

XTick: Rendering Omnidirectional Hit-and-Hold Impact Feedback All Round a Controller by Integrating Impact and Pressing Force

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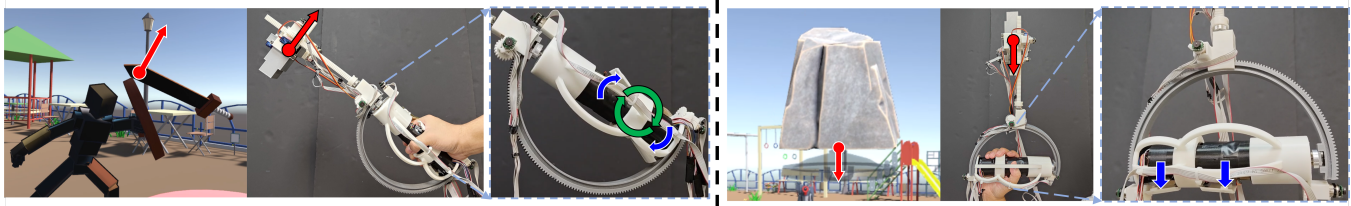


Figure 1: XTick renders omnidirectional short-duration instant impact and long-duration hit-and-hold impact feedback all round the controller by integrating impact and pressing force. Hit-and-hold impact in sword press against shield (left) and shield blocking falling rock (right). Red dots and arrows show impact position and direction. Blue and green arrows show pressing force and torque.

ABSTRACT

Impact feedback, with a sharp force increase and short duration, is common in VR. However, in some scenarios, force feedback consists of an impact force peak followed by sustained force with a smaller magnitude, extending the overall force application duration of such *hit-and-hold* impact force feedback, e.g., when swords press against each other, or when a shield resists propelled projectiles or falling rocks, which is critical but less discussed. Moreover, rendering impact at the position and direction corresponding to VR scenarios is also crucial. We propose a controller, XTick, to render omnidirectional short-duration instant impact and long-duration hit-and-hold impact feedback all round the controller by integrating impact and pressing force. It enables omnidirectional pressing force and integrates it with impact at various positions and directions to render impact in any duration. To achieve seamless integration, this work investigated two critical factors: force magnitude alignment between impact and pressing force in a feedback integration study, and the transition between initial impact and sustained force states in an impact extension study. Based on the results and guidelines, a VR study was conducted to verify that the integrated feedback from XTick enhances VR experiences and show some applications.

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CCS CONCEPTS

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

KEYWORDS

Haptic feedback, Force feedback, Impact, Virtual Reality, Controller

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1 INTRODUCTION

Impact force feedback is common and crucial in virtual reality (VR) experiences, such as hitting, punching, or being struck in VR games. It typically occurs instantly with a sharp increase in force and lasts for a short duration. However, in some scenarios, force feedback consists of an impact force peak followed by sustained force with a smaller magnitude, extending the overall force application duration of such *hit-and-hold* impact force feedback, such as when swords press against each other, or when a shield resists propelled projectiles or falling rocks. In these cases, the sustained force occurs after the initial impact due to the opponent's motion, propulsion, or gravity. *Hit-and-hold* impact feedback with two states, initial impact and sustained force states, represents a common variant of impact feedback. Thus, both typical instant impact in short duration and

hit-and-hold impact in long duration are essential for VR. In addition to temporal aspects, the spatial issue of dynamically rendering the position and direction of impact force according to VR scenarios is also critical in enhancing VR experiences [4, 37]. However, current ungrounded haptic devices only render short-duration instant impact feedback or impact in specific positions and/or directions. Therefore, rendering omnidirectional short-duration instant impact and long-duration hit-and-hold impact all round the ungrounded haptic device to address both temporal and spatial issues is required.

Previous research has proposed various force feedback approaches, including motor pulling or pressing [6, 20, 27, 30, 35], propeller propulsion [10, 13, 14, 23], and airbag pressing [7], capable of sustaining force feedback for extended durations. Instead of directly generating force feedback at the point of application of force (PAF) from virtual collisions or impact, PaCaPa [27] explores the sensation of indirect yet inherent pressure and shape change transmitted from the PAF by pressing wings on the hand when using virtual stick-like tools. Although these methods press against mechanoreceptors to achieve long-duration force feedback, they can only render a gradual force increase instead of a sharp force increase in instant impact force feedback [33]. To render instant impact, solenoids [28], elastic force [31, 33, 37], air jets [29, 36] and electrical muscle stimulation (EMS) [17, 18] are leveraged. However, solenoids and elastic force only generate short-duration impact. Although air jets and EMS could achieve impact for any duration, they either require a bulky air compressor and cause airflow interference or internally overwrite user movements rather than rendering external feedback. Furthermore, these approaches only render force feedback in specific positions and directions, making it difficult to maintain consistency with dynamic virtual scenarios. transPAF [4] renders impact in dynamic PAF and direction, first achieving omnidirectional impact force all round the controller, but it is still limited to short-duration instant impact. Therefore, a device capable of fulfilling both temporal and spatial requirements for rendering both instant and hit-and-hold impact feedback remains to be developed.

We propose a controller, XTick, to render omnidirectional short-duration instant impact and long-duration hit-and-hold impact feedback all round the controller by integrating impact and pressing force feedback. XTick consists of a rotatable controller, tracks, and impactor to render instant impact in dynamic PAF and direction. Furthermore, two extrudable and tiltable three degrees-of-freedom (3DoF) platforms on rotatable modules in the controller render omnidirectional pressing force to the hand for any duration. By combining impact feedback from the impactor using elastic force in the initial impact state with pressing force from the controller as the indirect yet inherent pressure sensation in the sustained force state, XTick extends the force application duration for both instant and hit-and-hold impact. This extended impact feedback can also allow users to perceive stronger impact, as a side effect, as proven in [29]. The integration involves several aspects, including *two haptic sensations* (impact and pressing force), *two states* (initial impact and sustained force states), and *two types of impact feedback* (instant impact and hit-and-hold impact feedback). Notably, although this work focuses on the feedback on a controller, the integration of impact and pressing force has not been explored even in grounded devices. To the best of our knowledge, this is the first work to investigate such integration, and its findings and guidelines can be

further applied to future research. This work focuses on two critical, unexplored factors for seamless integration: force magnitude alignment between haptic sensations and transition between states for both impact types. A feedback integration study investigated force magnitude alignment by examining the relationship between impact force level and tilt and/or extrusion of the platforms in various impact positions and directions for both impact types. Based on the results, an impact extension study explored the transition by adjusting the platform speed during the releasing phase after pressing, observing how it affects transition experiences, perceived impact duration, and force magnitude. A VR experience study then verified that the integrated feedback from XTick enhances user experiences compared to others and show applications of XTick.

The contributions of this paper are in the following:

- (1) Proposing a handheld device to enable rendering both omnidirectional short-duration instant impact and long-duration hit-and-hold impact feedback all round the controller by integrating impact and pressing force.
- (2) First to integrate impact and pressing force and investigate their force magnitude alignment for seamless integration.
- (3) Exploring transition between the initial impact and sustained force states, obtaining appropriate platform release speed, observing perceived magnitude and duration, and deriving guidelines applicable to future research, even for grounded devices.
- (4) Verifying that the integrated feedback enhances user experiences and showcasing applications of XTick.

2 RELATED WORK

2.1 Force Feedback Devices

Previous works have utilized various mechanisms to render force feedback. Vibrotactile actuators [11, 12] simulate force feedback, but the force illusions differ from force feedback. Leveraging motors to pull or push belts, strings, or tactors is common for rendering force feedback. Prior methods [3, 8, 30, 35] use motors to generate pulling and pressing force on the forearm, hand, and face through belts and fishing lines. CLAW [6] renders pressing force on the hand by controlling the device's arm movement through a motor. In addition, pressing force feedback is generated not only directly at the PAF, where virtual collisions or impact occur, but also indirectly at the hand's grip position on the controller, as the force is transmitted from the PAF when using virtual stick-like tools. PaCaPa [27] investigates such sensation of indirect yet inherent pressure and shape change by pressing two opposite wings from the controller to the hand using servo motors. Furthermore, propeller propulsion also renders force feedback on controllers or wearable devices, as in [10, 13, 14, 23]. Besides, Force Jacket [7] inflates 26 airbags to render pressing force on the body and arms, and PullUps [38] uses pneumatic artificial muscles (PAMs) to pull the body. Although all these methods effectively present force feedback for any duration, their force feedback is gradual and differs from instant impact feedback with a sharp force increase, as proven in [31, 33].

2.2 Impact Force Rendering

To render instant impact force with a sharp force increase, Virtual Tennis [28] installs two solenoids on a racket-shaped controller to

provide feedback when hitting a ball. Furthermore, storing elastic force by extending elastic bands or compressing springs and then releasing it to generate instant impact on the hand(s), head, and body has been accomplished in a series of works by Tsai *et al.* [31–33, 37]. However, solenoids and elastic force can only render short-duration instant impact. Air jets [29, 36] also render instant impact and sustain output force over an extended period, due to their properties. Furthermore, AirRacket not only provides long-duration impact but also explores the illusion of increased perceived force magnitude with prolonged duration, a side effect yet a benefit of extended impact feedback, also investigated in this work. In addition, EMS [17, 18] is used to render impact, with solenoids further incorporated in [17]. Although air jets and EMS can render both short- and long-duration impact, air jets require a bulky air compressor and create airflow interference, while EMS stimulates muscle and overwrites user movement internally, differing from external impact feedback. In addition, they render impact only at specific positions and/or directions, failing to meet both temporal and spatial requirements of the proposed impact feedback.

