AirCharge: Amplifying Ungrounded Impact Force by Accumulating Air Propulsion Momentum

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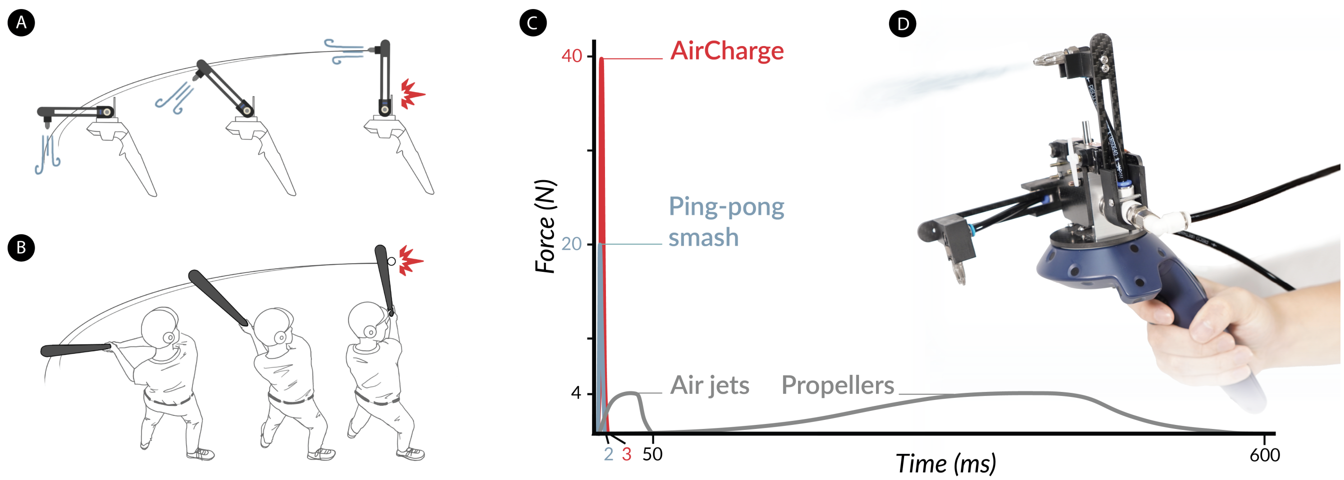

Figure 1: AirCharge is a novel haptic device that: a) uses a rotating swingarm design to accumulate momentum from ungrounded force feedback technologies, thus achieving instantaneous, directional impact force; b) is inspired by baseball swings; c) amplifies the impact force magnitude by over 10x compared to conventional air jet and propeller technologies and matches real-world impact durations like a ping-pong smash; and d) AirCharge uses a *novel reciprocating dual-swingarm design* with a reversing bevel gearbox to eliminate gyro effects and achieve high-frequency impact force feedback of 10Hz.

ABSTRACT

Impact events, which generate directional forces with extremely short impulse durations and large force magnitudes, are prevalent in both virtual reality (VR) games and real-world experiences. However, despite recent advancement in ungrounded force feedback technologies, such as air jet propulsion and propellers, these technologies remain 5-100x weaker and 10-500x slower compared to real-world impact events. For instance, they can only achieve 4N with a minimal duration of 50-500ms compared to the 20-400N forces generated within 1-5ms for baseball, ping-pong, drumming, and tennis. To overcome these limitations, we present AirCharge, a novel haptic device that accumulates air propulsion momentum to generate instantaneous, directional impact forces. By mounting compressed air jets on rotating swingarms, AirCharge can amplify impact force magnitude by more than 10x while matching real-world impulse duration of 3ms. To support high-frequency impacts, we explored and evaluated a series of device designs, culminating in a *novel reciprocating dual-swingarm design* that leverages a reversing bevel gearbox to eliminate gyro effects and to achieve impact feedback of up to 10Hz. User experience evaluation (n = 16) showed that AirCharge significantly enhanced realism and is preferred by participants compared to air jets without the charging mechanism.

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CCS CONCEPTS

• **Human-centered computing → Haptic devices**.

KEYWORDS

Haptics, ungrounded force feedback, virtual reality, air propulsion, impact forces

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1 INTRODUCTION

Real-world impact events generate directional forces that have extremely short impulse duration and large force magnitude. For example, the impulse duration is 1*ms* for baseball and 5*ms* for tennis [9], and the force magnitude is up to 20*N*- 400*N* for ping-pong [25] and tennis [9]. Despite extensive research into ungrounded force feedback technologies that allow users to move and interact freely in VR, current technologies are still 5-100x weaker [9, 24, 25] in force magnitude and 10-500x slower [9, 10, 24] in impulse duration than these real-world impact forces.

Specifically, the two key ungrounded force feedback technologies available today are propellers and compressed air jets. Propeller-based systems, e.g. WindBlaster [12] and Thor's Hammer [10], can generate forces of 4*N* but its impulse duration is long at 500 *ms*, as the propellers must physically speed up then slow down. Air jet-based systems, e.g. JetController [24] and AirRacket [22], use compressed air to generate propulsion forces more rapidly, which can achieve 4*N* with a shorter impulse duration of 50*ms*. Even with its 10x more rapid impulse than propellers, it is still 10x-50x longer than everyday real-world impact forces.

Drawing inspiration from how baseballs can be hit farther by rewinding the bat farther back and taking a longer swing [14] (Figure 1(ab)), we developed AirCharge, a novel haptic device capable of generating instantaneous, directional impact forces that are comparable to real-world impact forces. By using swingarms to accumulate air propulsion momentum over time prior to an instantaneous impact, as shown in Figure 1(a), AirCharge can amplify air jets' force magnitude by 10x while making the impulse 20x more rapid to achieve 40*N* at 3*ms*, which matches the sub-5*ms* duration of real-world impacts. Figure 1 C shows the 4 impulse curves generated by AirCharge, propellers, air jets, and a real-world ping-pong smash.

Although AirCharge's swingarm concept is easy to relate to, its implementation in a practical handheld device presents three significant challenges that must be overcome to ensure good user experience: 1) the rotating swingarm noticeably shifts the balance of the device (i.e., center of mass); 2) the swingarm's angular momentum causes momentary gyroscopic effects; and 3) rewinding the swingarm to its starting position is slow and limits actuation frequency.

We developed three major device design iterations, each with several revisions, to address these challenges. We initially started with a single-swingarm design that used a motor and an electromagnetic clutch to rewind the swingarm, but found that it had a long rewinding time and significant shifts in device balance. We finally created a novel, 10*Hz* high-frequency design that addresses all three challenges, by using two swingarms connected via a reversing bevel gearbox, as shown in Figure 1(d). This reciprocating mechanism eliminates the rewinding time, because a swingarm gets rewound into its ready position at the exact moment the opposing swingarm impacts. Furthermore, this design addresses the undesirable side effects that may degrade the user experience, including eliminating gyroscopic effects and minimizing changes in the device's center of mass.

