AirRacket: Perceptual Design of Ungrounded, Directional Force Feedback to Improve Virtual Racket Sports Experiences

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Figure 1: AirRacket explores perceptual force feedback design of air propulsion jets to improve the haptic experience of virtual racket sports: ping-pong, badminton, and tennis (note: white smoke added for illustrative purpose only, actual compressed air is invisible).

ABSTRACT

We present AirRacket, perceptual modeling and design of ungrounded, directional force feedback for virtual racket sports. Using compressed air propulsion jets to provide directional impact forces, we iteratively designed for three popular sports that span a wide range of force magnitudes: ping-pong, badminton, and tennis. To address the limited force magnitude of ungrounded force feedback technologies, we conducted a perception study which discovered the novel illusion that users perceive larger impact force magnitudes with longer impact duration, by an average factor of 2.57x. Through a series of formative, perceptual, and user experience studies with a combined total of 72 unique participants, we explored several perceptual designs using force magnitude scaling and duration scaling methods to expand the dynamic range of perceived force magnitude. Our user experience evaluation showed that perceptual designs can significantly improve realism and preference vs. physics-based designs for ungrounded force feedback systems.

CHI '22, April 29-May 5, 2022, New Orleans, LA, USA

ACM ISBN 978-1-4503-9157-3/22/04…$15.00
https://doi.org/10.1145/3491102.3502034

CCS CONCEPTS

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

KEYWORDS

Haptics, force perception, perceptual design, air propulsion, ungrounded force feedback, virtual reality.

ACM Reference Format:
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 *CHI Conference on Human Factors in Computing Systems (CHI '22), April 29-May 5, 2022, New Orleans, LA, USA.* ACM, New York, NY, USA, 15 pages. https://doi.org/10.1145/3491102.3502034

1 INTRODUCTION

Racket sports, such as ping-pong (i.e. table tennis), badminton, and tennis, are some of the most popular virtual experiences. For example, Wii Sports, which includes ping-pong and tennis, is one of the all-time best-selling games with more than 80 million copies sold [47]. Recent racket sports games, such as Eleven Table Tennis VR [35], have introduced online gameplay to provide social and competitive multiplayer experiences.

These games use controller vibration and optional racket-shaped adaptors [25] to enhance the virtual experience. Researchers have also explored other approaches to further enhance the haptic experience, such as solenoid actuators [66–68], weight shifting mechanism [60], and electric muscle stimulation (EMS) [18, 41]. However, existing approaches have yet to create directional impact force on the racket to reproduce the haptic experience of racket sports in the real world.

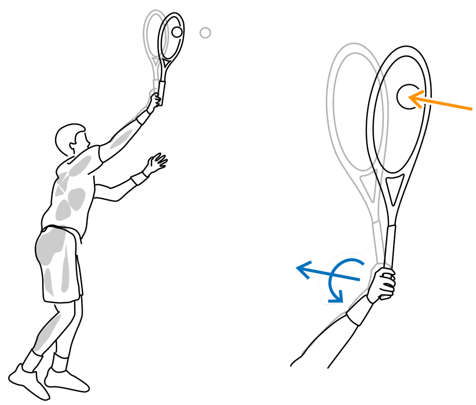

Figure 2: An overhead racket swing that shows the impact force on the racket resulting in rotational and transitional acceleration, and the multiple muscle groups working together to counter the impact force.

As shown in Figure 2, when a racket hits a ball or shuttlecock, the resulting impulse (i.e. directional force over a short period of time) creates both linear and rotational acceleration of the racket. The muscles in the user's hand, arm, shoulder, torso, and legs must work together to direct the racket and maintain body posture. This haptic experience consists of: 1) tactile sensation in the hand grasping the racket handle, including pressure, skin stretch, and vibration, and 2) kinesthesia and proprioception [42], including joint position and contraction of multiple muscle groups, to counter the impact force through the racket [55].

Directional, ungrounded force feedback technologies such as air jets [22, 56, 73] and propellers [24, 30] enable player mobility and have the potential to provide more realistic haptic experience for racket sports. However, their maximum force magnitude of ~4N is 2 orders of magnitude smaller than real-world racket sports which can exceed 400N [8, 13, 33]. This drastic difference in force magnitude makes haptic feedback for racket sports especially challenging to design.

We present AirRacket, which explores the perceptual design of ungrounded, directional force feedback to improve virtual racket sports experiences. As shown in Figure 1, we created devices for three popular virtual racket sports that span a wide range of impact forces: ping-pong, badminton, and tennis, using compressed air propulsion jets to provide directional impact force.

