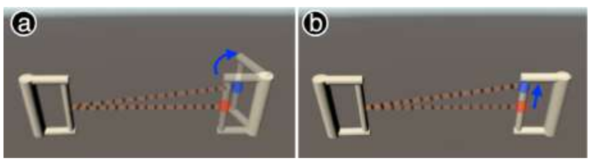

Figure 7. Two VR scenes were built for the force perception study 2. The participants adjusted the PAF (a) rotation and (b) offset on the controller. The red point is the initial PAF, and the blue one is the PAF adjusted by the participants.

Task and Procedure

For each force type, the PAF for different rotation and offset movement were examined, respectively. The same perception approaches were used in this study as the prior. However, when perceiving the force feedback, the participants distinguished the PAF position instead of the force level in this study. As in the previous study, only the PAF on the controller with the wire brake of the impact link changed, so the participants only had to distinguish the PAF of this controller, and the PAF of the other controller was at its initial position. Furthermore, the force level of the visual and force feedback for both force types were constant in this study. Based on the previous study results, the level 2 of resistive force (0.76) and impact (8.1N) were used in this study. For the visual feedback, the elastic band width scale 2.44, and the ball size scale 2.77 from the previous results were used.

Since the rotation and offset movement were examined, respectively, after perceiving force feedback, the participants freely adjusted the examined virtual PAF movement, either the rotation or offset, depending on the torque and force direction until it best matched the perceived force feedback. The range of the PAF rotation was between -90 (outward) and 60 (inward) and the range of the PAF offset was between -1 and 1, as in the previous study. The participants could adjust rotation in outward/inward by 1 degree scale, and adjust offset by moving up or down by 0.1 scale, respectively, by asking the experimenter to do so. Notably, although the examined range of the PAF rotation was 150 degrees, the participants could still adjust the visual feedback by entire 360 degrees based on their perception. They could try as many times as they wanted until the best-matching PAF position was decided. By conducting a pilot study, the numbers for examining stimuli in rotation and offset within their ranges for each force types were decided upon. Since impact occurred instantly but resistive force could be perceived for a longer time, it was more difficult to distinguish different impact PAF for both rotation and offset. Therefore, 6 rotation stimuli (-90, -60, -30, 0, 30, 60) and 4 offset stimuli (-1, -0.33, 0.33, 1) for resistive force were more than 4 rotation stimuli (-90, -45, 0, 45) and 3 offset stimuli (-1, 0, 1) for impact.

Initially, the participants sat on a chair and were introduced to the procedure of this study and how to perceive both of the types of force feedback as in the previous study. They were then shown the ranges of the visual and force feedback, so they could have a notion how to match these types of feedback. When perceiving force feedback, they adjusted the examined PAF movement in the visual feedback to match the force feedback best. A total of 51 (= (10 (resistive force tasks with 6 rotation and 4 offset stimuli) + 7 (impact force tasks with 4 rotation and 3 offset stimuli)) $\times$ 3 (repetitions)) trials were examined by each participant. Notably, all participants held the controller with the wire brake of the impact link in the dominant hand. The nondominant hand held the other controller and laid on the armrest of the chair. This part is different from the previous study. The force types and the PAF factors of movement were counterbalanced. Only one PAF movement was examined per trial. For the other PAF movement, we divided rotation and offset ranges into three regions, and randomly but not repeatedly chose one of the regions and further randomly selected the PAF position within the region for each repetition, as in the previous study. For the visual feedback, the controller with examined PAF movement was in its initial position and with non-examined PAF movement was in its real assigned position. The participants filled out a questionnaire after the experiment. This study took about two hours.

Results and Discussion

The results of users' PAF distinguishability of rotation and offset for resistive force and impact are shown in Figure 8. Repeated measures ANOVA and Bonferroni correction were used for statistical analyses.

For resistive force, significant main effects are found regarding both rotation ($F_{1.41,14.36} = 9.18, p < 0.01$) and offset ($F_{3,33} = 12.39, p < 0.01$). Post-hoc pairwise tests reveal significant differences only in the pair (-90, 30) in rotation, and among all pairs except between (-0.33, 0.33) in offset. For impact, significant main effects are found for both rotation ($F_{1.49,16.33} = 9.13, p < 0.01$) and offset ($F_{2,22} = 10.06, p < 0.01$). Post-hoc pairwise tests reveal significant differences only in the pair (-90, 45) in rotation, and among all pairs except between (0, 1) in offset.