One inherent limitation of AirCharge is the latency incurred while accumulating momentum, which ranges from 30-140*ms* depending on the target force magnitude. While there are techniques to mask some of this latency, such as impact and motion prediction, we were interested in understanding the user experience of the worst-case latency condition, as well as any unintended side effects caused by the device. Therefore, we conducted a small exploratory study (n=16) to compare AirCharge with 150*ms* latency vs. two baselines: JetController and AirRacket, for single- and high-frequency impact experiences. Participants reported that AirCharge significantly improved realism vs. the two baselines and that its force feedback timing was perceived to be accurate.

Our contributions are as follows:

(1) The first ungrounded force feedback device capable of generating instantaneous impact forces with comparable force magnitude and impulse duration as real-world impact forces.
(2) A novel reciprocating dual-swingarm design that enables high frequency force feedback (10*Hz*), eliminates undesirable gyroscopic effects, and minimizes shifts in device's balance (center of mass) vs. straightforward single-swingarm designs.
(3) Open-sourcing of AirCharge's[1] hardware and software for others to experience and build upon our progress.

2 RELATED WORK

Extensive research has explored a wide range of approaches to simulate impact experiences. We categorize them into impact feedback devices that are *active* vs. devices that can only provide *reactive* forces to user motion.

2.1 Active Impact Feedback Devices

Moving mass-based approaches include linear actuators based on solenoids [20, 21], pneumatic-driven pistons [3], motor-driven shafts [16], and weights attached to elastic bands (e.g. ElasticImpact [23]). These actuators generate vibration when the moving mass impacts the actuator enclosure. However, Newton's 3rd law states that such moving mass does not produce net forces outside the actuator, as two equal and opposite forces are created between the moving mass and its enclosure. Moreover, moving mass devices produce undesirable reaction force, vibration, and latency when returning to their initial position, and also shifts the device balance (center of mass) during both the actuation and return phases. Su et al. [20] leveraged human's nonlinear sensory properties for

[1]Open sourced at https://github.com/ntu-hci-lab/AirCharge

asymmetric forces, and used a spring and friction damper to create asymmetric feedback during the actuation and return of the moving mass. However, the perceived directionality of such design remains ambiguous with users only able to recognize impact direction with 79-93% accuracy. In contrast, AirCharge, like rockets hitting a target, generates true directional impact force without any confusing and ambiguous reaction force. Additionally, AirCharge can provide sustained directional forces with desired durations, which is not achievable with a moving mass mechanism.

Electrical Muscle Stimulation (EMS) is another approach to simulate physical impact. Impacto [13] combines tactile stimulation and EMS to simulate the impact on the forearm. Farbiz et al. also proposes an approach [7] to simulate the impact on a tennis racket using EMS. However, for impact feedback, EMS actuates the opposing muscle groups, which results in qualitatively distinct sensations from a real-world external impact force [22]. In addition to the mismatch in haptic experience, EMS has issues with discomfort and requires a calibration process for each user. In contrast, AirCharge generates directional forces comparable to real-world impact forces.

Furthermore, there are devices utilizing the gyroscopic effect to actively apply force to the user using a motor to turn a spinning flywheel. For example, TorqueScreen [15] is a tablet attached by a flywheel and a gimbal, while iTorqU [26, 27] is a handheld device with a metal flywheel inside a two-axis actuated gimbal. By controlling the gimbal, the systems apply torque to the users and thus can generate an impact-like sensation. However, using this kind of mechanism to provide the feedback of torque requires the device to be held still. Otherwise, users will perceive unintentional resistive gyro force feedback.

Speeding up and braking a motor of a momentum wheel instantly can also provide a rotational impulse. This mechanism has been used in guidance, especially in the medical field, such as in colonoscopy simulation [17] or endovascular catheterization [4]. However, the torque of such a system always comes in pairs: when the system generates a torque clockwise while speeding up the motor, it generates a torque counter-clockwise while decelerating it. To only provide the torque in one direction, the system must accelerate or decelerate the motor slowly enough to make the contrary torque unperceivable.

Compressed air jet [22, 24] and propeller [1, 10–12, 18] approaches have been developed to generate directional forces to simulate the haptic experience of real-world impact, which render actual external force with none of the above side effects. However, even with such systems, all the above method's maximum force is not enough for real-world impact. For example, max magnitude for air jet and propeller system is around $4N$, and their shortest impulse duration for $4N$ requires a minimum of $50ms$ and $500ms$, respectively [10, 22, 24]. The $500ms$ impulse duration of propellers is significantly longer than the user-acceptable impulse duration of $337ms$ for virtual tennis [22]. To address the limitations of magnitude and duration of these ungrounded air propulsion technologies, AirCharge uses swingarm to accumulate momentum to amplify the force magnitude and match the instantaneous impact duration of real-world impact forces.

2.2 Reactive Impact Feedback Devices

With a different actuation metaphor, there are also other devices that can potentially render an impact experience but rely on users' motion. Adjusting the angular momentum vector while the user moves the device can provide reactive feedback. Gyrotab [2] is a system that provides reactive torque feedback using two flywheels spun in opposite directions. By speeding up one flywheel while decelerating the other, it can rapidly alter the angular momentum of the system. These approaches offer the benefit of providing feedback throughout the entire movement. However, they can only provide feedback on the moving direction and cannot replicate a realistic impact pulse as they require time to adjust the speed of the flywheels.

Braking mechanisms can provide very strong feedback. Wireality [6] uses wire and ratchet gears to stop users' hands while they attach objects in the virtual world. Wolverine [5] is a glove with brake-based locking sliders. It can provide over $100N$ between each finger and the thumb. Approaches using braking mechanisms can provide consistent stiffness, but to make them portable, it has to be grounded on the body. Externally grounded devices can generate large force, but severely limits user and controller movement due to limited operating space and the anchoring of controllers to the environment. Unlike externally grounded systems, body-grounded devices with mobility capabilities can be applied to a wider range of scenarios. Despite the above benefits, body-grounded devices also have some limitations. Due to the limited places available to ground them on the body, generating force feedback in arbitrary three-dimensional directions (i.e., 3-DoF force feedback) can be challenging. Additionally, the primary limitation of body-grounded devices is the perceivable reaction forces due to the mounting of on-body pivot points, and this inexplicable tactile feedback may break the virtual experience.

Weight-shifting mechanisms have been used to provide impact feedback by altering the center of mass of the device [19]. This technique can create the illusory impression of a resistive force when rotating the racket during active swinging motions, but it cannot generate impact forces on the handheld item by itself when being static. Furthermore, this approach lacks translational force in the direction of the impact.

In general, reactive feedback can create a more substantial sensation relative to the energy input of the user's movement. However, its reliance on users' motion limits its usage when the user is not actively moving. Additionally, reactive feedback, which is generated by offsetting the user's movement, is unable to provide certain haptic sensations, such as rebounding the user's hand.

3 SYSTEM DESIGN AND IMPLEMENTATION

The key concept of AirCharge is the accumulation of momentum from propulsion forces before generating an instantaneous impact force. In this section, we first describe the physics background of impulse, time, force magnitude, and momentum in the context of AirCharge. We then present our exploration of 3 major device design iterations and detail our final implementation.