To better understand the user experience of AirRacket with a physics-based force feedback model, as well as any areas for improvement, we conducted a user study (n=12) and compared it to existing vibrotactile feedback used in commercial games. Study results showed significantly improved realism and preference for both badminton and tennis; however, participants commented that the directional force feedback was too weak and that all impact felt similar regardless of ball speed and swing speed. These are due to the limited force magnitude of ungrounded force feedback technologies combined with the physics-based model, which resulted in nearly all force feedback being rendered at the system's maximum output (of only 3.2N).

To improve upon the physics-based model given the limitation of existing technologies, we explored perceptual designs to: 1) increase perceived force magnitude, and 2) increase perceived dynamic range. We first discovered a novel illusion that impact forces with longer duration, without any visual feedback, are perceived to have larger magnitude. We verified this observation through a magnitude estimation study (n=12), which showed significantly larger perceived magnitude of 2.57x on average and up to 5.25x (350ms vs. 50ms). In order to apply this discovery to racket sports, we conducted a formative study (n=12) to identify the range of acceptable impact duration for each of the three racket sports. Participants reported that the most realistic force duration was 50-100x of the real-world impact duration of 5ms, and that significantly longer force duration felt more realistic for stronger impact.

To increase the effective and perceived dynamic range, we explored three force mapping designs that combined force magnitude scaling and duration scaling, and conducted a formative study (n=24) to identify the minimum perceivable impact forces for these force mappings. User experience evaluation (n=24) of these models showed that perceptual designs can significantly improve realism and were preferred by users.

In summary, our key contributions are as follows:

- We present the first force feedback system capable of providing directional impact forces for virtual racket sports, and showed that directional force feedback significantly improves realism and is preferred by users vs. vibrotactile feedback.
- We discovered the perceptual illusion that impact with longer duration, without visual feedback, is perceived to be of significantly larger force magnitude.
- We explored perceptual designs to expand the effective and perceived dynamic range of ungrounded, directional force feedback systems, which can significantly improve realism and are preferred by users vs. physics-based modeling.

- We have open-sourced AirRacket[1], including racket designs and the entire pneumatic system's hardware/software, so that anyone can experience and build upon our progress.

2 RELATED WORK

In this section, we first describe relevant methods and previous findings on perceptual design of haptic patterns, then discuss force feedback technologies in the context of racket sports.

2.1 Perceptual Design of Force Feedback

Researchers have discovered various approaches to augment and alter human perception of haptic experiences. Visuo-haptic coupling approaches affect perceived haptic sensations through only visual effects [5, 36, 57]. By manipulating the Control-Display (CD) gain in the virtual environment, the perceived weight of the same passive haptic props can be changed [57]. Through modulating the brightness value of an object, the expected and perceived weight can be reduced [4]. Using slow-motion and stop-motion visual effects during the impact of a ball in virtual tennis can increase the perceived impact intensity even though the amplitude of vibrotactile feedback remains constant [5].

Shifting the timing between applied haptic feedback relative to visual prediction also affects the perceived haptic sensation. In a virtual ball-catching task, virtual balls are perceived as heavier when force feedback is applied in advance of the catch (by 60ms) [32]. In a virtual object lifting task, the virtual objects are perceived as heavier when the force feedback persists beyond the moment that the virtual object was lifted [15].

Compared to the above visuo-haptic approaches that requires visual feedback, our discovery is that the perceived impact force magnitude increases with force duration without any visual feedback. Combined with our observation that users have a wide range of acceptable duration for racket sports, we were able to apply our discovery to enhance virtual racket sports experiences. Because our approach does not require visual feedback, it can potentially be used in combination with visuo-haptic techniques.

2.2 Force Feedback for Racket Sports

Besides vibrotactile feedback for virtual racket sports, researchers have explored different force feedback approaches. Solenoid actuators [66–68] create impact that produces subsequent vibration; however, they do not create net directional forces as the coil of the solenoid would generate a force equal in magnitude but in opposing direction to the moving core of the solenoid. Researchers have also explored ungrounded, illusory haptic feedback. Traxion [54] and Lead-Me [1] are handheld tactile devices that oscillate with asymmetric acceleration. By exploring the non-linearity of human force perception, they can cause users to perceive a small virtual force (0.292 N). However, because these do not provide true directional forces, the force directions are sometimes incorrectly recognized by users, even when applied for 2 seconds [1].