2.3 Force Feedback with Dynamic Direction and Position

The spatial requirement for realistic impact feedback involves dynamic force direction and position/PAF. For dynamic force direction, a common approach is using an actuator(s) with motor-driven direction control. Wind-Blaster [14] and HeadiCopter [26] use motors to adjust the direction of two propellers on the hand and head. AirPush [19] uses two motors to move an air jet nozzle, rendering force within a hemisphere area around the finger. GuideBand [30] leverages two motors to control pulling direction, achieving the first 3D force guidance on a wrist-worn device. Guidance++ [5] further uses two poking sets, each with two tiltable tactors, moving along the wristband to render 6DoF poking force guidance. GamesBond [21] utilizes a twisting and two bending servo motors to rotate and bend each controller, simulating the connection between them for 4DoF force feedback. On the other hand, combining multiple static actuators could also achieve dynamic force direction. LevioPole [23] mounts two propeller sets on both ends of the pole to provide directional force. Thor’s Hammer [10] uses six propellers along three axes to achieve ungrounded 3D force feedback. JetController [36] uses five nozzles to render 3D force feedback. MetamorphX [9] uses four control moment gyroscopes to provide 3DoF moment feedback. Elastimpact [31] combines two static impactors for normal force and a rotatable impactor for tangential force, accomplishing 2.5D impact on the head. While some of these methods can achieve omnidirectional force feedback, their PAFs are either fixed or limited.

For dynamic force position or PAF, weight-shifting mechanisms change PAFs in [22, 25, 39]. However, their force direction is limited to downward due to gravity. Aero-plane [13] uses two propellers to generate force and torque to simulate dynamic weight motion on a plane. ElastiLinks [37] was the first to investigate the dynamic PAF issue and proves that matching PAF(s) with VR scenarios enhances realism by rendering resistive and impact force at different positions between the controllers. Although these works achieve dynamic PAF(s), their force directions are fixed or limited.

transPAF [4] is the first to accomplish both dynamic force direction and position to render omnidirectional impact feedback all round the controller. However, its impactor using elastic force renders only short-duration impact, while our device is inspired by its design concept. Therefore, an ungrounded device that can fulfill both temporal and spatial requirements for impact feedback still waits to be explored.

3 XTICK

We propose a controller, XTick, to render both instant and *hit-and-hold* impact feedback, comprising an initial impact and a sustained force state, for any duration and in dynamic position and direction, fulfilling both temporal and spatial requirements. Since our previous work, transPAF [4], achieved omnidirectional instant impact all round the controller, we modified and improved its design concept. However, rendering hit-and-hold impact requires sustained force beyond short-duration impact. While vibration and pressing force feedback are common approaches, vibration only generates force illusions. Therefore, XTick incorporates pressing force to render sustained force, extending the duration of hit-and-hold impact. When impact occurs while holding a stick-like virtual object, impact force at the PAF also transmits to the hand’s grip, causing an indirect pressure sensation, an effect used in [27]. This indicates both direct impact and indirect pressing force are inherent and fundamental to impact feedback. Therefore, XTick integrates impact for the initial impact and inherent pressing force for the sustained force, extending the overall force application duration of hit-and-hold impact. Although impact occurs at various PAFs and directions, the pressing force PAF remains fixed at the users’ grip. Thus, transmitted impact is only perceived as pressing or torque feedback. This indicates that omnidirectional pressing feedback with a fixed PAF is essential in impact feedback integration.

3.1 Design Considerations

- *DC1. Realism.* To render realistic instant impact with a sharp force increase, solenoids, elastic force, air jets, and EMS are feasible mechanisms. Elastic force is suitable for ungrounded devices, since it avoids bulky air compressors, heavy devices, airflow interference, and internal movement overwriting. For sustained force in hit-and-hold impact, vibrotactile illusions are insufficient. Pressing force feedback, an authentic, common, and inherent component of impact for indirect pressure sensation, is more appropriate. Moreover, careful integration and force profile mapping of these two haptic sensations are crucial for realistic impact.
- *DC2. Versatility.* Versatile impact feedback requires control over position, direction, duration, and magnitude. While transPAF [4] enables various positions, directions, and magnitudes of direct impact, varying duration requires integrating indirect pressing force. Spatially, different PAFs and directions produce distinct pressing or torque directions on the hand. Various impact magnitudes lead to different pressing force levels. Temporally, various impact durations require matched durations of pressing feedback. Thus, omnidirectional pressing feedback with adjustable magnitude, and variable durations is necessary for versatility.

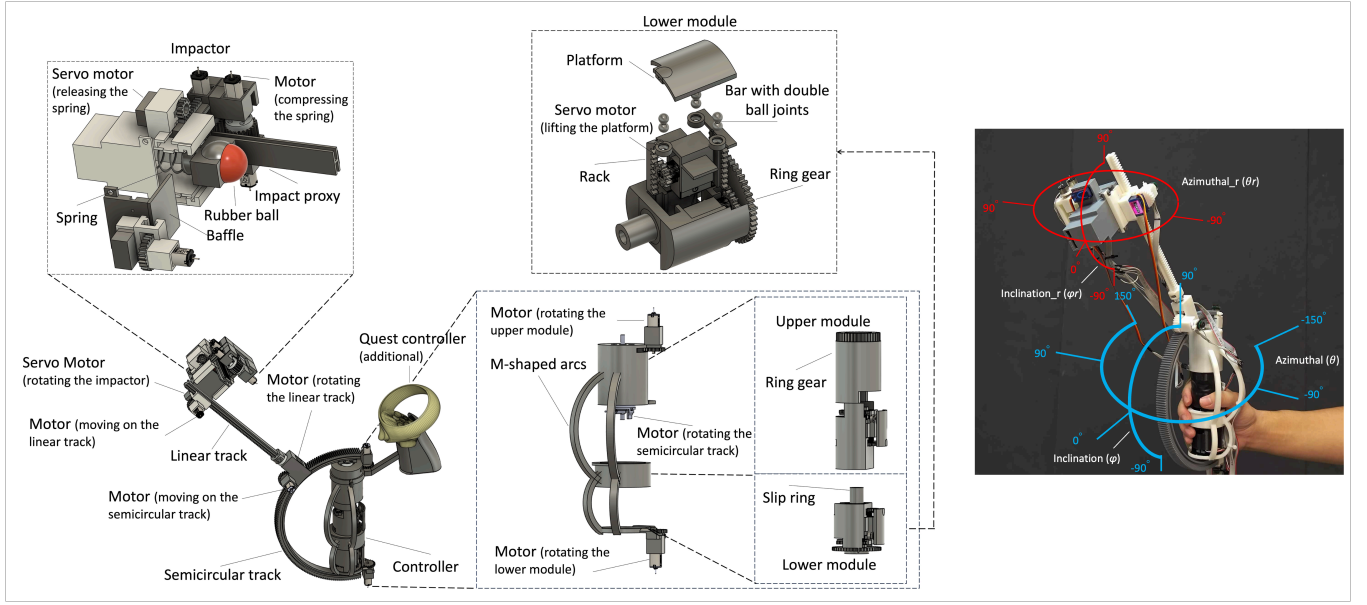


Figure 2: The 3D model of the XTick prototype (left). The spherical coordinate system of dynamic impactor position and direction in $(\theta, \phi, \text{offset}, \theta_r, \phi_r)$ (right).

- **DC3. Form Factor.** Cylindrical or elliptical cylindrical shapes are commonly used for controllers due to their grasping suitability. To enable omnidirectional pressing feedback for realism and versatility, the controller must accommodate mechanisms for force in various directions. A cylindrical surface provides uniform hand contact, enabling effective omnidirectional force feedback.

3.2 Implementation

To achieve impact with dynamic position and direction, we modified and improved the design concept in [4] to develop XTick. XTick consists of a *controller*, a *semicircular track*, a *linear track*, and an *impactor*, which are all rotatable, enabling instant impact and initial impact in hit-and-hold impact. To render omnidirectional indirect yet inherent pressing force for any duration, two *extrudable and tiltable platforms* are mounted on two *rotatable modules* within the controller. Notably, this design is the first to enable omnidirectional pressing force without airflow interference or an air compressor.