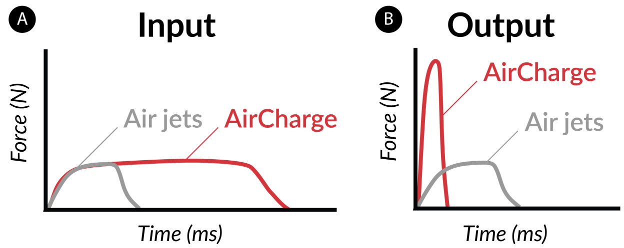

Figure 2: Impulse is the force applied over time, or the area under a force-time curve: a) AirCharge extends the input force duration to accumulate momentum, i.e. increased area under the force-time curve; b) AirCharge shortens the output force duration, resulting in an output force-time curve with increased force magnitude.

3.1 Physics Background

In physics, impulse is the change in momentum of an object caused by a force over a period of time. It is defined as the integral of a force, F, over the time interval, t, for which it acts, and can be visualized as the area under a force-time curve. Since force is a vector quantity, impulse is also a vector quantity.

AirCharge uses two mechanisms to convert a relatively weak input force into an instantaneous output force with amplified magnitude. First, it extends the air propulsion input force duration by using a swingarm. As shown in Figure 2(a), the area of the input impulse curve increases proportionally as duration increases. Second, it shortens the output force duration by using a physical backstop to stop the swingarm instantaneously. Figure 2(b) shows two impulses with equal magnitude, ie. having the same area under force-time curves, and the one with shorter duration will have a proportionally higher force magnitude.

In a single-swingarm design, the momentum transfers from the swingarm to the controller in a single impact. In a dual-swingarm design, because of the spacing between gear teeth, there will be two independent impact impulses. The first impulse is caused by the direct impact by the first swingarm hitting the backstop. The second impulse is caused by the 2nd swingarm continuing rotating until it hits the next gear tooth.

3.2 Device Evolution and Prototypes

3.2.1 Single Swingarm, Single Nozzle Prototype. As straightforward as it seems, our first attempt of putting AirCharge into practice is implemented with a single-swingarm prototype as shown in Figure 3(a). The device mainly consists of two components: (1) a servo motor that pre-rotates the swingarm to a predefined angle and (2) a compressed air nozzle mounted on the swingarm to lead to striking impact on the backstop. The motor as well as its driving shaft are connected to the swingarm through an electromagnetic clutch, which engages when the motor are rotating the whole swingarm to a target preloaded angle. To avoid the friction of the servo motor from countering the propulsion force output, the clutch disengages the motor whenever the propulsion force is rendering. We implement the device with a Pololu metal gearmotors with its magnetic encoder pair kit and a micro excitation operative clutch. The nozzle is connected to a rotary pneumatic connector to avoid the bending force of the tubing from interfering with the swingarm's rotation.

The total response time of the single-swingarm device is 510.7ms for a 15° preload angle and 1055.7ms for a 90° angle at 0.6MPa. It is divided into three phases: rewinding (966.2ms), clutch release (15ms), and swingarm impact (74.5ms). These phases encompass the time of receiving a serial command from the PC, slowly rotating to a predefined angle by the servo motor to keep the reaction torque below perceptual threshold, disengaging the swingarm from the servo motor using the electromagnetic clutch, triggering the propulsion force, and the time it takes for the swingarm to move from 90° to striking impact on the handheld device.

Although such response time might be enough to support discrete impact events such as tennis strike (0.5Hz [9]), it hinders the use of high-frequency impact experience such as machine gun recoiling or continual strike of weapons. In addition, the single swingarm design induces a considerable shift of the center of mass (COM), which creates noticeable differences in wielding sensation at various angles.

3.2.2 Single Swingarm, Two Nozzle Prototype. To reduce the long preloading time of the servo motor actuation and the disengagement of the electromagnetic clutch, we developed the second major prototype, as shown in Figure 3. In this version, we removed the motor and clutch and added an extra nozzle, both connected to our pneumatic control system. With the two nozzles mounted on the same swingarm, when one nozzle propels the swingarm to strike against one backstop, the other nozzle is being reversely rewound to the preloaded angle for the next strike on the opposite backstop. This design eliminates the need for pre-rotating the swingarm or engaging the clutch, thus reducing the system's response time and enabling high-frequency applications. Unfortunately, this version of the prototype introduced a more noticeable weight shifting sensation on the roll axis. Despite this, the reciprocating mechanism served as inspiration for our final system design.

3.3 Final System Design

Our final system design for AirCharge features a dual-swingarm version, shown in Figure 3(c), with two nozzles that operate reciprocally. Likewise, this version offers improved timewise performance compared to the original design, as the two swingarms are interconnected by a reversing bevel gearbox. This means that while one swingarm strikes the handheld device, the other is rewound to the preloaded angle in reverse motion, reducing response time and enabling high-frequency applications.

Furthermore, compared to the second prototype, the dual-swingarm design minimizes the shift of the device's center of mass (COM) due to its symmetric movement. In our last design, the COM moved along a circular trajectory as the swingarm rotated. In contrast, the movement of the COM in the dual-swingarm version is limited to the displacement between the geometric center of the two swingarms and the midpoint of the circular trajectory, resulting in more stably perceived COM. In addition, our initial design mounted nozzles outside of the swingarms, resulting in noticeable torque. To mitigate the torque, we made a revision by mounting the nozzles inside the swingarm, at a distance of 2cm from center as shown in Figure 3(c).