Electrical Muscle Stimulation (EMS) has been proposed to simulate the experience of ping-pong [41] and tennis [18], and tactile stimulation from a solenoid has been used to augment EMS [41]. However, in order to artificially create hand/racket movement in the direction of ball impact, EMS-based techniques fundamentally must contract muscles in opposition to the actual muscles used in real racket sports. For example, one of the muscles that contracts in a real racket swing is the anterior, biceps muscle, but EMS-based techniques would actuate the posterior, triceps muscle. Thus, the proposed EMS techniques actuate posterior forearm muscles that are not part of the multiple muscle groups that work together to counter directional impact force, as shown in Figure 2, resulting in a distinctly and qualitatively different proprioception experience.

Changing the center of mass of rackets by weight-shifting mechanisms has also been utilized to render feedback for racket sports [60]. It renders the sensation of resistive force to racket rotation during active swinging motions, but is not able to actively render impact forces on rackets. Furthermore, it generates unexpected translational forces and vibration in the direction of weight shifting mechanism that is perpendicular to the real-world impact force, yet lacks the translational force in the direction of the balls. In contrast, AirRacket is capable of generating directional impact force on rackets to re-create the same set of haptic sensations as real racket sports, including tactile, kinesthesia, and proprioception.

2.3 Ungrounded, Directional Force Feedback

Propellers have recently been used to produce ungrounded force feedback in handheld and wearable devices. Wind-blaster [30] is a wrist-worn pair of propellers that can generate up to 1.5N of force. It weighs 167g, though two sets would be needed to support bi-directional forces. Aero-plane [29] is a handheld device with two miniature jet-propellers capable of forces up to 7N in 2 degrees of freedom (DOF) to simulate weight shifting sensations. Thor's Hammer [24] is a handheld device that uses 6 orthogonal propellers to produce 3-DOF forces at up to 4N, and weighs 692g. Leviopole [58] provides upward, lifting forces with two propellers. The two key limitations of propellers are: 1) slow force rise and fall time of 300ms [24, 29] which is much longer than the 100-200ms necessary to be perceived as instantaneous impact [3, 53], and 2) weight that exceeds the 120-250g [70] and 70-160g [44] range of total racket weight for ping-pong and badminton, respectively.

Air propulsion jets have also been used for directional force feedback. AirWand [56] is a pen-shaped controller with two air nozzles that generates 1-DOF force feedback. AirGlove [22] uses six orthogonal air jets attached to the wrist to simulate the weight of virtual objects in 3-DOF. Jetto [20] integrates a single rotating air nozzle with smartwatches, and uses compressed air from a miniature air tank to provide lateral force. HeadBlaster [39] mounts 2-DOF air nozzles to VR headsets to create persistent motion perception of lateral acceleration in 360 degrees. JetController [73] enables high-speed (50Hz) 3-DOF force feedback on VR controllers to support a wide range of virtual experiences. AirRacket applies air jet propulsion to racket sports and our key contribution is the perceptual design approach to address the limited force output of ungrounded force devices. Specifically, we discovered a perceptual illusion that magnifies perceived force magnitude through increased impact duration, then explored different perceptual designs to significantly enhance the haptic experience for racket sports.