The *controller* is equipped with a DC motor (Pololu Metal Gearmotor with gear ratio 499:1 and a 48 counts per revolution encoder) and two bearings, mounted at its upper and lower ends, to rotate the *semicircular track*. The track moves on the azimuthal (θ) plane of a spherical coordinate system (Figure 2 (right)), where 0° and 180° is the outward and toward the wrist, respectively. Due to wrist and forearm constraints, the effective θ range is limited to -150° to 150° . The *linear track* moves along the semicircular track in the inclination (ϕ) plane using a DC motor (Micro Metal Gearmotor with gear ratio 380:1) with a rotary encoder (12 counts per revolution), where 90° is vertical upward and 0° is horizontal. The impactor moves along the linear track using a DC motor (380:1) over a 15cm radial range, with its position defined by an offset from 0 to 150 (0 closest to the controller). In addition, the linear track

spins on the semicircular track via a DC motor (380:1), allowing the impactor to rotate in its azimuthal (θ_r) plane from -180° to 180° . A servo motor (Tower Pro SG92R) rotates the impactor along the linear track on its inclination (ϕ_r) plane from -90° to 90° . These mechanisms enable the impactor to move to any position $(\theta, \phi, \text{offset})$ around the controller and render omnidirectional impact (θ_r, ϕ_r) , fulfilling the versatility (DC2), as in [4]. The initial state of $(\theta, \phi, \text{offset}, \theta_r, \phi_r)$ is set to $(0^\circ, 90^\circ, 150, 0^\circ, 0^\circ)$.

For omnidirectional pressing force, two similar *modules* are equipped in the controller, positioned inversely in sequence. Each module includes a *3DoF Stewart platform* formed by three servo-driven (GHS-37D) rack-and-pinion mechanisms (16mm lift range), enabling 2DoF tilting and 1DoF extrusion, as in NormalTouch [2]. The curved platforms ($34\text{mm} \times 29\text{mm}$) match the controller (radius: 24mm, height: 179.6mm) and connect to the racks via 10mm double ball-jointed bars for smooth tilting. Each platform has three ball joint sockets: two horizontally spaced 22.5mm apart, and the third is centered 22.5mm vertically from them. This arrangement, combined with a 16mm lift range, enables a 45° tilt. Each module has a ring gear driven by a DC motor (210:1), with a slip ring between modules to prevent wire entanglement. The controller has two hollow sections for the modules to provide direct pressing feedback. The top, middle, and bottom parts are connected by two M-shaped arcs, positioned 45° apart around the controller, ensuring structural robustness while keeping the grip area unobstructed. A Velcro strap across the top and bottom secures the device to the palm, supporting its weight and reducing grip force to avoid hindering module rotation. This design meets the form factor (DC3) requirement.

The two rotatable 3DoF platforms render omnidirectional pressing and torque feedback, demonstrated in five cases in Figure 3: case 1: *inclination tilt toward/outward to the wrist*, case 2: *inclination tilt leftward/rightward to the wrist*, case 3: *azimuthal tilt*

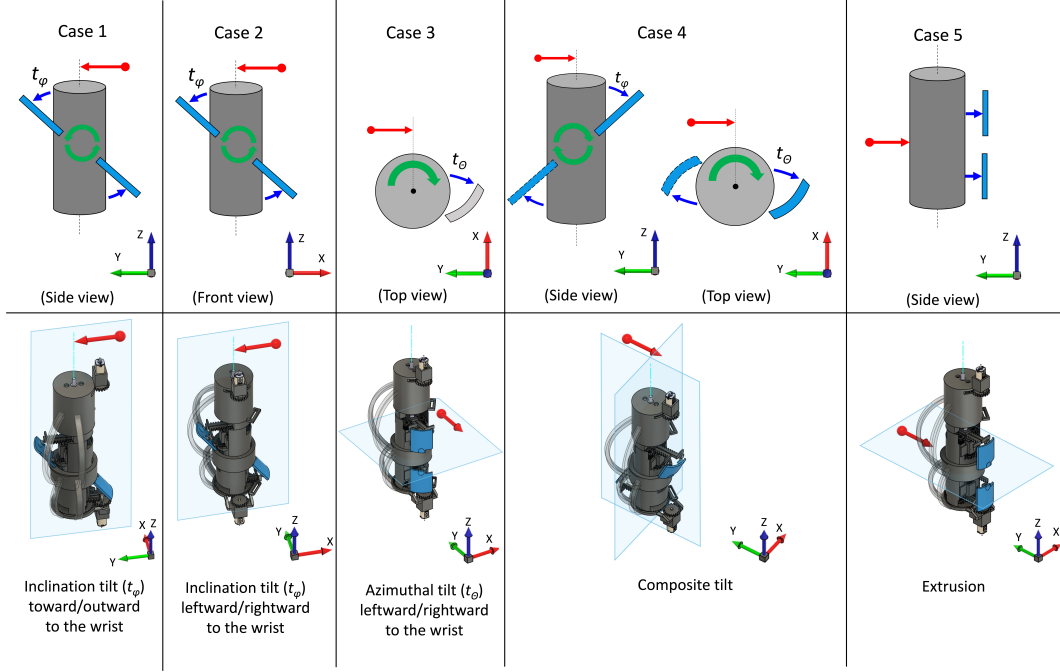


Figure 3: The generalizable 5 cases of pressing force demonstrate the functionality of XTick. The front/side/top views of the controller (upper). The pressing force on the 3D controller model (lower). Red dots and arrows represent the impact position and direction. Blue and green arrows mean the pressing force and torque feedback on the controller.

leftward/rightward to the wrist, case 4: composite tilt, and case 5: extrusion. Notably, these cases show common pressing directions while remaining generalizable; XTick achieves full omnidirectional feedback. For *inclination tilt* (cases 1 and 2), the platforms rotate oppositely, and the horizontal racks lift equally to tilt them on the (t_ϕ) plane, simulating torque feedback for impact above or below the controller along its vertical axis. For *azimuthal tilt* (case 3), the platforms rotate in the same direction, and one horizontal rack on each lifts to tilt them on the (t_θ) plane, while the center rack supports them, simulating torque from off-center horizontal impact. *Composite tilt* (case 4) combines inclination and azimuthal tilt by rotating the platforms oppositely and lifting all racks to tilt them (t_ϕ, t_θ) , simulating composite torque from impact in both above/below and off its vertical axis. *Extrusion* (case 5) simulates pressing feedback from impact on the horizontal plane through the controller's center by rotating the platforms in the same direction and lifting all racks uniformly to extrude them. The platforms' positions depend on the impact direction's horizontal component, and their inclination and azimuthal tilt directions are determined by the torque generated by the impact, with with inclination (t_ϕ) , azimuthal (t_θ) , and extrusion displacement (*displacement*) representing pressing force levels relative to the impact magnitude. All values are non-negative. Rendering pressing force magnitude via tilting angles and displacement is a common approach [3, 24, 27]. Unlike previous devices [2, 24, 27], which cannot achieve omnidirectional pressing force on a controller, XTick achieves this, fulfilling realism (DC1) and versatility (DC2).

Although XTick's *impactor* is based on transPAF [4], which uses elastic force, its larger and heavier controller requires stronger impact to ensure prominent feedback. The improved impactor includes a stronger compression spring (SAMINI SWP-A/SUS304-WPB 12-2223, spring constant: 1.76 N/mm), a servo motor, four DC motors, rack and pinion mechanisms, a barrel, and an impact proxy. The spring connects to the impact proxy with a rubber ball in the barrel and is compressed by a rack driven by two pinions powered by the four DC motors (1000:1). This multi-motor setup balances size, weight, and output force magnitude. The other rack and pinion mechanism, driven by the servo motor (SG92R), lifts the DC motors to disengage their rack and release the spring, allowing the proxy to hit the barrel's baffle and re-engaging. The design provides multilevel instant impact for realism (DC1) and versatility (DC2). Notably, since the impact collision occurs between the rubber ball in the impact proxy and the baffle in the impactor, which is away from the hand, this ensures safety, as in [4].

XTick weighs 825g, including 10 DC motors and 8 servo motors: 4 DC and 1 servo for the impactor's dynamic position and direction control, 2 DC and 6 servos for the two modules, and 4 DC and 1 servo for the impactor itself. An additional Quest 2 controller can be attached for tracking. Dual TB6612FNG motor drivers and two Arduino Mega boards control the motors, with one signal wire of each encoder connected to an interrupt pin. Power is supplied at 12V and 6V. The 195g impactor achieves 21N (only 4.5N in [4]), measured by TAL220 with an HX711 amplifier on an aluminum extrusion frame, with a 1650ms storage time. Average adjustment

delays are 2740ms (azimuthal angle (θ)), 1980ms (inclination angle (ϕ)), 960ms (offset), 830ms (impactor azimuthal angle (θ_r)), and 330ms (impactor inclination angle (ϕ_r)). Average controller delays are 690ms (platform rotation), 200ms (inclination tilt (t_ϕ)), 180ms (azimuthal tilt (t_θ)), and 220ms (extrusion (*displacement*)). Since impactor and platform rotation adjustments can occur simultaneously, the total average delay is 2740ms. The impact duration (rise, peak, fall) is about 220ms. Notably, since XTick builds on transPAF [4], the latency issues and solutions are similar. The longest adjustment delays, 2740ms (θ), 1980ms (ϕ), and 960ms (offset), are in tool switching before the interaction, affecting the experience little. The impactor can also store impact power in advance. Thus, the remaining adjustment delays, including platform delays, reach up to 830ms. The design involves tradeoffs among device speed, force, and weight. We prioritized sufficient impact and pressing forces for effective feedback. We selected a maximum impact force of 21N for the impactor, sufficient for two distinguishable impact levels. Based on this requirement, we chose motors that were as small and lightweight as possible. For motors with similar size and weight, we selected the fastest ones with sufficient torque, resulting in different gear ratios used in XTick. While the force was prioritized over speed, the tradeoff ensures feedback effectiveness, as validated in the VR study. For pressing force feedback, both force and speed are considered for integration with instant impact. XTick uses rack-and-pinion mechanisms and up to 6 servo motors pressing the hand (depending on cases), providing strong pressing force while resisting grip force of up to 78.6N. As in PaCaPa [27], excessively strong grip force can affect pressing feedback rendering. The Velcro strap supports the weight and reduces grip force to avoid hindering module rotation and users are also instructed accordingly. Thus, users usually loosen the grip slightly during operation, and such behaviors were included in the studies, which are still demonstrated promising results.