For rotation, the participants could only clearly distinguish between one pair for resistive force and impact, respectively. By analyzing the rotation data for both resistive force and impact, we observed that two PAFs with the same rotation angle from the initial position but in the opposite direction

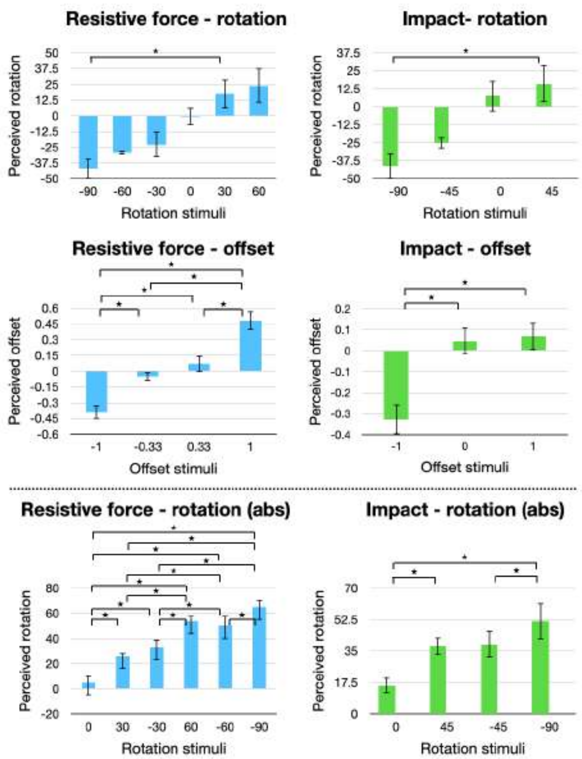

Figure 8. The results of the force perception study 2.

were easily confused by most participants. However, by removing the direction from the consideration, it seemed that they still could distinguish the PAF rotation angles. Therefore, we computed the absolute values of the rotation data, and further statistically analyzed these. Significant main effects are found for both resistive force ($F_{5,55} = 28.96, p < 0.01$) and impact ($F_{1.44,15.87} = 10.08, p < 0.01$) in rotation (absolute). Post-hoc pairwise tests show significant differences among all pairs, except between (-60, 60), (-90, 60) and (-30, 30) pairs for resistive force, and significant differences between (0, 45), (-90, -45) and (-90, 0) pairs for impact. The results showed that the participants could distinguish the rotation of the PAF stimuli but not the torque direction.

For rotation of resistive force, the participants generally used two clues, torque direction and magnitude, to make distinctions. 5 participants (*P2*, *P4*, *P5*, *P7*, *P12*) mentioned that the random offset did not influence them in distinguishing the PAF rotation stimuli. However, 3 participants (*P6*, *P9*, *P11*) felt that it was more difficult to distinguish the PAF rotation stimuli when the offset was further from its initial position. For offset of resistive force, the participants generally used the middle finger as a reference point, and then distinguished the PAF position relative to it to adjust the offset. *P3* stated that the visual feedback was so dominant that s/he could not adjust it to the best-matching offset. *P1* supposed that compared to the stimuli with PAF offset in -1 and 1, the stimuli with PAF offset in -0.33 and 0.33, near the initial offset position, were more difficult to distinguish. For impact, the participants used the same strategy as for resistive force to distinguish the PAF rotation and offset stimuli. 8 participants (*P1*, *P2*, *P3*, *P4*, *P5*, *P7*, *P9*, *P10*) mentioned that the random offset did not influence them in distinguishing the PAF rotation stimuli. 8 participants (*P2*, *P3*, *P4*, *P7*, *P8*, *P10*, *P11*, *P12*) stated the that random rotation did not influence them to distinguish the PAF offset stimuli.

Based on the results, for resistive force, six PAF rotation stimuli (-90, -60, -30, 0, 30, 60) and three PAF offset stimuli (-1, 0.33, 1) or (-1, -0.33, 1) are distinguishable, which could imply that three PAF offset stimuli (-1, 0, 1) are distinguishable. For impact, three PAF rotation stimuli (-90, 0, 45) and two PAF offset stimuli (-1, 1) are distinguishable. The results are consistent with the pilot study that resistive force with a longer application time than impact has better PAF distinguishability.