[1] Open sourced at https://www.airracket.com

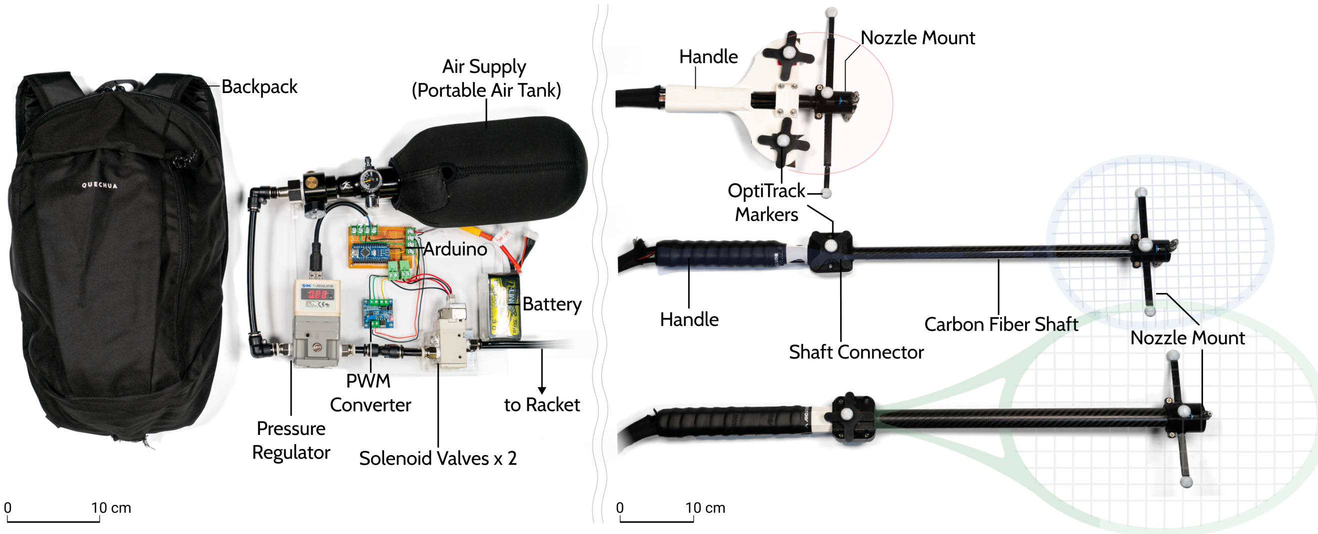

Figure 3: AirRacket system showing (1) *Pneumatic control system*: a pressure regulator controlling force magnitude and two solenoid valves controlling force direction, which fits inside a small backpack, and (2) *Custom-designed racket devices*: for ping-pong, badminton, and tennis, each consisting of a sport-specific handle, a carbon fiber shaft, connectors, nozzle mount, and two nozzles with separate tubing.

3 SYSTEM DESIGN, IMPLEMENTATION, AND VALIDATION

3.1 Nozzle Layout and Racket Device Design

Our design goals for the handheld racket devices are to achieve weight and wielding sensations similar to real rackets in ping-pong, badminton, and tennis. Figure 3 shows the designs of the devices, each with a 3D-printed handle, a carbon fiber shaft (of 14mm and 23mm diameter), and two noise-reducing nozzles on a 3D-printed nozzle mount. Each nozzle is connected via a L-shape fitting to a 6mm low-friction polyurethane tubing [52] that runs inside the shaft and handles to the pneumatic control system. Each device is fitted with a sports-specific handle grip to match the tactility of real rackets. The shaft length for each device is chosen so that the nozzles are at the center of the racket face (i.e. sweet spot of percussion) to better simulate the effect of impact force on real rackets. Our custom-designed devices for ping-pong, badminton, and tennis weigh 147g, 157g, and 258g, respectively, which is in the range of real rackets of 120-250g [70], 70-160g [44], and 230-270g [10].

3.2 Pneumatic Control System

Our pneumatic system is based on the combination of the high-speed circuitry of JetController [73] and the light-weight solenoid valves used by HeadBlaster [39]. Because each impact event has only a single force direction, we use a single pressure regulator to reduce weight and two solenoid valves for each force direction, as shown in Figure 4. The SMC SYJ712 solenoid valves has a switching time of 3ms and is rated for 5Hz continuous operation. Compressed air can be provided through stationary air compressors, or could be using high-pressure portable tanks that offer full mobility and is thus limited only by the VR tracking area. Figure 3 shows a mobile version of the AirRacket system with a 1.1L high-pressure air tank and a 24V DC battery that easily fits inside a small backpack. The air tank weighs 1.5Kg and supports a maximum pressure of 31MPa (4500psi), and the rest of the pneumatic control system weighs 848g. It is capable of rendering 570 impulses at 3.0N and 2000+ impulses at 1N, which is sufficient for typical tennis matches of 300~500 hits (junior to Grand Slam tournaments). The tubing length from the solenoid valve to the nozzle is 140cm, which is the combined length of an average arm (63.5cm) [75] plus the length of our longest racket device (76.5cm).

3.3 Hardware and Software Control

We use 2SC1384 transistors as the power driver to control our solenoid valves with fast switching times (rated at 200MHz) [51]. The regulator is controlled by a PWM-to-voltage D/A converter, sending an analog signal (0~10V) to control the output pressure (0.005~0.7MPa). The PWM converter and transistors are controlled by an Arduino Nano board. A PC that runs Unity 2019.4.8f1 renders VR experiences through a HTC VIVE Pro headset, and sends serial commands to the Arduino Nano to control the force feedback. The serial command is a 3-byte signal, specifying which solenoid valve to open, duration length, and PWM values for the control of pressure regulator.

For tracking the handheld devices in VR, we attached reflective motion capture markers to each handheld device as shown in Figure 3 and tracked them using six OptiTrack cameras [50]. We then calibrated the OptiTrack coordinates with the Unity coordinates using a VIVE tracker attached with markers. To support future applications with consumer-grade tracking, without a separate motion capture system, we have also designed and open sourced tracker mounts for SteamVR/VIVE.