Building upon transPAF [4], XTick introduces two innovations: (1) the two 3DoF platforms spinning along the controller to enable omnidirectional pressing feedback, and (2) the upgraded impactor generating stronger impact force while balancing size, weight, and force magnitude. To the best of our knowledge, XTick is the first device to achieve omnidirectional pressing feedback. Whereas transPAF only renders omnidirectional instant impact, XTick integrates this novel omnidirectional pressing design with the transPAF-based design to enable both omnidirectional short-duration instant impact and long-duration hit-and-hold impact feedback all round the controller. Since integration in XTick involves multiple aspects, including *two types of impact feedback*, *two haptic sensations*, and *two states*, several factors must be considered, such as alignment of force magnitude, timing, and duration between the haptic sensations, and the transition between the two states. This paper focuses on force magnitude alignment and state transitions between the initial impact and sustained force states for seamless integration, with other parameters tuned via pilot studies. Since XTick is the first device to enable such integration, these factors have not been explored in prior work. Notably, although the sustained force rendered by pressing force cannot actually prevent hand movements, our studies validated that XTick can effectively allow users to perceive long-duration hit-and-hold impact, enhancing immersion.

Compared to prior methods like air jets [29, 36] and EMS [17, 18], XTick is the first mobile device to achieve hit-and-hold impact without a bulky air compressor, airflow interference, or overwriting user movement internally, and these methods cannot render impact feedback in any direction and position.

4 FEEDBACK INTEGRATION STUDY - FORCE MAGNITUDE ALIGNMENT

To seamlessly integrate the two haptic sensations (impact and pressing), we first explored the relationship between their magnitudes for both impact types (instant and hit-and-hold impact), separately across different positions and directions. While the force magnitude of both haptic sensations can be measured by force sensors, perceived pressing force in XTick, inspired by PaCaPa [27], depends not only on actual magnitude but also on the platforms' shape change on the hand. Therefore, measuring and rendering only target force magnitudes is insufficient. Moreover, measuring omnidirectional pressing force directly is challenging, as 3DoF/6DoF force sensors are large and costly. Thus, we used platform tilt and extrusion magnitude as proxies for the pressing force, based on [27], and observed their relationship with impact force measured by a force sensor.

4.1 Apparatus and Participants

Participants held XTick with their dominant hand while wearing a eye mask and noise-isolating headphones playing white noise to block visual and auditory feedback. 12 participants (6 female, all right-handed) aged 22-29 (mean: 24.67) were recruited.

4.2 Task and Procedure

We chose two impact force levels, 14N (L1) and 21N (L2), to observe the relationship between impact and perceived pressing force magnitude. L2 is the impactor's maximum force, while L1, 50% less, was chosen based on [4, 32] and a pilot study to ensure clear differentiation. Participants adjusted pressing force magnitude by modifying platform tilt (t_ϕ , t_θ) and extrusion (*displacement*) to match the impact force. While only two impact levels were tested, we expected that the derived relationship could generalize to other impact magnitudes. Notably, since the impact reaches its peak (~ 110 ms) much faster than the platforms achieve maximum tilt and extrusion (~ 360 ms), we first determined the timing alignment. A pilot study compared aligning the onset, peaks, or actuating impact during the pressing midpoint. Aligning the onset was preferred, producing better integrated feedback, while the others caused pressing feedback to dominate, as it occurred first. Furthermore, the platforms' releasing phase after the pressing peak differed between impact types. For instant impact, the platforms returned to their initial states at maximum speed. For hit-and-hold impact, consisting of initial impact and sustained force states, the pressing force either stabilized at the peak or weakened slightly before stabilizing. In the latter case, platforms returned to a stabilized magnitude at maximum speed and held it for 2s, much longer than instant impact or the initial impact state (< 500 ms). Notably, although the return speed was set to maximum in this study, its effect on state transitions was explored in the following study. Since participants determined pressing force magnitude in the sustained force state after perceiving the peak, instant impact (session 1) was conducted first,

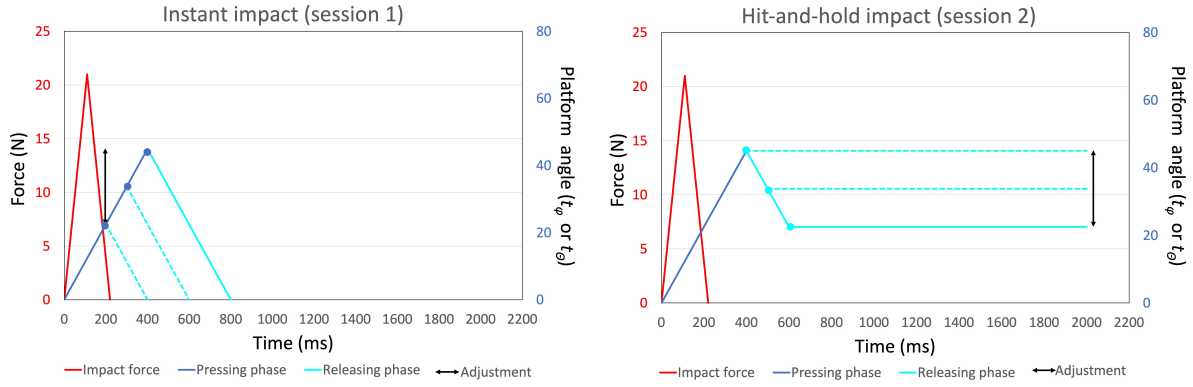


Figure 4: The adjustment concept of tilt angle and extrusion displacement for the pressing feedback in the feedback integration study. The pressing peak magnitude was adjusted in instant impact (left). The pressing force magnitude in the sustained state after the peak was adjusted in hit-and-hold impact (right).

followed by hit-and-hold impact (session 2), allowing participants to reference their previously determined peaks during session 2. Impact in various positions and directions was explored in both sessions across 5 cases in Figure 3, with additional subcases for generalization, as shown in Figure 5.

The experimenter first introduced the device and study design. Participants sat on a chair, holding XTick and could rest at any time to reduce fatigue. For each trial, they first experienced the impact alone, then with small and maximal platform tilt or extrusion to understand the pressing force range. They then freely adjusted the platforms by verbally requesting the experimenter to adjust the platforms one step at a time while repeatedly experiencing the impact until the pressing force matched the perceived impact. Adjustment parameters were: case 1: t_ϕ ; case 2: t_θ ; case 3: t_θ ; case 4: t_ϕ and t_θ ; and case 5: *displacement*, as in Figure 5. Tilt parameters (t_ϕ , t_θ) ranged from 0° – 45° in 1° step; extrusion ranged from 0–16mm in 1mm step. In case 4 (composite tilt), t_ϕ and t_θ were adjusted independently. Notably, although each rotatable platform provides 3DoF, participants adjusted only the examined parameters (t_ϕ , t_θ , and/or *displacement*) in the corresponding cases, which were mapped to 3DoF platform parameters using pre-defined regression models. Session 2 differed only in that participants adjusted the pressing force to match the sustained force state after perceiving the peaks determined in session 1. A total of 60 (= 2 (sessions) $\times$ 2 (force levels) $\times$ 5 (cases) $\times$ 3 (repetitions)) trials were examined, with fixed session order, counterbalanced force levels, randomized cases, and evenly distributed, randomly assigned subcases. A post-experiment interview was conducted. The study took about 3 hours.

4.3 Results and Discussion

The results are in Figure 5. While we aimed to align the pressing force magnitude with the two distinguishable impact levels, we still conducted statistical analysis using repeated measures ANOVA and Bonferroni correction for post-hoc pairwise tests. For instant impact, significant main effects of force level were found in case 1 ($p = 0.04$), case 2 ($p = 0.02$), and case 5 ($p < 0.05$). For hit-and-hold impact, significant main effects were revealed only in case 1

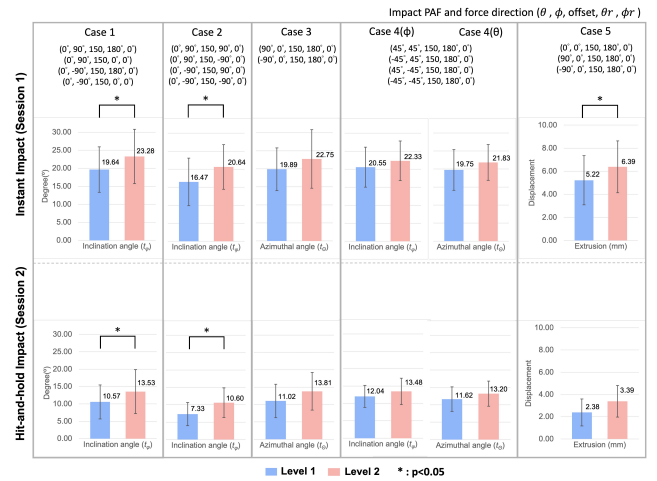


Figure 5: The results of feedback integration study. The error bars represent the standard deviation.