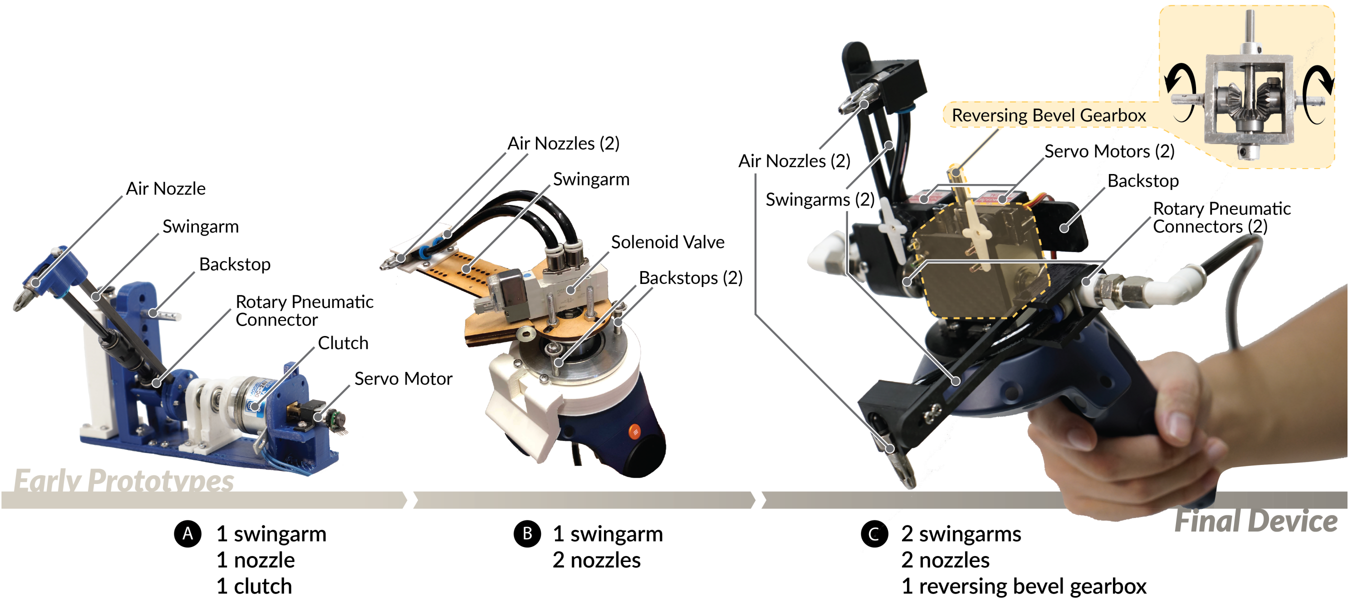

Figure 3: System design evolution: a) Single-swingarm + single-nozzle design that rewinds to initial position using a servo motor and electromagnetic clutch; b) Single-swingarm + two-nozzle design that eliminates rewind time, but causes significant shift in balance; and c) Final *reciprocating dual-swingarm design* with a reversing bevel gearbox to eliminate gyro effects, to minimize shift in balance, and to achieve high-frequency impact force feedback of 10Hz.

We manufactured two sets (total = 4) of carbon-fiber swingarms with different preloaded angles. Each swingarm has 12 screw holes that can be fastened onto the gearbox flange. The screw holes of the two sets of swingarms have a 15° offset from each other. By interchanging and locking the two swingarms with different rotational offsets, we can achieve preloaded angles of 15°, 30°, 45°, 60°, 75°, and 90°. Although the preloaded angle has to be predetermined, the output force magnitude can be dynamically modified by adjusting the air pressure during use.

Our control software utilizes OpenVR to read the vibration commands sent from the application to VR controllers. It then transmits this signal to the microcontroller board, adjusting the air pressure and duration parameters to modulate the control signals for the regulator, valve, and servos. To prevent the swingarm from shifting arbitrarily during intense use, we incorporated two servo motors to lock its position when the propulsion force is not active. The servo takes approximately 20ms to lock the swingarms, matching the rise time of the air jet.

The final version of the AirCharge module, as shown in Figure 3(c), can be mounted on VR controllers or on other body locations with corresponding adaptors. The total weight of the device is around 300g, with the carbon-fiber swingarm, nozzle, and tubing accounting for 24g. The device's volume (excluding the controller) measures 15cm × 23cm × 4cm. The noise level of our pneumatic setup was reported as 75dB at 0.6MPa [24], while the impact creates much lower noise.

3.4 Pneumatic Control System

Our swingarm component is then connected to the pneumatic control system (Figure 4), which is based on the combination of JetController's [24] high-frequency valve selection and AirRacket's [22] pneumatic layout for bi-directional force output. Each of our compressed air nozzles is connected to a Festo MHE4 high-speed solenoid valve through a 150cm PU tubing. The two solenoid valves are then connected to a single SMC ITV2050 electro-pneumatic pressure regulator (with repeatability within 0.5% and sensitivity within 0.2%) for modulating the output air pressure. Both solenoid valves and the regulator are connected to a customized PCB board and react to the control signal of a ESP32 control board, which receives serial commands from our PC.

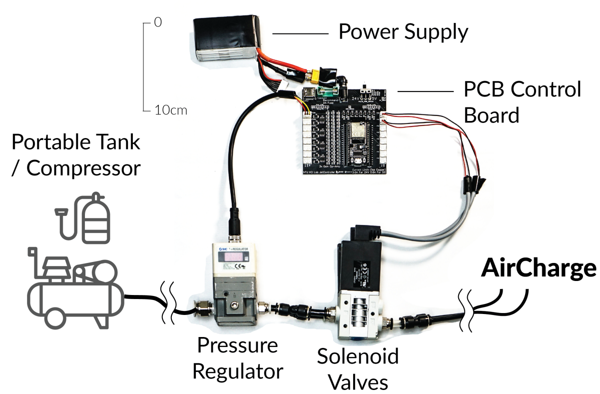

Figure 4: Pneumatic control system.

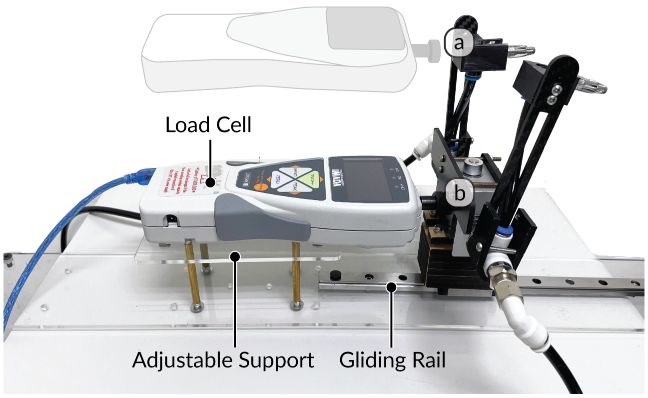

Figure 5: Experimental setup for force measurement using a load cell at two impact locations.

Similar to the mobile model presented in previous work [24], the compressed air of the whole system is supplied by a stationary air compressor, while alternatively, a portable air tank could be another option for a fully mobile usage. Figure 4 shows our pneumatic control system.

4 SYSTEM CHARACTERIZATION

The goal of our work is to provide a reshaped force curve that matches real-world impact events, which we characterize as large peak force and short response time. However, there is a tradeoff between these ideal characteristics. To understand how different design considerations affect AirCharge's impact force output, we first look at how nozzle placement influence the characteristics, and then conduct a series of technical evaluations of various (1) preload angles and (2) air pressure to see their effects on AirCharge's (1) peak force and (2) response time, and further examine the performance of (3) frequency.

4.1 Experimental Setup and Design

To conduct our system characterization, we employed an IMADA ZTS-50N load cell sensor featuring a sensing rate of 2000Hz and an accuracy rating of 0.2% (0.04N), affixed to a customized laser-cut support structure. For equitable comparison with previous air jet devices, we implemented a similar experimental setup where the load cell was positioned at the rear of the nozzle as shown in Figure 5 (position a). In addition, this setup is capable of precisely gauging swingarm traverse duration while mitigating vibration effects attributed to gearbox activity. AirCharge's module was then secured onto a ball-bearing platform that rested on a smoothly gliding rail.

4.2 Nozzle Placement

Different nozzle placements lead to different swingarm lengths and weight distribution, which makes a tradeoff between force magnitude, response time, weight and compactness. To understand its effects on AirCharge's force output, we varied the distance between the nozzle and the rotary pivot by 10cm, 12.5cm, and 15cm, which is chosen after exploring lengths from 8-25cm. For each trial, we first set the regulator to 0.2MPa, and then we opened the solenoid valve for 300ms to make sure the swingarm collides with the backstop on the loadcell. The preloaded angle was set at 90° for all conditions, and the actuated air pressure was 0.2MPa, as it is the minimum pressure needed for a complete swing. For each distance, we repeated the trial for 20 times.