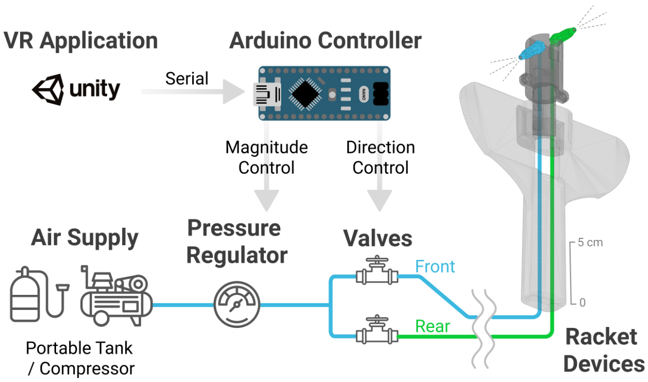

Figure 4: System architecture diagram showing a pressure regulator controlling force magnitude and two solenoid valves controlling 1-DoF force directions, connected to noise-reducing nozzles on one of our custom designed hand-held racket devices.

3.4 System Validation

3.4.1 Force Magnitude. To measure force magnitude of air jets, we attached a nozzle to an IMADA ZTS-50N load cell sensor [28] sampling at 2000Hz with an accuracy rating of 0.2%(0.04N), via an L-shape fitting and a 3D-printed mount. We linearly increased the air pressure in 55 equal increments until it achieved the solenoid valve's maximum supported air pressure of 0.7MPa, and repeated for 10 trials. The average magnitude vs. air pressure is shown in Figure 5a, with the maximum force being 3.23N at 0.7MPa.

3.4.2 Force Rise and Fall Time. The average of rise and fall times vs. force magnitude are shown in Figure 5b. Except at very low force magnitude (<0.3N), both rise time and fall time gradually increase with force magnitude, reaching 25ms rise time and 15ms fall time at 3.2N. The overall latency of AirRacket is less than the sum of the 15-21ms response latency and the 25ms rise time, because users can perceive forces before magnitude reaches 3N. The upper bound of total latency of 46ms (21+25ms) is still within the 50ms threshold of visual-tactile synchronicity [14], so that there should be no perceivable delay between visual and AirRacket's haptic feedback. To demonstrate our system's ability to create impact force with short rise and fall time, Figure 5d shows actual force measurements of full impulses of 1.0N at 40Hz and 3.0N at 25Hz.

3.4.3 Operating Noise. The noise experiments were based on the same procedure as force magnitude experiments. To minimize the influence of the environment, the experiment was fully automated in a vacant room overnight with a base ambient level of 51dB. For noise measurement, we placed a WS1361C decibel meter with sampling rate 1Hz at 1m from the nozzle. The noise vs. force magnitude results are shown in Figure 5c, showing 77dB of noise at the maximum force magnitude of 3.2N. According to Centers for Disease Control and Prevention (CDC), USA, 60db is equivalent to "Normal conversation", 70db to "Washing machine", and 80-85db to "City Traffic". To put AirRacket's maximum noise level in context of real-world sports, 77dB is similar to the noise level of tennis hits, and significantly lower than the 116-122dB of softball hits and 120-130dB of golf hits [48]. Furthermore, HeadBlaster [39] which mounted 80dB nozzles to VR headsets, had reported that active noise canceling (ANC) headphones with insertion loss (IL) of 15-40dB were effective in mitigating air jet noises such that noise is not an usability issue.

3.4.4 Response Latency. Response latency of a haptic device is the latency between a software command and the corresponding haptic feedback occurs, which in our system would primarily be the time for the solenoid to open and for air to flow through tubing to the nozzles. To capture AirRacket's response time, we timestamp a control signal sent to Arduino via serial port and compare that with timestamped reading of the load cell when a force exceeds 0.04N, which is the rated error threshold of the load cell. The latency was sampled at 1, 2, and 3N for each of the nozzle condition over 100 trials. The average response latency was measured to be 21ms at 1N, 17ms at 2N, and 15ms at 3N, showing that the response latency decreases as force magnitude increases.