($p = 0.04$) and case 2 ($p = 0.02$). This indicates that the inclination tilt (t_ϕ) in cases 1 and 2 was significantly larger at L2 than L1 in both impact types. Extrusion in case 5 was significantly larger at L2 than L1 in instant impact but not in hit-and-hold impact ($p = 0.05$). This supports our assumption, consistent with [27], that greater tilt and extrusion correspond to stronger impact force. However, no statistical significance of force level was found in cases 3 and 4 for either impact type, although the trends followed our expectations.

All participants reported perceiving impact and pressing force as integrated feedback through their adjustments, supporting XTick's use of the two haptic sensations to generate both impact types. Regarding actuation onset, 9 participants were satisfied, consistent with our pilot study, while P5, P8, and P10 preferred slightly earlier platform actuation in some cases. For instant impact, 9 found the releasing phase reasonable; P4 noted that it enhanced the sensation of fading pressing force. However, P6, P8, and P10 disliked the delay despite maximum speed. For hit-and-hold impact, 7 participants

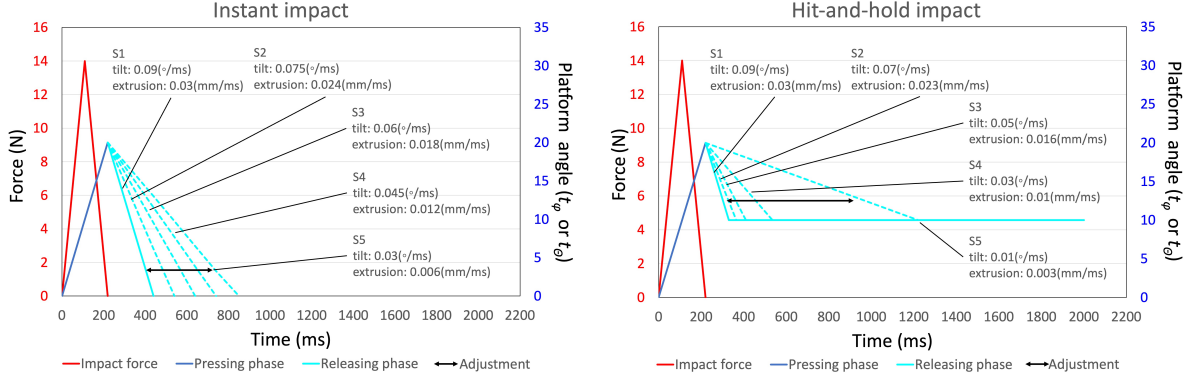


Figure 6: The adjustment concept of release speed of the pressing force feedback in instant impact (left) and hit-and-hold impact (right) in the impact extension study.

perceived controller shape change instead of pressing feedback, but 4 of them (P_2 , P_4 , P_8 , P_9) specified that this occurred only when the sustained tilt and extrusion magnitudes were large. In contrast, P_3 appreciated the pressing feedback, stating that “It was like pressing a stick against the wall, with gradual angle change.”

Most participants, except P_4 and P_5 , agreed that tilt and extrusion magnitudes matched impact magnitude and adjusted them to fit their desired impact experiences. P_1 , P_2 , P_3 , and P_{11} noted that device weight distribution sometimes required stronger grip, increasing pressing feedback. For hit-and-hold, all, except P_4 , preferred lower tilt and extrusion magnitudes in sustained force than at the peak; P_2 and P_6 explained that sustained force should be weaker than the initial impact to match everyday experiences. P_8 and P_9 adjusted the magnitudes to represent the sustained force without noticeable shape change, indicating both pressing force magnitude and shape change contribute to perceived pressing force, as in [27]. When asked about stronger impact than L2, P_1 , P_2 , P_7 , P_8 , and P_{10} considered the current tilt and extrusion limits sufficient, whereas P_3 , P_6 , and P_{11} preferred faster pressing rendering.

Based on the results, we obtained the tilt angles (t_ϕ , t_θ) and extrusion displacement (*displacement*) at two force levels across five cases for both impact types. The comments indicated that integrated impact and pressing force were appreciated, their timing alignment was reasonable, tilt and extrusion magnitudes related to impact magnitude, and shape change contributed to perceived pressing force, consistent with our assumptions, pilot study, and [27].

5 IMPACT EXTENSION STUDY - TRANSITION

While the previous study established force magnitude alignment, it did not fully explore the transition between the initial impact and sustained force states, since the platform speed during the releasing phase was fixed at maximum. Based on those results, we explored how varying releasing speed affects user experiences across different impact levels, positions, and directions. Although the transition occurs only in hit-and-hold impact, we also examined whether the delayed platform return in instant impact extends the perceived impact duration. Additionally, we investigated whether the extended feedback in both impact types increases perceived force magnitude, a side effect yet a benefit of XTick, as in [29]. Thus,

we regarded the releasing phase in instant impact as a transition between the peak and the returned initial state, and explored the transition between the states for both impact types separately.

The apparatus and setup were the same as the previous study. 12 participants (5 female, all right-handed) aged 22-27 (mean: 23.92) were recruited. 4 of them had participated in the previous study, with an interval of more than a week between the two studies.

5.1 Task and Procedure

Various platform speeds in the releasing phase were examined, while the pressing phase always used the maximum speed to produce a sharp force increase. The upper bounds corresponded to the platforms' maximum in tilt and extrusion speeds, and the lower bounds were determined in a pilot study as the slowest speeds that did not disrupt feedback integration. Since speed and duration are relevant, speeds with constant intervals (more distinguishable than durations) were selected separately for tilt and extrusion. 5 examined speeds (s_1 , s_2 , s_3 , s_4 , s_5) (high to low) are shown in Figure 6. The procedure followed the previous study. Participants first experienced impact alone (baseline), and then evaluated integrated feedback at each speed, rating satisfaction on a 7-point Likert scale, the perceived impact force magnitude ratio for both impact types, and the perceived duration ratio for instant impact only, as in [34]. The two impact levels and five cases (with subcases) were examined as before. Tilt and extrusion magnitudes for the pressing force peak and sustained state were based on the previous study. A total of 100 ($= 2$ (sessions) $\times 2$ (force levels) $\times 5$ (cases) $\times 5$ (speeds)) trials were examined, with fixed session and speed (high to low) orders, counterbalanced force levels, randomized cases, and evenly distributed, randomly assigned subcases. An interview followed the experiment. The study took about 3 hours.

5.2 Results and Discussion

A Friedman test and Wilcoxon signed-rank tests with Bonferroni correction for post-hoc pairwise tests analyzed satisfaction. Repeated measures ANOVA with Bonferroni correction for post-hoc pairwise tests analyzed the perceived impact magnitude and duration ratios relative to the baseline. The results and post-hoc pairwise

comparisons are shown in Figure 9 in the appendix. For instant impact: (1) in case 1 and 2 at L1, s_2 scored significantly higher than the others, making it preferred; (2) in case 3, 5 at L1, and in case 2, 5 at L2, s_1 - s_4 scored significantly higher than s_5 but not among themselves, indicating s_1 - s_4 acceptable; (3) in case 4 at L1, s_3 scored significantly higher than s_4 , with no statistical significance among s_1 - s_3 , and in case 3, 4 at L2, s_1 - s_3 scored significantly higher than the others, meaning s_1 - s_3 acceptable; (4) in case 1 at L2, s_1 and s_2 scored significantly higher than the others, making them preferred. For hit-and-hold impact: (1) in case 1 at L1 and case 3 at L2, s_1 - s_3 scored significantly higher than the others, except between s_1 and s_4 , and were also significantly higher than the others in case 2 at L2, indicating their acceptability; (2) in case 3, 4 at L1, and case 5 at L2, s_1 - s_4 scored significantly higher than s_5 , with s_3 significantly higher than s_4 , meaning s_1 - s_3 acceptable; (3) in case 2, 5 at L1, and case 1, 4 at L2, s_1 - s_4 scored significantly higher than s_5 , with s_2 significantly higher than s_1 in case 2 at L1 and s_3 significantly higher than s_2 in case 5 at L1, indicating s_1 - s_4 as better choices.

Participants generally expressed higher satisfaction at higher speeds, since slower speed separated the integrated feedback into distinct impact and pressing sensations ($P1$, $P7$, $P11$, $P12$). For instant impact, $P1$ and $P6$ found the lowest speed (s_5) disruptive to integration. Interestingly, s_2 scored significantly higher than s_1 in case 1, 2 at L1 for instant impact, and in case 2 at L1 for hit-and-hold impact. $P5$, $P6$, $P8$, and $P10$ explained that high speeds masked a desirable *shock wave* sensation after impact, leading them to prefer s_2 over s_1 . In case 5 (extrusion), $P1$, $P3$, and $P5$ preferred lower speeds, since extrusion on the same side made the feedback much more obvious, resembling a real-world *recoil* sensation, making s_1 - s_4 acceptable. For hit-and-hold impact, slower speeds (s_3 and even s_4) were also acceptable as they facilitated the transition from the peak to the sustained state ($P7$, $P11$, $P12$), consistent with our design. $P2$ and $P9$ preferred moderate speeds to perceive the transition.