To calculate the response time, we record the timestamp of when the serial command is sent and compare it to the timestamp when the loadcell received a force value larger than 3N, which is our sensor's error range. The response time for 10cm, 12.5cm, and 15cm are 125.3ms, 127.3ms, and 141.2ms, respectively.

Based on the result, moving the nozzle farther away from the rotational center slows the rotational speed, which we believe is affected by larger inertia contributed by both the shift of the nozzle and the added length of the swingarm. We chose 10cm as our nozzle placement for the final device since it comes with the shortest response time, but different placement should also be feasible.

4.3 Peak Force Magnitude

The maximum force magnitude of air jets varies with preload angle and air pressure. We studied how the factors affect the force characteristics and visualized the results in Figure 6. It shows the force magnitudes at various air pressures for different angle configurations. Six preload angles were tested from 15° to 90° with 15° increments. An additional 0° was tested where continuous force feedback was provided. To account for both our system's maximum sustainable air pressure and the constraints imposed by a 90° preload angle, we established an incremental range of air pressure from 0.2 to 0.6MPa with intervals of 0.02MPa. Each condition was repeated for 20 trials. The mean peak forces throughout the trials were computed, and a linear regression method was employed to estimate the trend (all R^2>0.7). Results demonstrated that a larger preload angle exerts a greater force for every pressure condition. In all cases, higher air pressure leads to a greater force magnitude. Overall, the device attains an 70N force magnitude with a 90° preload angle at 0.6MPa.

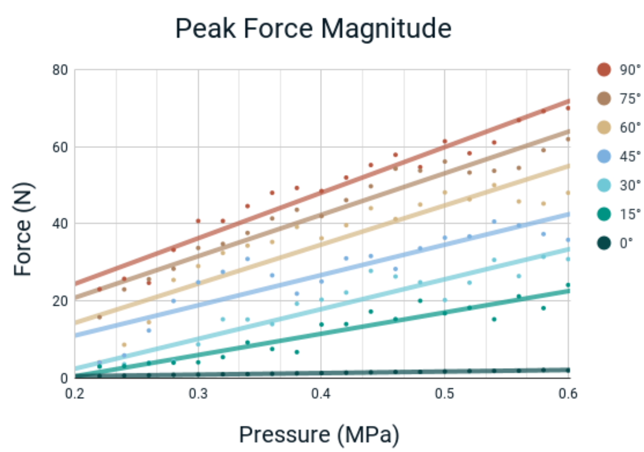

Figure 6: Peak force magnitudes across preloaded angles and air pressures.

4.4 Response Time and Impact Time

The response time of a pneumatic system measures the latency between sending a command signal and the start of an impact. To investigate the influence of the preload angle and air pressure, we implemented a similar study procedure for the response time. The response time curves of varying configurations were presented in Figure 7, where power series was utilized to approximate the patterns (all R^2>0.9). For every preload angle, the response time gradually decreases as pressure increases. Furthermore, a larger preload angle results in a longer response time. At $0.6MPa$, the device requires a response time of $125ms$ at a preloaded angle of 90°.

To capture the impact time, we compute the intervals of the zero-crossings when our device output force curve is above 90 percent of its maximum force magnitude. The average impact time at $0.6MPa$, 90° preload angle is $3.2ms$.

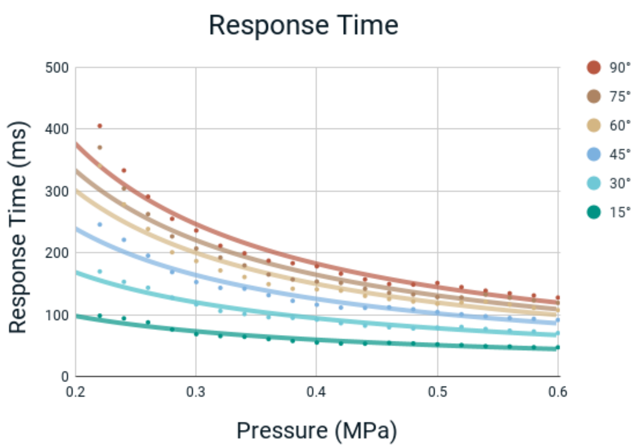

Figure 7: Response time across preloaded angles and air pressures.

4.5 Frequency

The frequency refers to the rate at which consecutive impact events take place. Again, we examine how the preload angle and air pressure affect the frequency, so as to provide a design practice for future designers who want to create experiences of different frequencies. According to the previous evaluations, we set the preload angle and air pressure constant at 90° and $0.6MPa$, for it achieves an overall higher force magnitude and shorter response time. With this setting, we measure the frequency of various air jet duration ranging from $120ms$ to $170ms$ with $10ms$ increments. Overall, the frequency is $8.03Hz$ (SD = 0.067) at $120ms$ and $6.38Hz$ (SD = 0.067) at $170ms$, gradually decreasing as air jet duration increases. Figure 8 further provides results at 60° and 90° with different air propulsion durations.

4.6 Additional Evaluation on Different Device Position

To better understand the device's impact output, we further conducted this technical evaluation with another sample position

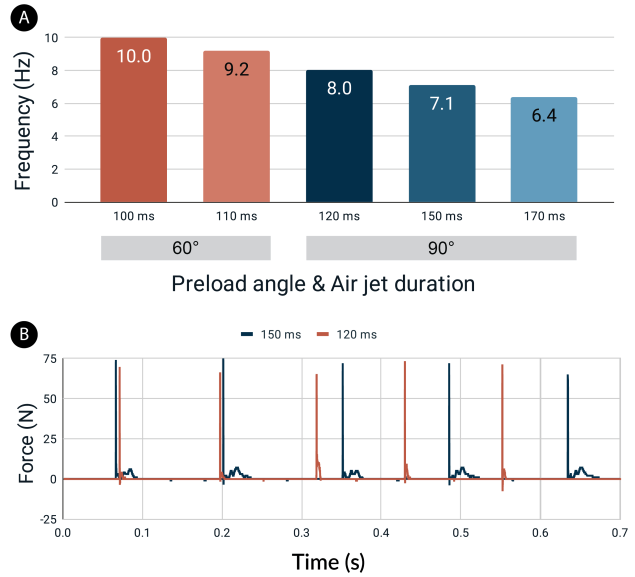

Figure 8: Impact: a) measured impact frequencies across air jet actuation durations at 60° and 90° preload angles; b) example measured force response curves for the 90° preload angle at 8.0Hz and 7.1Hz.

shown as position b in Figure 5. Compared to the above evaluation measure at position a (Figure 5), we secured and ensured the contact between the carbon fiber housing of the gearbox and the sensor throughout the testing. Additionally, slow-motion footage of collisions as proof of continuous attachment between the load cell and device upon impact was recorded. In this setup, the 20-trial average result at 90°, $0.8MPa$ is $40.39N$, while the $0.6MPa$ result is $26.51N$. The average impact time at $0.6MPa$, 90° preload angle is $3.0ms$. In general, the maximum force magnitude is lower as it excludes the internal force of the whole system. (Note: this is the data we reported in the Abstract and Introduction)

5 USER EXPERIENCE EVALUATION

To understand AirCharge's user experience, we compared its haptic experience with existing ungrounded force technologies, including the conventional air jet experience of JetController [24] and another approach with extended air jet duration proposed by AirRacket [22]. Our evaluation focus on: (1) Whether the reshaped impulse curve improves users' perceived haptic realism and (2) whether users experienced any side effects.