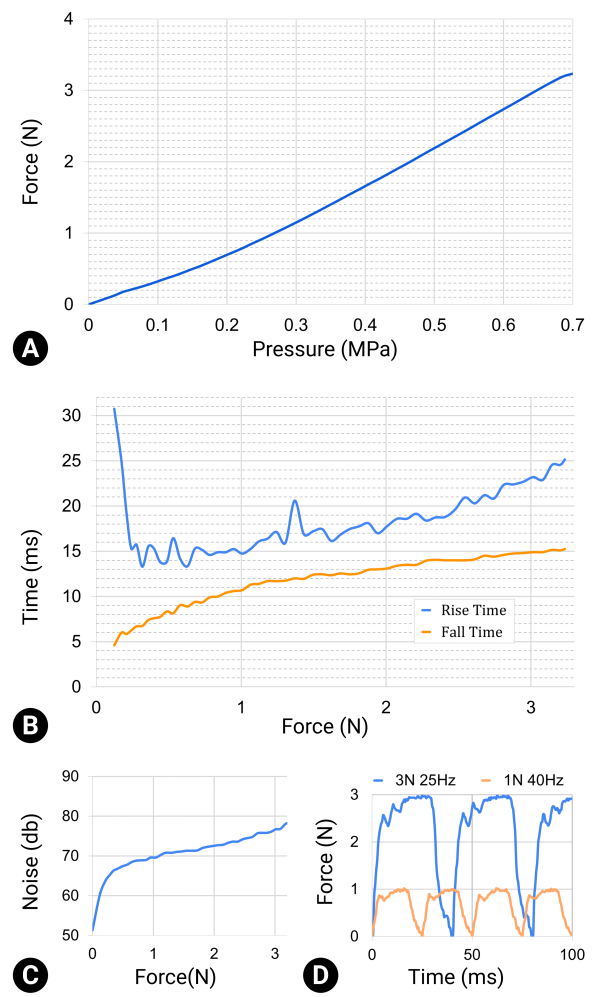

Figure 5: Evaluation result on device's performance: a) force magnitude, b) noise, c) rise time and fall time, and d) frequency.

4 STUDY: HAPTIC EXPERIENCE OF AIRRACKET WITH PHYSICS-BASED MODEL

Being the first ungrounded force feedback device for racket sports, we evaluated the AirRacket with a physics-based model vs. existing vibrotactile feedback to understand its user experience, limitations, and insights into improving its feedback design.

4.1 Physics-based Impact Force Design

When the ball contacts the racket, it exerts force on the string-bed of the racket for an extremely short duration of about 5ms. This impulse force transmits through the racket to the handle, causing vibration, reaction force, and torque to the hand, as shown in Figure 2.

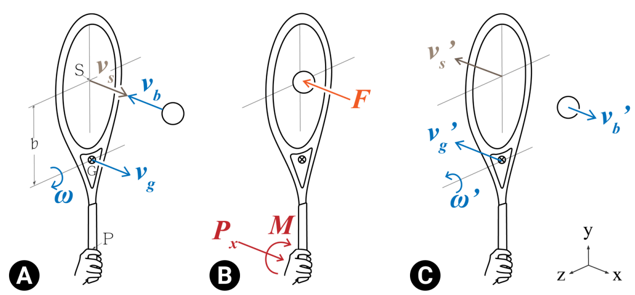

Figure 6: Racket and ball impact modeling: a) motion before the impact; b) free body diagram of the racket during the impact; c) motion after the impact.

Figure 6 shows a simplified force model for the impact, in which the racket is rigid and the racket handle is a pivot joint [40]. Prior to the impact, the racket is swung with an initial angular velocity ω and initial linear speed v_g at the center of the mass (COM) G, as shown in figure 6a. The ball moves towards the racket with velocity v_b. After the impact, the racket has angular velocity ω' and linear velocity v_g' at G, and the ball has outgoing speed v_b', as shown in figure 6c. During impact, Figure 6b shows reaction forces P_x and P_y at the pivot P, reaction torque M at the pivot P, and the force given by ball F at impact point S. Because the time for the force wave to travel from the impact point to the handle and back is generally longer than the contact time [9], the effect on the ball from the collision with the racket can be described using Newton's law of restitution.

The coefficient of restitution e gives the fixed fraction of the relative speed before and after the collision. We applied e based experimental data from prior studies: 0.8-0.9 for ping-pong [11], 0.9-1.2 for badminton [2], and 0.3-0.7 for tennis [21]. The impact of the racket and the ball is eccentric and involves both angular and linear speed, which is more complicated than a typical head-on collision. However, the model can be simplified as two objects collide linearly by replacing the mass of the racket to an "effective mass" m_e that involves the information of rotation and replaces the motion of the racket with the linear velocity v_s at the contact point S, where $v_s = v_g + b\omega$ and b is the distance from G to S. The outgoing speed of the ball v_b' can then be calculated as [12]:

$$v_b' = -(\frac{1+e}{1+m_b/m_e})v_s + (\frac{e-m_b/m_e}{1+m_b/m_e})v_b$$

, where $m_e = \frac{1}{\frac{1}{m_r}+\frac{b^2}{I_{cm}}}$, m_r is the mass of the racket, m_b is the mass of the ball, and I_{cm} is the inertia of the racket at G.