In perceived impact magnitude, for instant impact, speed was the primary factor over duration, with half the participants ($P1$, $P7$, $P9$, $P10$, $P11$, $P12$) reporting weaker force at lower speeds, while the other perceived stronger force. $P4$ noted that longer releasing durations with higher impact levels increased perceived force, and $P6$ felt slower speeds prolonged pressing, amplifying the perceived force, consistent with [29]. XTick enhanced perceived impact up to 253% of the rendered impact, achieved at s_4 in case 5 at L2 due to pronounced extrusion. For hit-and-hold, perceived magnitude was generally lower than the initial impact, as the pressing force slightly weakens after the peak. However, $P4$, $P6$, and $P8$ perceived stronger force at lower speeds due to prolonged pressing, as in [29]. For perceived impact duration in instant impact, all, except $P3$, perceived longer durations at slower speeds, unless the speed was too slow to maintain integrated feedback. Perceived durations remained below 200% of the baseline (impact alone). At the highest tilt speed s_1 (cases 1-4), integrated feedback reached 442ms, about 200% of the baseline (220ms), indicating perceived durations are shorter than actual feedback but exceed impact alone. Most participants found s_5 too slow, making pressing feel separate, with $P1$ and $P2$ perceiving the shortest duration, equal to the baseline.

Based on this and previous studies, we obtained guidelines for integrating impact and pressing force: (1) Higher platform speeds improved experiences but should not mask the *shock wave* in instant

impact, making s_2 sometimes preferable. (2) For hit-and-hold, lower speeds (s_3 or even s_4) allowed smoother state transitions, while extremely low speeds (s_5) disrupted integration. (3) Slower speeds were perceived as weaker by some and stronger by others due to prolonged pressing [29], reducing statistical significance; instant impact generally enhanced perceived magnitude, whereas hit-and-hold was weaker due to pressing force decline after the peak. (4) Slower speeds extended perceived duration for instant impact only if integration was preserved. Based on the guidelines and results, we selected common pressing force parameters across cases. L1: Peak (t_ϕ , t_θ , $displacement$) = (20° , 20° , 5mm) for both impact types; sustained state = (10° , 10° , 3mm) for hit-and-hold. Releasing speeds (t_ϕ , t_θ , $displacement$) = (s_2 , s_2 , s_3) for instant, (s_3 , s_3 , s_4) for hit-and-hold. L2: Peak (t_ϕ , t_θ , $displacement$) = (22° , 22° , 6mm); sustained = (13° , 13° , 3mm). Releasing speeds = (s_2 , s_3 , s_4) for instant, (s_3 , s_3 , s_3) for hit-and-hold. For consistency, case 4 (composite tilt) uses the higher speed (s_2) for both tilts at L2 instant impact. These profiles establish the relationship between impact and pressing force magnitudes, enabling derivation of other impact magnitudes.

6 VR EXPERIENCE STUDY

Based on previous studies, we determined the parameters for force magnitude alignment and transitions in both impact types, and then conducted this VR study to verify whether incorporating omnidirectional pressing with impact enhances VR experiences.

The setup was the same as in previous studies, with XTick tracked via a Quest 2 controller and VR content shown on the headset. 12 participants (4 female, all right-handed) aged 22-29 (mean: 24.42) were recruited. None had participated in prior studies.

6.1 Task and Procedure

Two methods were compared: impact alone based on transPAF [4] (I) and feedback integration from XTick (X), with XTick rendering feedback for both. Although XTick enables omnidirectional pressing, pressing alone was excluded since impact alone, with sharp force increase, has been proven to outperform pressing alone, with only gradual force increase, in instant impact scenarios in [31, 33]. The study aimed to verify whether integrated feedback outperforms the state-of-the-art impact. 7 applications, including the 5 cases discussed previously, were used to demonstrate XTick's usage and for comparison (Figure 7 and 10 in the appendix). 3 tools types, swords, rackets, and shields, were used across the the applications, with parameter values selected based on prior study guidelines.

For *sword slash*, participants slashed a cartoon enemy with a wooden sword near its handle. Feedback was rendered upon the collision, and the enemy was then defeated. Instant impact at L1 was used, since the enemy provided no resistance. The impact PAF and force direction were in case 1, with detailed parameters (θ , ϕ , offset, θ_r , ϕ_r) for all applications shown in Figure 10 in the appendix. For *sword press against shield*, they slashed an enemy with the sword tip, but the attack was blocked by a shield. They then pressed the sword against the shield for 2 seconds, guided by a "Hold" indicator showing the defending duration. Due to shield defense, hit-and-hold impact was at L2, with the impact PAF and force direction also in case 1. For *side hit on badminton racket*, participants hit a shuttlecock that struck the left side of a badminton racket. Since the

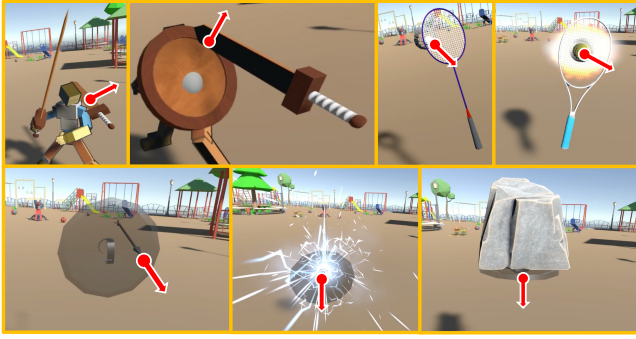


Figure 7: 7 applications in the VR study: sword slash, sword press against shield, side hit on badminton racket, sweet spot tennis hit, shield blocking side arrow, shield blocking center laser, and shield blocking falling rock at center. Red dots and arrows represent the impact position and direction.

shuttlecock was light, instant impact was at L1, with the PAF and force direction in case 4. For *sweet spot tennis hit*, they used a tennis racket to hit a powerful fireball at the sweet spot. Hit-and-hold was at L2 for the heavy ball. Since tennis and badminton rackets were held differently, the impact PAF and force direction were in case 2. Swinging motions were involved in the sword and racket applications, and device robustness was verified through the study. However, extremely rapid swinging motions were discouraged.

For *shield blocking side arrow*, participants defended against an arrow striking the shield's right side; the transparent shield allowed them to see the attack. Instant impact was at L1, since the arrow fell after impact, with the impact PAF and force direction in case 3. For *shield blocking center laser*, they blocked a laser attack at the center for 2s. Hit-and-hold was at L2 for the powerful laser, with the PAF and direction in case 5. The laser attack represented typical energy attacks in games and animations. For *shield blocking falling rock at center*, they raised the shield upward to block a rock falling from above, which stayed on top of the shield for 2s, demonstrating gravity-induced hit-and-hold impact at L2 for the heavy rock, with the PAF and force direction in case 5. The experimenter introduced the device, feedback, and the study design. Participants held XTick and experienced the 7 applications for both methods, with methods counterbalanced and applications in fixed order. After the experiment, they rated their experience on a 7-point Likert scale and were interviewed. The study took about an hour.

6.2 Results and Discussion

The results are in Figure 8. A Friedman test and Wilcoxon signed-rank tests with Bonferroni correction for post-hoc pairwise tests analyzed the subjective scales. Significant main effects were revealed in all factors, including realism ($\chi^2(1) = 11, p = 0.001$), distinguishability ($\chi^2(1) = 5.44, p = 0.02$), enjoyment ($\chi^2(1) = 6.4, p = 0.01$), and preference ($\chi^2(1) = 5.44, p = 0.02$), indicating that integrated impact feedback significantly enhances VR experiences. We further investigated realism and distinguishability per application (Figure 11 in the appendix). For the 3 instant impact applications, *sword slash*, *side hit on badminton racket*, and *shield blocking side arrow*, (I) was previously preferred [4], yet incorporating pressing in (X)

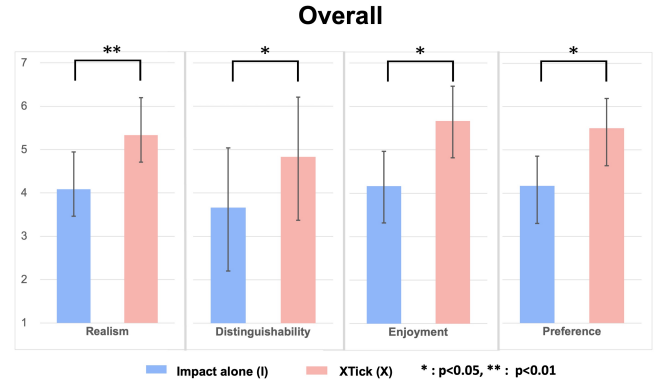


Figure 8: The VR study results, including realism, distinguishability, enjoyment, and preference.

significantly improved realism in *shield blocking side arrow* and distinguishability in all three. However, no statistical significance was found in *shield blocking center laser* for either factor.