VR EXPERIENCE STUDY

We conducted the VR experience study to observe how dynamic PAFs affect users in VR and verify whether the force feedback with dynamic PAFs from ElastiLinks enhances the VR experience. Although force feedback between controllers is mainly used for bimanual interactions, it could also be used for interactions holding one controller with the other grounded on the body (*e.g.*, the waist or arm) or in the environment (*e.g.*, a desk) as in [12]. We built three VR applications to allow users to experience these three kinds of interactions, respectively.

Apparatus and Participants

The apparatus was the same as in the previous study. 12 participants (5 female), aged 22-31 (mean: 24.5) were recruited for this study. All participants had had VR experience before. Although eight of them had attended to one of the previous two studies, more than a week had elapsed between this study and the two prior studies.

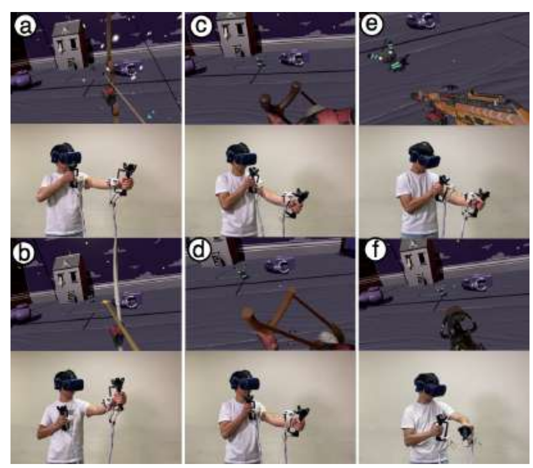

Figure 9. The survival shooter game includes (a) (b) bows, (c) (d) slingshots, (e) a rifle and (f) a launcher.

Application 1: Survival Shooter Game

This application demonstrated how ElastiLinks were used for *bimanual interactions*. Based on the results of the previous studies, the following weapons were provided for the participants (Figure 9). Two bows with different power levels (resistive force level 2 and 3) and the same PAF (rotation: 0 degrees, offset: 0 for both controllers) provided resistive force feedback when these were pulled. Two slingshots with different power levels (resistive force level 1 and 2) with the same PAF (rotation: 0 degrees, offset: 1 for the controller with virtual slingshot, rotation: 0 degrees, offset: 0 for the other controller) provided resistive force feedback when these were pulled. A rifle (impact level 2, PAF rotation: 0 degrees, offset: 1 for both controllers) rendered impact feedback from recoil. A launcher (impact level 3, PAF rotation: 0 degrees, offset: -1 for the triggering controller, PAF rotation: -90 degrees, offset: 0 for the other controller) rendered impact feedback from recoil. In the virtual environment, participants used these weapons to prevent zombies from approaching. For the bows and slingshots, they held these weapons using the controller on the nondominant hand, while pressing and holding the button on the other controller with the dominant hand to pull the bows and slingshots, and releasing the button to fire the bows and slingshots. For the riffle and launcher, they held these weapons using the controller with the nondominant hand and pressed the trigger via the other controller with the dominant hand to fire the weapons. Notably, since our devices needed power storing time for impact, the rifle or launcher would become transparent when the devices were not ready, which is similar somehow to the period necessary for loading those weapons. The participants could press the button on the controller with the nondominant hand to switch the weapons. By comparing force feedback from the bows and slingshots, the participants could perceive not only different resistive force levels but also different PAFs. Similarly, since the rifle and launcher required different holding poses to hold them, different impact levels and PAFs could be perceived.

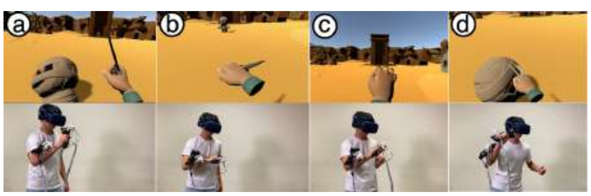

Figure 10. The fighting game includes (a) a knife, (b) a knife with the reverse grip, (c) a knuckle and (d) a claw.