The impact given by the ball is characterized by a large peak force and a short impact duration. However, the maximum force generated by our air jet system is limited to 3.23N, which is much smaller than the maximum peak force in a racket-ball impact, typically 350N in badminton and 440N in tennis [8, 33]. Therefore, we simulate the impact magnitude by the average of the impact force, obtained by:

$$F_{avg} = \frac{\int Fdt}{\Delta t} = \frac{m_b(v_b' - v_b)}{\Delta t}$$

, where Δt is 5ms [2, 11, 21].

4.2 Vibrotactile Feedback Design

We implemented vibrotactile feedback based on the popular VIVE [26] and Nintendo Switch [45] controllers, which both have racket sport games [27, 46] and attachable racket handle accessories [25]. We captured the vibration duration of VIVE's Virtual Racket game by monitoring the controlling signal of a VIVE controller using OpenVR API [72], which showed a 100ms vibration for all impulses. We then physically measured the peak vibration amplitude to be 0.2N on the surface of the controller. To provide the same vibrotactile feedback, we embedded the same Linear Resonant Actuator (LRA) used by the controllers into the handles of our devices, as shown in Figure 7a, and controlled it using an Adafruit/TI DRV2605L driver with Arduino's 5V power supply. To validate the correctness of our LRA implementation, we conducted a 100-trial test similar to the evaluation in Section 3.4.4 on our racket devices. The results showed an average response latency of 7ms. To make sure the peak vibration amplitude at the surface is 0.2N for each of our three device handles, we adjust the input for the driver, which control the sine waveform of constant amplitude on our LRAs. We then set our vibrotactile and force feedback pattern to the same 100ms duration as the commercial implementations.

4.3 Study Design

Our experiment was a within-subject design with a single independent variable of two haptic feedback types: directional force vs. vibrotactile. Participants were asked to play ping-pong, badminton, and tennis in VR and hit the ball/shuttlecock at varying speeds towards different target areas, while experiencing different types of haptic feedback.

4.4 Participants

We recruited 12 participants (3 male, 8 female, 1 non-binary), all were right-handed, ages 19 to 54 (mean=24.0, SD=9.2). For participants' prior experience with VR, 2 used VR more than once in the last 3 months, 1 monthly, 5 about once a year, and 4 never. For prior haptic experience, 5 participants had experience with VR controllers and 11 had experience with game console controllers.

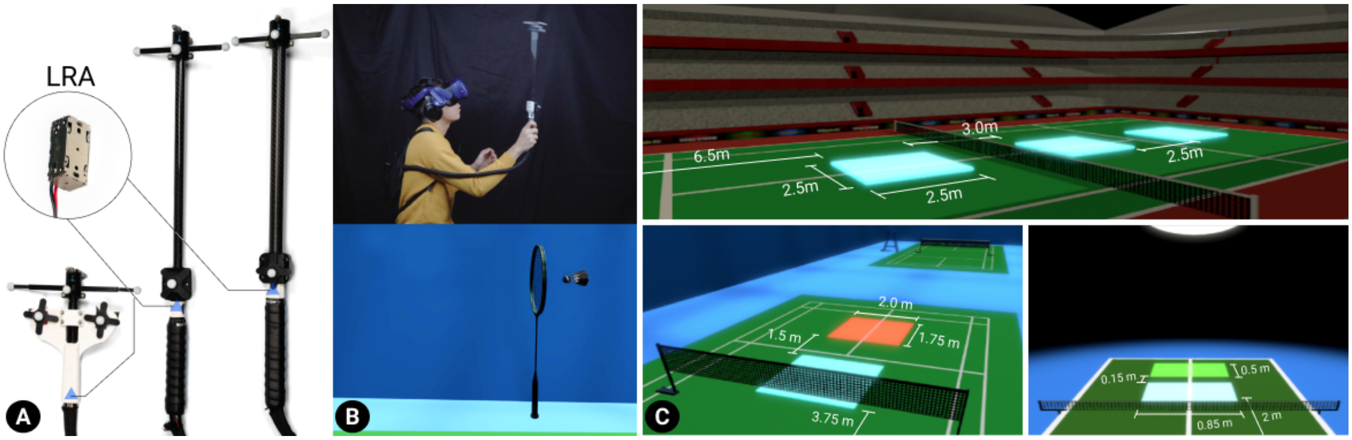

Figure 7: Study setup: a) A linear resonant actuator and the location that it is embedded into each racket device; b) A participant holding a racket in a virtual badminton environment; c) The highlighted target areas for the three sports, which appeared individually during our study; A red highlight indicates a shot missing the target area, whereas a green highlight indicates a shot hitting the target. (We removed the nearest target zone for tennis during the study in Section 6.)