All participants, except *P10*, found (X) more realistic than (I). *P9* noted that (I) lacked sustained force expected in hit-and-hold scenarios, while *P7* and *P12* appreciated the tilting platforms of (X) as feeling like a stick pressing the hand, confirming pressing as inherent feedback. Most participants, except *P1*, *P5*, *P8*, *P10*, perceived (X) as more distinguishable, with *P2* and *P3* attributing this to pressing feedback better aligning impact direction with visual feedback. *P1*, *P5*, and *P8* reported similar distinguishability, and *P10* preferred (I) due to incoherent pressing in (X). 7 (*P1*, *P2*, *P4*, *P6*, *P7*, *P8*, *P9*) found (X) more enjoyable and preferable, consistent with results showing (X) significantly better than (I) in all factors.

For *sword slash*, participants generally agreed that feedback in both methods aligned with visual feedback and should feel weaker than *sword press against shield*. While no statistical significance was revealed in realism, 7 participants (*P2*, *P3*, *P4*, *P7*, *P8*, *P11*, *P12*) perceived (X) as more concrete and realistic. *P8* noted that integrated feedback (X) produced the expected shock wave of impact, while *P7* felt prolonged impact in (X) better matched slashing, indicating that pressing in (X) extended perceived impact duration. However, *P9* and *P10* considered the force in (X) too strong and long. For distinguishability, (X) outperformed (I); *P1*, *P2*, and *P6* reported unclear impact direction in (I) but clear direction and strike point in (X), indicating that the incorporated pressing enhanced the distinguishability of the impact PAF and direction, even at lower magnitudes. For *sword press against shield*, (X) significantly outperformed (I) in realism and distinguishability. 5 (*P2*, *P6*, *P8*, *P9*, *P10*) expected continuous resistive force when blocking the sword, which was only perceived in (X), showing that the sustained force in hit-and-hold enhanced experiences. *P6* and *P8* also reported the expected shock wave in (X). All, except *P1* and *P5*, reported better distinguishability in (X) due to pressing clarifying impact direction, though *P1*, *P3*, and *P5* felt it was already perceivable in (I).

For *side hit on badminton racket*, 7 (*P2*, *P3*, *P4*, *P7*, *P10*, *P11*, *P12*) felt (X) better conveyed the sensation of the shuttlecock staying on the racket, highlighting extended perceived duration. *P10* and *P11*

appreciated clearer impact on the hand from pressing in (X), while P6, P8, and P9 found it too strong. P1 and P5 felt (I) suited regular strokes but (X) suited powerful smashes, leading to no statistical significance in realism. For distinguishability, (X) was significantly higher, as P4 and P7 noted pressing in (X) clarified impact direction, though P1, P3, P6, and P10 found it already distinguishable in (I). For *sweet spot tennis hit*, all, except P10, found (X) much more realistic. P1, P4, P6, P8, and P9 felt pressing in (X) amplified perceived force, matching real hits and highlighting its role in enhancing perceived magnitude. Additionally, P1, P3, P5, and P8 noted that although the ball visually stayed on the racket, impact (I) occurred only at contact. For distinguishability, most participants, except P3, P5, and P8, found (X) with pressing more distinguishable.

For *shield blocking side arrow*, most participants, except P3, P8, and P11, found (X) much more realistic. P1, P2, P6, P9, and P10 noted clear shock waves, stronger magnitude, and better alignment with visual feedback in (X), while P1 and P6 felt (I) was too weak, leading to significantly higher realism in (X), even for the instant impact scenario. P1, P3, P8, P9 and P10 perceived higher distinguishability in (X), clearly sensing the strike on the shield's right edge, though P3 and P7 expected handle rotation rather than side tilt or expansion. For *shield blocking center laser*, participants enjoyed both methods, but most preferred (X), perceiving the beam as a shock wave consistent with our hit-and-hold design. P1 and P8 felt pressing in (X) matched their expectations for continuous force. However, P6, P7, and P10 expected milder discrete impact and preferred (I), leading to no statistical significance. Distinguishability was similar in both methods, partly since the imaginary laser visual feedback led P6, P7, and P10 to envision different haptics; they agreed an energy beam concept might better match the design. For *shield blocking falling rock at center*, (X) was significantly more realistic and distinguishable than (I). P7, P9, P10, and P11 praised the pressure sensation in (X), while most found (I) unsatisfactory due to short impact conflicting with visual feedback, highlighting the effectiveness of hit-and-hold in extending force duration. Although the feedback design was identical to the laser case, the rock scenario aligned better with expectations.

Overall, (X) was well appreciated, showing significantly better performance across all factors. Pressing in (X) improved distinguishability of impact PAF and direction, while the shock wave sensation enhanced experiences. In hit-and-hold scenarios, sustained force in (X) supported continuous resistive force; in instant impact, (X) increased the perceived magnitude and duration, making strong impact more convincing. Weight distribution sometimes affected experiences: azimuthal tilt (t_θ) caused unstable holds and weaker impact perception, while other cases benefited from tool-matching weight [4, 25, 39], with experienced players noting enhanced realism in the tennis scenario. The results confirm that integrated feedback enhances impact experiences, supporting our design goals.

7 LIMITATIONS AND FUTURE WORK

While XTick was generally appreciated, some limitations remain. XTick (825g) is relatively heavy, although its weight is comparable to or lighter than some handheld devices (e.g., Aero-Plane 1069g [13], MobileGravity ~1460g [15], SpinOcchio 883g [16], MetamorphX 840g [9]). A VR cable management system, a commercial

product commonly used in XR exhibitions or VR game zones for headset cable management, could be used to mitigate the device weight in practical use via a retractable ceiling pulley system while preserving portability, similar to [31]. Weight distribution, especially in cases 3 and 4 with azimuthal tilt (t_θ), may affect feedback perception, though it could be beneficial when aligned with virtual tools; reducing the impactor weight with fewer or lighter motors could help. Impactor delays are mostly limited to mode switching and can be masked with animations or visual effects [25, 39]. Furthermore, prediction methods, e.g., recognizing and tracking the direction of an approaching impact target before the actual collision, also allow the system to perform adjustments in advance, as in [4]. Moreover, retargeting techniques can be used to align visual feedback and VR events with the prepared haptic feedback, as in [1]. Although we intended to include more impact levels in the feedback integration and impact extension studies to derive relationships for generalization, this was constrained by the need to avoid an excessive number of trials under diverse conditions. 2 impact types and 5 cases already required 3 hours for each study. More impact levels could be included for generalization in the future. The first two studies focused on force magnitude alignment and state transitions, while the third verified that integrated feedback outperforms the state-of-the-art impact feedback. Future work could include a full comparison with pressing feedback, despite its proven underperformance compared to impact feedback.

8 CONCLUSION

We propose XTick to render omnidirectional impact all round the controller for instant and hit-and-hold impact by integrating impact and pressing force. Two rotatable 3DoF platforms, tilting and extruding, enable omnidirectional pressing for integration. We investigated force magnitude alignment and state transitions: an integration study determined tilt (t_ϕ , t_θ) and extrusion (*displacement*) magnitudes at two impact levels across five generalizable cases, while an extension study investigated platform release speeds for smooth transitions. The integrated feedback enhances perceived impact magnitude and duration. Based on these results, guidelines for impact-pressing magnitude alignment and state transitions were also obtained. A VR study confirmed that integrated feedback from XTick significantly enhances user experiences.

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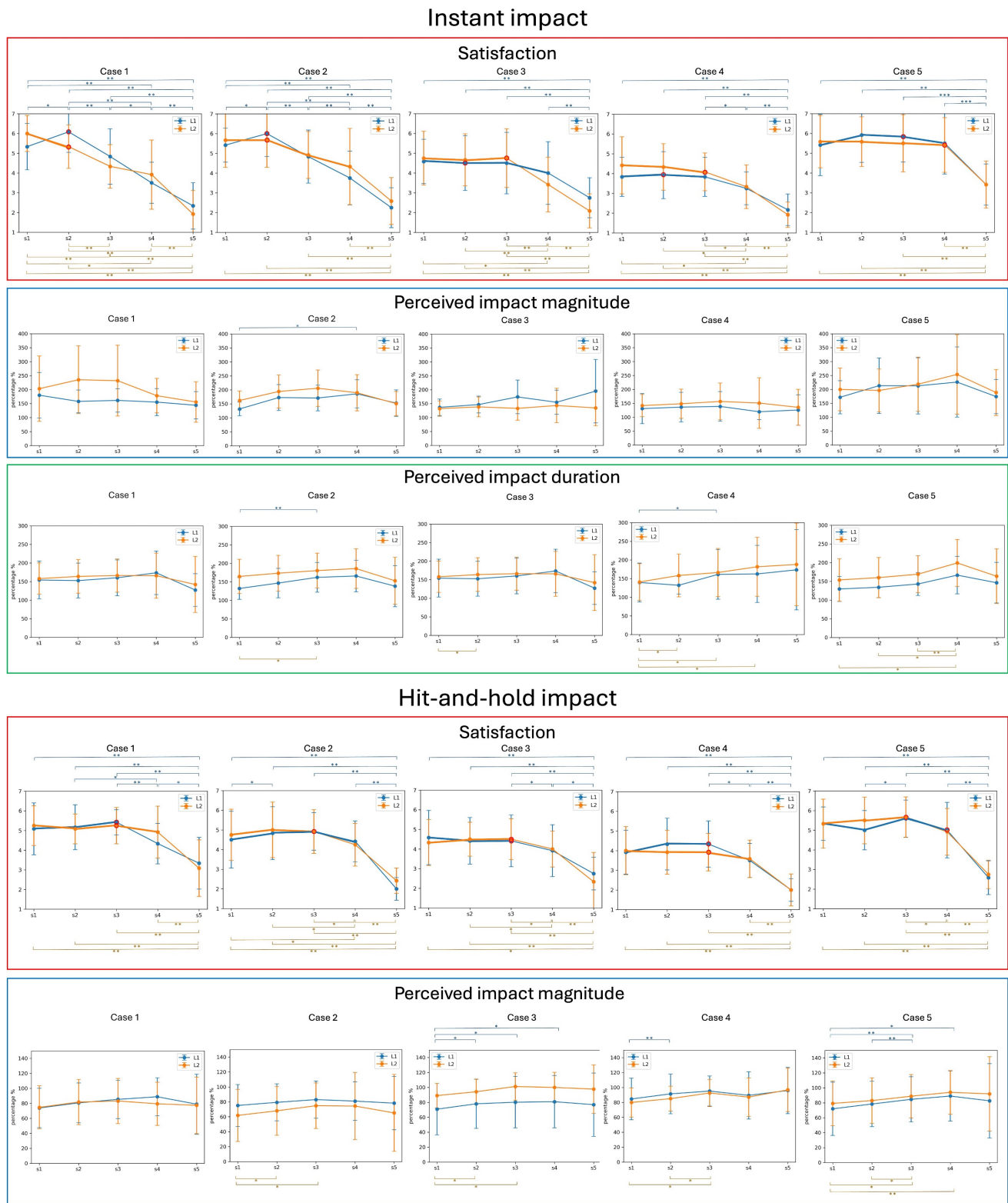