Application 2: Fighting Game

In this application, we explored how ElastiLinks were used for interactions *grounded on the body*. Inspired by Haptic Links [12], one controller was fixed on the arm, and the other was held by the dominant hand. Notably, we did a pilot study and found that the feasible controller range of rotation is between -90 (outward) and 120 (inward) for the one-handed condition, which is larger than the range for the bimanual condition but still smaller than the range caused by the device limitation. Therefore, we designed these one-handed interactions with PAF of in this range. In this VR application, the participants needed to attack approaching mummies, as shown in Figure 10. When attacking a mummy, ElastiLinks generated impact feedback to the hand. Four weapons with different impact force levels and PAFs, including a knuckle (level 3, PAF rotation: 30 degrees, offset: 0), a knife (level 2, PAF rotation: 30 degrees, offset: 1), a knife with the reverse grip (level 2, PAF rotation: 30 degrees, offset: -1), and a claw (level 3, PAF rotation: 90 degrees, offset: 0), were provided. These four weapons had different poses to hold or wear, and methods of attack, so the participants could perceive not only different impact levels but also various PAFs in this application.

Figure 11. The fishing game with a controller grounded on the desk.

Application 3: Fishing

In this application, we anchored one controller on a desk to show how ElastiLinks were used for interactions *grounded in the environment*. The participants held the other controller as a fishing rod in VR, as shown in Figure 11. When they pulled a fish from the water, the grounded controller rotated the track back and forth between -45 degrees and 45 degrees to simulate the fish moving against the participants. The resistive force feedback (level 1, PAF rotation: 0 degrees, offset: 1) was provided.

Task and Procedure

We introduced each application and how the devices worked to the participants. We then showed what kind of force feedback would be perceived in the applications. Three feedback methods were compared in this study, including vibration (V), fixed PAFs (F) and ElastiLinks (E). (V) with vibration from the Vive controllers was regarded as the baseline for the comparisons. (F) was implemented by ElastiLinks devices with multilevel resistive force and impact but with fixed PAF. Therefore, by comparing (F) and (E) with dynamic PAFs, we could understand whether the force feedback with dynamic PAFs enhances the VR experience. In this study, we instructed the participants to experience the three applications and asked them to evaluate the realism, enjoyment and distinguishability among these methods. A total of 9 (= 3 (applications) $\times$ 3 (feedback methods)) conditions were experienced by each participant. We did not limit the time for experiencing and the participants were asked to perceive all events in all applications. The order of the feedback methods was counterbalanced. Finally, the participants were asked to fill out a questionnaire with a 7-point Likert scale, allowing decimal scores, and were interviewed for some further feedback.

Results and Discussion

The results are shown in Figure 12. Repeated measures ANOVA and Bonferroni correction were used for statistical analyses.

Survival Shooter Game

Significant differences are found in realism ($F_{2,22} = 105.06, p < 0.01$), enjoyment ($F_{2,22} = 20.54, p < 0.01$) and distinguishability ($F_{2,22} = 115.78, p < 0.01$). 6 participants (*P1*, *P2*, *P7*, *P8*, *P9*, *P11*) reported that *"The resistive force of drawing the bow and slingshot is quite realistic."* 2 participants (*P4*, *P9*) said that *"Using the resistive force feedback,*

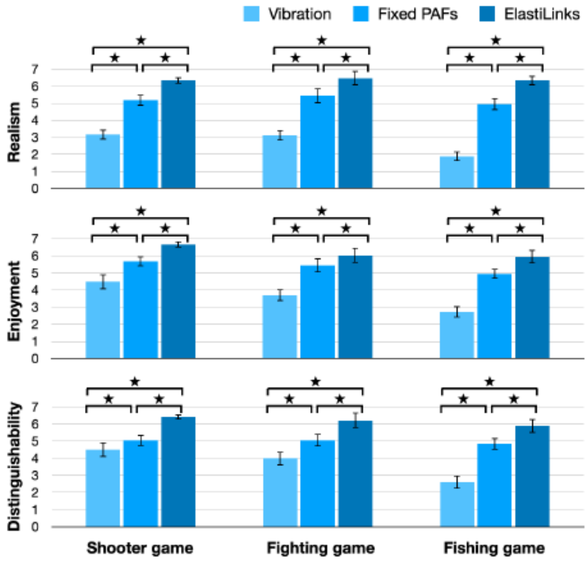

Figure 12. The results of the VR experience study in regard to realism, enjoyment and distinguishability in 7-point Likert scale.