5.1 Task and Procedure

Our study was conducted in a VR environment using the add-on of the commercial game Half-life Alyx. To compare the impact experience in low and high-frequency events, we applied two types of guns, a single-shot weapon and a multi-shot weapon as shown in Figure 9, as our study scenario. We conducted a two-session within-subject study using pairwise comparison, with the ordering of the conditions fully counterbalanced. To start, participants first practiced using the device and familiarized themselves with the VR setting. In the first session, they were asked to experience the single-shot weapon scenario with two pairs of haptic experiences, namely AirCharge vs. one of the baseline haptic experiences (JetController or AirRacket) and AirCharge vs. the other baseline. In the second session, they repeated the comparisons with the multi-shot weapon scenario. In total, each participant underwent 2 FEEDBACK TYPE × 2 COMPARISON × 2 SCENARIO = 8 conditions in total. Each shooting experience lasted for one minute per condition. Participants were allowed a three-minute break between blocks and a ten-minute break between sessions. For each condition, we asked participants to choose which haptic experience best matches the strength of a real-world impact and rate it on a 7-point Likert scale. In addition, we gathered qualitative feedback about what their decisions were based upon and whether the timing of an impact felt accurate. The questions were adapted from Presence Questionnaire [28]'s questions 7 and 14. Later on, we specifically asked participants to comment on the perceived latency between feedback from AirCharge vs.our baselines.

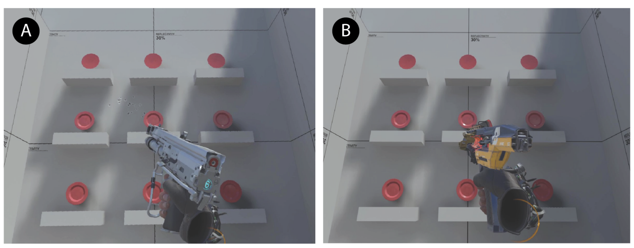

Figure 9: Target practice scenes from the VR game Half-life Alyx used for the user study: a) a single-shot weapon, b) a multi-shot weapon.

5.2 Participants

We recruited 16 participants, 7 male and 9 female, aged 18 to 30 (M = 22.4, SD = 3.32). All participants are right-handed with normal or corrected to normal vision. Five participants had no prior VR experience, ten had little VR experience, and the other was familiar with VR. As for shooting experience, three had never shot a gun before, nine had experienced no more often than once a year, two had no more than once three months, and the other two had shot once a month on average. All participants wore noise-canceling headphones with white noise playing in the background. Every subject received nominal compensation for the study.

5.3 Force Feedback Design

In light of clarity and fair comparison, we define air jet time as the duration of an air jet propulsion and impact time as the instantaneous duration upon collision with the backstop. For the study, we used air jet time as a design variable.

5.3.1 AirCharge Force Feedback. We set the preload angle to 90° and air pressure to $0.6MPa$ for it exerts the largest stable force that supports a high-frequency scenario (multi-shot weapon) provided by our air compressor. According to the result of the system characterization, AirCharge's' response time with a 90° preload angle at $0.6MPa$ is $125ms$. Hence, we set $150ms$ as the air jet time for AirCharge in this study.

5.3.2 Baseline Force Feedback. Both JetController and AirRacket have nozzles directly connected to the controller, which generates force feedback that is similar to AirCharge with a 0° preload angle. For this reason, we used AirCharge as the haptic device for all of the conditions throughout the study. This also eliminates irrelevant effects that may be induced across devices due to different system characteristics. To mimic the setup of JetController, we measured the response time of AirCharge with a 0° preload angle at $0.6MPa$. The time between sending a command signal and the moment of peak force is $30ms$. As for emulating AirRacket, we set its air jet time to $150ms$ which is the same as AirCharge for equitable comparison.

5.4 Result

5.4.1 Perceived Realism (Quantitative). Figure 10 shows participants' ratings of perceived differences in realism for the four comparisons on a 7-point Likert scale. For the comparison between AirCharge and JetController, every single user opted for the former in terms of realism for the single-shot weapon scenario and 14 for the multi-shot weapon scenario. Wilcoxon signed-rank test for a single sample showed a statistically significant difference from neutral with a large effect size ($r > 0.5$). (Single-shot weapon: one-tailed $p < 0.001$, $r = 0.91$; Multi-shot weapon: one-tailed $p < 0.01$, $r = 0.59$). For the comparison between AirCharge and AirRacket, 13 and 14 users chose AirCharge over the other for single-shot weapon and multi-shot weapon scenario respectively (Single-shot weapon: one-tailed $p < 0.05$, $r = 0.5$; Multi-shot weapon: one-tailed $p < 0.001$, $r = 0.79$). No participants reported that limited prior experiences hinder their judgment of realism.

5.4.2 Perceived Realism (Qualitative). Regarding realism, participants in the study reported that AirCharge had a more immediate shooting experience and larger recoil. For example, *"You will feel that its (AirCharge) actual shooting is more immediate, and its recoil is larger. After the impact, you will need to adjust your grip. It is more in line with the experience of a real gun."* [P12] *"(AirCharge) ... the recoil is relatively strong, and the gun's shaking amplitude is relatively large."* [P3] *"Because the controller held in hand is relatively light, but in reality, it needs to have a larger force feedback to achieve a realistic feeling."* [P5] *"It (AirCharge) has a more pronounced sense of firing, while the other (AirRacket) feels more like a backward shake."* [P14]

5.4.3 Perceived Latency. In terms of latency, participants also reported that there was not much difference in terms of haptic latency. For the single-shot weapon scenario, participants reported that *"In terms of time accuracy, I don't think there is much difference between the two (AirCharge vs JetController)."* [P7] *"(AirCharge) ... The delay was noticed at the very beginning, but after firing a few shots, it didn't seem to have a significant effect."* [P10] For the multi-shot weapon scenario, the delay was more noticeable: *" the second one (JetController) is better in terms of time accuracy, mainly because its (AirCharge) intervals are a bit uneven when firing in bursts."* [P10] *"The first one (AirCharge) seems slower."* [P9] However, overall, most participants still prefer AirCharge, as *"The second one (AirCharge) is more accurate because each bullet felt more distinct."* [P16]

5.4.4 Discussion. To sum up, the results showed that AirCharge provides a significantly more realistic impact experience vs.the two previous ungrounded force rendering methods, particularly in