Figure 9: The results of the impact extension study. Satisfaction, perceived impact magnitude, and perceived impact duration are in instant impact (upper). Satisfaction and perceived impact magnitude are in hit-and-hold impact (lower).

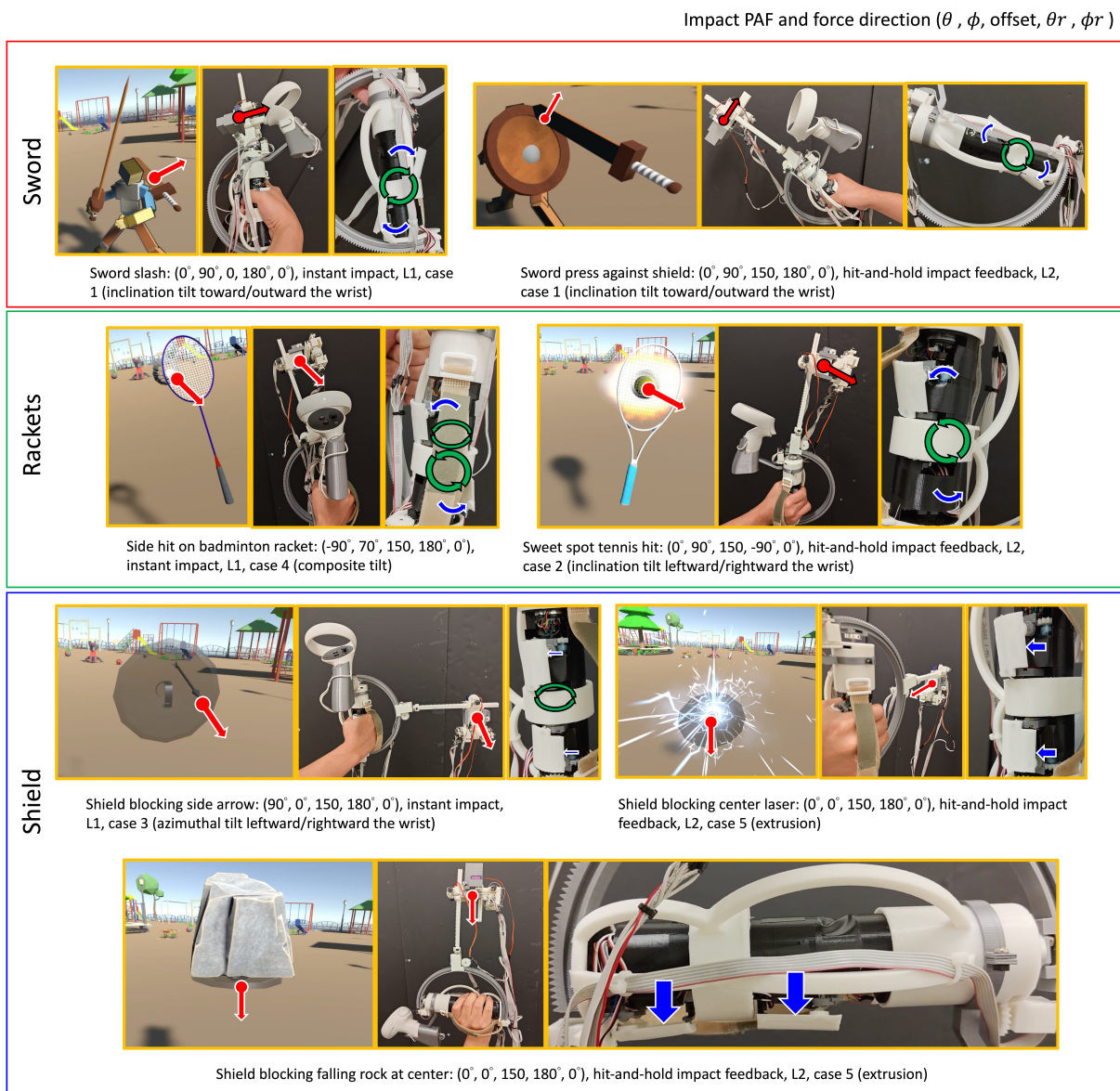


Figure 10: 7 applications in the VR study. Red dots and arrows represent the impact position and direction.

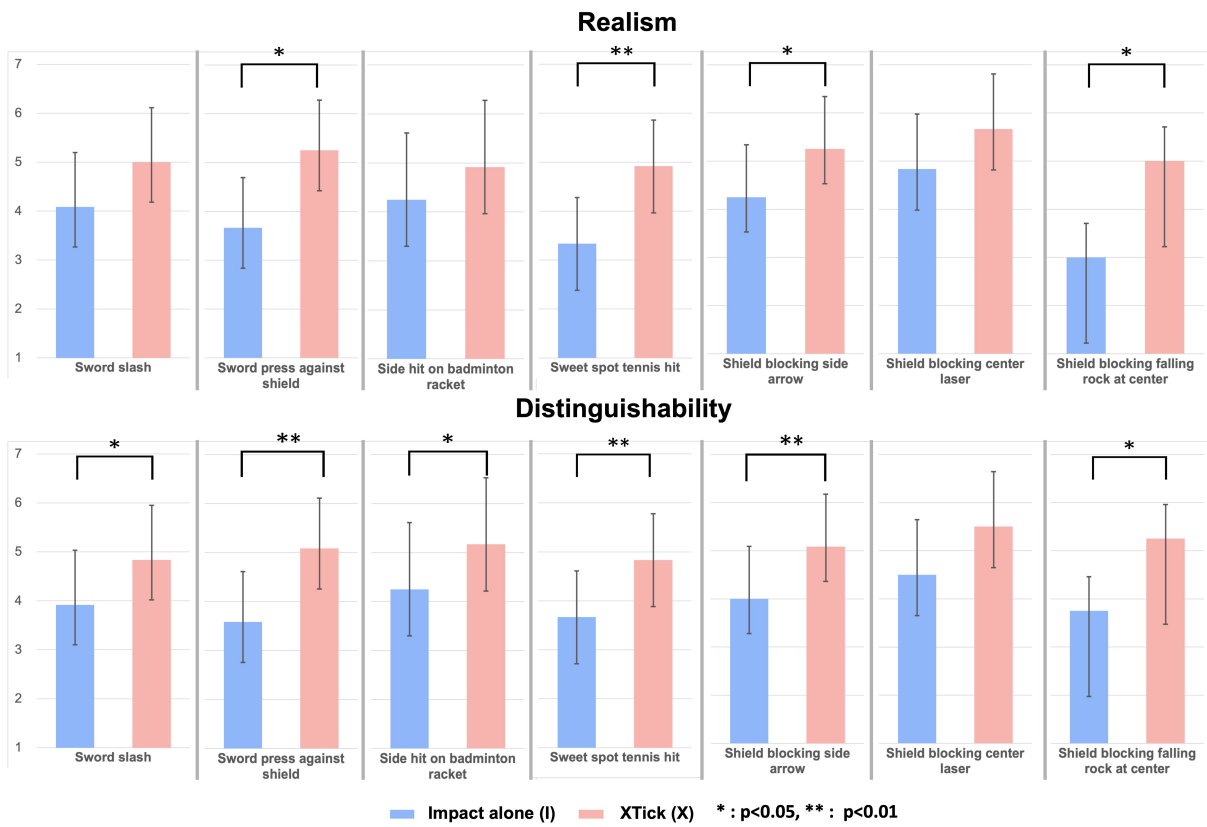


Figure 11: The results of the realism and distinguishability for each application in the VR study.