I could aim at the target easier." *P9* and *P10* mentioned that *"Pulling the bow and slingshot with stronger resistive force was more realistic since I really needed to pull the these hard in real world."* For impact, half of the participants commented that *"Impact from the rifle and launcher were novel and the recoil was clear."* *P10* said that *"The magnitude of impact should be stronger to match the scenario."* Therefore, although the high impact levels require the longer motor delays, it is still essential for realistic impact force feedback. For dynamic PAFs, 4 participants (*P2*, *P8*, *P9*, *P12*) reported that *"The PAF of the slingshot was closer to reality using ElastiLinks."* *P1* and *P8* said that *"ElastiLinks was a bit heavy to control."* However, another three participants indicated that *"The weight of the device made me feel just like I was holding a real rifle."* All participants except *P11* considered that (E) made the games more interesting. *P11* said that *"Because the PAF changed, the resistive force became stronger, which made pulling the slingshots harder."* Due to the limitation of the ElastiLinks devices, most of the participants mentioned that unable to shoot consecutively was annoying. However, they also said that the impact feedback was nearly real.

Fighting Game
Significant differences are revealed on all realism ($F_{2,22} = 58.88, p < 0.01$), enjoyment ($F_{1.20,13.23} = 44, p < 0.01$) and distinguishability ($F_{2,22} = 64.73, p < 0.01$). Most of the participants indicated that *"The impact direction changed in (E) when using the knife in two different holding poses. It felt like a real blade cut an object."* The impact feedback from the knuckle and claw with different PAF rotation was obvious to distinguish. However, *P12* said that *"Using a handheld controller to represent the claw which was embedded into body was a bit weird."* In (V) and (F), 7 participants reported that *"The center of mass of the weapons did not change that made me feel like I still used the same weapon."* *P7* said that *"Vibration did not matched the visual feedback, which reduced the immersion in VR ."* Although most of the participants felt the change of center of the mass in (E), they still supposed that the ElastiLinks devices were too heavy and restricted their arm movement. *P9* commented that *"No matter how hard s/he hit and attacked, the impact level of the same weapon was the same."* *P9* suggested that the impact level could be made to correspond to the speed of the hand movement. In addition, we designed that the time for generating mummies matched the latency of power storing for impact. Therefore, no participant reported that the delay from ElastiLinks affected their experience.

Fishing Game
Significant effects are found in realism ($F_{2,22} = 45.19, p < 0.01$), enjoyment ($F_{2,22} = 36.26, p < 0.01$) and distinguishability ($F_{2,22} = 67.83, p < 0.01$). All participants reported that *"They could feel that the force direction changed, just like when a fish fought on the fishing line."* They were surprised that the force feedback with a moving PAF on the grounded controller was such realistic. 4 participants (*P6*, *P9*, *P10*, *P12*) said that *"Although resistive force could still be felt in (F), the PAF on the controller held by the hand was at the palm which made me confused."*

Limitations and Future Work

Although ElastiLinks obtained quite positive comments from the studies, there are still some limitations in the current design. Motor latency when preparing force feedback or moving to the corresponding PAF position cannot be ignored. Due to such latency, ElastiLinks cannot provide consecutive impact feedback and real-time dynamic PAF. Although the motor latency exists, users still have high acceptability based on the results of the VR experience study. The wire brake cannot lock the retractable wire when it is perpendicular to the winding axle. We may improve the wire brake by combining it with the design from Wireality [3] in the future to reduce the motor latency and ensure that the buckle can be locked. Due to the current design of the resistive force link, users only perceive resistive force when pulling the controllers apart. We may improve it by combining the design in Haptic Links [12] to achieve more versatile force feedback. The total weight of ElastiLinks is a bit heavy such that one controller grounded on the user's arm is not suitable for some users. However, if the controller is grounded at a position on the body that can bear weight, the users' experience could be improved.

Conclusion

We propose handheld controllers, ElastiLinks, to provide force feedback between controllers with dynamic PAFs. Two types of common force feedback, multilevel resistive and impact force feedback, are provided by ElastiLinks. We conducted a force perception study to understand that three resistive force and three impact force levels between controllers are distinguishable. Based on the results, we conducted another perception study to realize PAF distinguishability for rotation and offset for resistive force and impact, respectively. Finally, we performed a VR experience study to verify that force feedback with dynamic and proper PAFs from ElastiLinks indeed significantly enhances the VR experience.

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