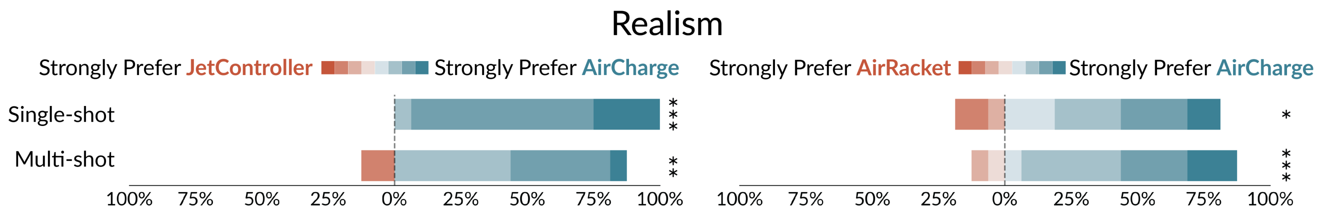

Figure 10: Realism evaluated on a Likert scale by comparing AirCharge to two force feedback designs: JetController [24] and AirRacket [22] (significance levels: *** p<.001, ** p<.01, * p<.05).

scenarios involving instantaneous impacts. According to qualitative feedback, AirCharge's large force feedback and its evident recoiling effect, the latter unexpected, greatly increased perceived realism, which has yet to be achieved by other technologies. Although slight latency exists, it does not subvert the overall preference from the participants. In fact, the shooting scenario is more intolerant to latency than other impact events, which serves as the lower bound that is more disadvantageous to our system. Additionally, latency can also pertain to the shooting frequency of the game settings, therefore we suggest that game designers take it into consideration.

6 DISCUSSION AND FUTURE WORK

6.1 Masking Latency

The main potential drawback of our method is that it introduces additional latency due to the time it takes for the swingarm to rotate and make contact with the backstop. However, there are several ways to mitigate this issue. One approach is to use motion prediction techniques in conjunction with our system. For instance, during a racket sport game, the user's swing motion and the trajectory of the virtual ball can be used to estimate when the racket will make contact with the ball, allowing the system to pre-actuate and provide a more accurate sense of impact timing. Continuous hand trajectory prediction [8] demonstrated an RMSE of $0.85cm$ for future hand positions up to 200 ms ahead, which is sufficient to mask AirCharge's latency. Another approach is to utilize predefined gaming events with fixed delays, such as a charged attack. Lastly, a smaller preloaded angle would also induce less latency.

However, we want to highlight that during our user study, we did not aim to filter or decrease latency, as it is almost impossible to predict when the user will trigger the button. Instead, we carried out the study using a 90° setup, which represents the most challenging situation in terms of response time. Therefore, we are confident about our system's performance based on the study results and believe that integrating it directly without the above solutions would still further enhance the impact experience.

6.2 Realism versus Enjoyment

Although previous studies on air jet feedback [22, 24] have reported that users perceive an evident gap between the intensity of the feedback and real-world experience, during our follow-up questionnaire, there are still a few participants in our study who did not prefer the impact feedback of AirCharge to these baselines. Two of them explained that the intense recoil force from the impact caused them to feel fatigued more easily. Therefore, they preferred to choose a smaller impact force for everyday gaming usage, even if it was not as realistic.

While our device can provide a more realistic impact sensation, we suggest that future designs offer a certain level of customizability, such as a dual-mode option between realism and enjoyment. We believe a more realistic feedback could be suitable for training usage, while milder feedback could be used for entertaining usage of a longer playing time.

6.3 Enlarging Perceived Persistent Force Feedback

Although our research focuses on providing instantaneous force feedback of less than $5ms$, there are VR sensations that require longer force feedback, such as slicing through an object or engaging in a sword fight. Similarly, these longer impulse sensations suffer from a significantly reduced force feedback output compared to real-world force magnitudes.

During our pilot testing, we observed that even with persistent force feedback lasting longer than one second, the perceived force magnitude with a preloaded angle can be larger than without a preloaded angle (which is 0°). While, physically, our charging module can only render a significant impact magnitude for the first few milliseconds during such persistent force duration, there is a possibility that the human perception system perceives the entire duration of force magnitude to be larger, although this effect may decay as the total duration lengthens. We believe it would be worthwhile to explore the potential benefits of AirCharge for longer force feedback durations.

6.4 Future Adaptation of AirCharge

The future version of AirCharge could include mounting options for different body parts, such as an on-haptic vest or foot, to enable a richer set of experiences, such as feeling on-body hits or simulating kicking a ball. Since AirCharge is a modular device, it can be easily fixed onto different body parts with corresponding mounts. Additionally, while our study focused on a shooting range gaming experience, our device can be easily applied to other virtual impact events that require impact feedback, such as racket sports, hammering, and punching. AirCharge can also be expanded by attaching additional nozzles to create accurate multi-directional impact experiences, such as topspin and slice in tennis. Moreover, implementing closed-loop control for servo lock offers the potential for a more robust controller movement. Finally, while our device generates impact through physical collision, we could improve the dedicated experience of certain impactors and force curves, by placing a softer texture on the backstop to simulate the feeling of a tennis ball, or extending air jet force to modulate the fall time and duration.

7 CONCLUSION

We presented AirCharge, a novel haptic module that addresses the limitations of current ungrounded impact feedback technologies in VR games and virtual experiences. By accumulating air propulsion momentum to generate an instantaneous, directional impact force, AirCharge can achieve impact force magnitudes more than 10x stronger and realistic impulse durations of $3ms$ as real-world impact events. Through exploring and evaluating a series of device designs, we arrived at a double swingarm design that achieved continual impact feedback up to 10x. User experience evaluation showed that AirCharge significantly improved realism and was preferred by participants, indicating its potential for improving haptic feedback in VR gaming and virtual experiences.

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REFERENCES

[1] Muhammad Abdullah, Minji Kim, Waseem Hassan, Yoshihiro Kuroda, and Seokhee Jeon. 2018. HapticDrone: An encountered-type kinesthetic haptic interface with controllable force feedback: Example of stiffness and weight rendering. In *2018 IEEE Haptics Symposium (HAPTICS)*. IEEE, San Francisco, CA, USA, 334–339. https://doi.org/10.1109/HAPTICS.2018.8357197

[2] Akash Badshah, Sidhant Gupta, Daniel Morris, Shwetak Patel, and Desney Tan. 2012. GyroTab: A Handheld Device That Provides Reactive Torque Feedback. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Austin, Texas, USA) *(CHI '12)*. Association for Computing Machinery, New York, NY, USA, 3153–3156. https://doi.org/10.1145/2207676.2208731

[3] Jose Berna-Moya and Diego Martinez Plasencia. 2019. *Exploring the Effects of Replicating Shape, Weight and Recoil Effects on VR Shooting Controllers*. Springer, Cham, 763–782. https://doi.org/10.1007/978-3-030-29381-9_45

[4] Wenqiang Chi, Hedyeh Rafii-Tari, Christopher J. Payne, Jindong Liu, Celia Riga, Colin Bicknell, and Guang-Zhong Yang. 2017. A learning based training and skill assessment platform with haptic guidance for endovascular catheterization. In *2017 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, IEEE, Singapore, 2357–2363. https://doi.org/10.1109/ICRA.2017.7989273

[5] Inrak Choi and Sean Follmer. 2016. Wolverine: A Wearable Haptic Interface for Grasping in VR. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology* (Tokyo, Japan) *(UIST '16 Adjunct)*. Association for Computing Machinery, New York, NY, USA, 117–119. https://doi.org/10.1145/2984751.2985725

[6] Cathy Fang, Yang Zhang, Matthew Dworman, and Chris Harrison. 2020. Wireality: Enabling Complex Tangible Geometries in Virtual Reality with Worn Multi-String Haptics. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–10. https://doi.org/10.1145/3313831.3376470

[7] Farzam Farbiz, Zhou Hao Yu, Corey Manders, and Waqas Ahmad. 2007. An Electrical Muscle Stimulation Haptic Feedback for Mixed Reality Tennis Game. In *ACM SIGGRAPH 2007 Posters* (San Diego, California) *(SIGGRAPH '07)*. Association for Computing Machinery, New York, NY, USA, 140–es. https://doi.org/10.1145/1280720.1280873

[8] Nisal Menuka Gamage, Deepana Ishtaweera, Martin Weigel, and Anusha Withana. 2021. So Predictable! Continuous 3D Hand Trajectory Prediction in Virtual Reality. In *The 34th Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '21)*. Association for Computing Machinery, New York, NY, USA, 332–343. https://doi.org/10.1145/3472749.3474753

[9] H Hatze. 1976. Forces and duration of impact, and grip tightness during the tennis stroke. *Med. Sci. Sports* 8, 2 (1976), 88–95.

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

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

[12] Seungwoo Je, Hyelip Lee, Myung Jin Kim, and Andrea Bianchi. 2018. Wind-Blaster: A Wearable Propeller-Based Prototype That Provides Ungrounded Force-Feedback. In *ACM SIGGRAPH 2018 Emerging Technologies* (Vancouver, British Columbia, Canada) *(SIGGRAPH '18)*. Association for Computing Machinery, New York, NY, USA, Article 23, 2 pages. https://doi.org/10.1145/3214907.3214915

[13] Pedro Lopes, Alexandra Ion, and Patrick Baudisch. 2015. Impacto: Simulating physical impact by combining tactile stimulation with electrical muscle stimulation. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*. Association for Computing Machinery, New York, NY, USA, 11–19.

[14] Peter Merton McGinnis. 2020. *Biomechanics of Sport and exercise.* Human Kinetics, Champaign, Illinois.

[15] Martin Murer, Bernhard Maurer, Hermann Huber, Ilhan Aslan, and Manfred Tscheligi. 2015. TorqueScreen: Actuated Flywheels for Ungrounded Kinaesthetic Feedback in Handheld Devices. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction* (Stanford, California, USA) *(TEI '15)*. Association for Computing Machinery, New York, NY, USA, 161–164. https://doi.org/10.1145/2677199.2680579

[16] Ali Rahimi, Jackson Zhou, and Sasan Haghani. 2020. A VR gun controller with Recoil Adjustability. In *2020 IEEE International Conference on Consumer Electronics (ICCE)*. IEEE, Las Vegas, NV, USA, 1–2. https://doi.org/10.1109/ICCE46568.2020.9043008

[17] Evren Samur, Lionel Flaction, Ulrich Spaelter, Hannes Bleuler, David Hellier, and Sebastien Ourselin. 2008. A Haptic Interface with Motor/Brake System for Colonoscopy Simulation. In *2008 Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*. IEEE, Reno, Nev., 477–478. https://doi.org/10.1109/HAPTICS.2008.4479998

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

[19] Shuntaro Shimizu, Takeru Hashimoto, Shigeo Yoshida, Reo Matsumura, Takuji Narumi, and Hideaki Kuzuoka. 2021. Unident: providing impact sensations on handheld objects via high-speed change of the rotational inertia. In *2021 IEEE Virtual Reality and 3D User Interfaces (VR)*. IEEE, IEEE, Lisboa, Portugal, 11–20.

[20] Yuning Su, Weizhi Nai, Xiaoying Sun, and Zuowei Sun. 2021. Design and Modeling of an Ungrounded Haptic Gun that Simulates Recoil Using Asymmetric Force. In *2021 IEEE World Haptics Conference (WHC)*. IEEE, Montreal, Canada, 361–366. https://doi.org/10.1109/WHC49131.2021.9517202

[21] Fong Wee Teck, Huang Zhiyong, Farzam Farbiz, Cher Jingting, Chin Ching Ling, and Susanto Rahardja. 2011. Ungrounded Handheld Device for Simulating High-Forces of Ball Impacts in Virtual Tennis. In *SIGGRAPH Asia 2011 Emerging Technologies* (Hong Kong, China) *(SA '11)*. Association for Computing Machinery, New York, NY, USA, Article 20, 1 pages. https://doi.org/10.1145/2073370.2073389

[22] Ching-Yi Tsai, I-Lun Tsai, Chao-Jung Lai, Derrek Chow, Lauren Wei, Lung-Pan Cheng, and Mike Y. Chen. 2022. AirRacket: Perceptual Design of Ungrounded, Directional Force Feedback to Improve Virtual Racket Sports Experiences. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 185, 15 pages. https://doi.org/10.1145/3491102.3502034

[23] Hsin-Ruey Tsai and Bing-Yu Chen. 2019. ElastImpact: 2.5D Multilevel Instant Impact Using Elasticity on Head-Mounted Displays. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology* (New Orleans, LA, USA) *(UIST '19)*. Association for Computing Machinery, New York, NY, USA, 429–437. https://doi.org/10.1145/3332165.3347931

[24] Yu-Wei Wang, Yu-Hsin Lin, Pin-Sung Ku, Yōko Miyatake, Yi-Hsuan Mao, Po Yu Chen, Chun-Miao Tseng, and Mike Y. Chen. 2021. JetController: High-Speed Ungrounded 3-DoF Force Feedback Controllers Using Air Propulsion Jets. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 124, 12 pages. https://doi.org/10.1145/3411764.3445549

[25] Ralf Widenhorn. 2016. The physics of juggling a spinning ping-pong ball. *American Journal of Physics* 84, 12 (2016), 936–942. https://doi.org/10.1119/1.4964104 arXiv:https://doi.org/10.1119/1.4964104

[26] Kyle N. Winfree, Jamie Gewirtz, Thomas Mather, Jonathan Fiene, and Katherine J. Kuchenbecker. 2009. A high fidelity ungrounded torque feedback device: The iTorqU 2.0. In *World Haptics 2009 - Third Joint EuroHaptics conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*. IEEE, Salt Lake City, UT, USA, 261–266. https://doi.org/10.1109/WHC.2009.4810866

[27] Kyle N. Winfree, Joseph M. Romano, Jamie Gewirtz, and Katherine J. Kuchenbecker. 2010. Control of a high fidelity ungrounded torque feedback device: The iTorqU 2.1. In *2010 IEEE International Conference on Robotics and Automation*. IEEE, Anchorage, AK, USA, 1347–1352. https://doi.org/10.1109/ROBOT.2010.5509485

[28] Bob G. Witmer, Christian J. Jerome, and Michael J. Singer. 2005. The Factor Structure of the Presence Questionnaire. *Presence: Teleoperators and Virtual Environments* 14, 3 (06 2005), 298–312. https://doi.org/10.1162/105474605323384654 arXiv:https://direct.mit.edu/pvar/article-pdf/14/3/298/1624394/105474605323384654.pdf