Table 1: Velocities and time intervals between serves for each ball type.

	Velocity (m/s)			Served
	Slow	Medium	Fast	Interval
Ping-pong	2.5	5	8	3 s
Badminton	5	10	20	4 s
Tennis	4.375	8.75	17.5	5 s

Regarding participants' expertise in each sport, we defined a beginner as having some experience with the sport; an intermediate player as playing on a regular basis; while an expert currently plays in a competitive setting. The distribution among *Beginner:Intermediate:Expert* was 5:7:0 for ping-pong, 7:5:0 for badminton, and 8:3:1 for tennis.

4.5 Procedure and Tasks

Participants first became familiar with the rackets and VR settings. For each session, they were asked to stand at a set position and return a ball/shuttlecock with their dominant hand. The balls were served at three noticeably different horizontal velocities (slow, medium, fast) as shown in Table 1, which were based on the real range of velocities for each sport. To ensure a consistent swing posture, the balls passed a fixed 10cm x 10cm bounding box at participants' dominant side, at the recommended position for performing a forehand flat drive for each sport [17, 38, 69]. Table 1 shows the time intervals between successive serves, which were based on average hit pace for each racket sport [7, 19, 62].

To ensure participants experienced the same number of hits at varying distances, we created target zones for participants to hit the balls to. The target zone appeared half a second before each ball was served, accompanied by an anticipatory sound. As shown in Figure 7c, we had two target zones for badminton and ping-pong, and three for tennis. Participants first practiced the three racket sports to become familiar with the system. We then ran a session for each of the three sports, consisting of two feedback condition blocks at 3 minutes each.

Participants rated their perceived haptic realism after each feedback condition on a 7-point Likert scale from 1 (completely unrealistic) to 7 (completely realistic). They were asked "How similar was the ping-pong/badminton/tennis impact experience you just experienced compared to the real-world?", which was adapted from Presence Questionnaire [74]. Each of the three sessions were followed by a 5 minute break where we collected preference and qualitative responses.

Each session had the same number of balls and targets, presented in shuffled order. The ordering of the three racket sports and the two haptic feedback conditions were counter-balanced by a balanced Latin square. Therefore, each participant experienced 2 types (of haptic conditions) x 3 sports = 6 sessions. Within each session, the total hitting attempts were 60, 45, 36 for ping-pong, badminton, and tennis, respectively, as each sport has a different average hitting pace.

4.6 Results

Figure 8 shows the average realism ratings on a 7-point Likert-scale were all higher for air jet vs. vibration for the three sports. Specifically, the average realism ratings for vibration vs. air jet was 4.25 vs. 4.50 for ping-poing, 4.00 vs. 5.58 for tennis, and 3.67 vs. 5.08 for tennis. Two-tailed Wilcoxon matched-pairs signed-rank test with Bonferroni correction (df = 11) showed that air jet significantly improved realism for badminton ($p<.01$, $r = 0.78$) and tennis ($p<.05$, $r = 0.65$), both with large effect size (Wilcoxon $r > 0.5$).

In terms of preference, 92% of participants preferred the air jet over vibration for both badminton and tennis ($p<.05$), while only 42% preferred the air jet for ping-pong, as shown in Figure 8.

Qualitative Feedback. Participants reported that "Air jet provided a more apparent force than vibration and made me feel like I actually hit a ball." (P8), "the propulsion force from air jet felt much more realistic than vibration." (P1), and "it was a fresh experience as it

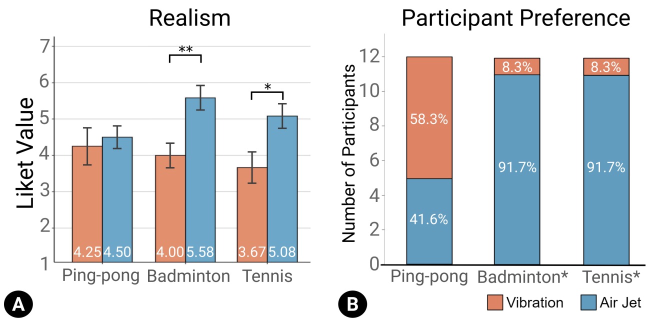

Figure 8: User study results for vibration vs. air jet for the three racket sports: (a) average realism rating (with standard error) on a 7-point Likert scale, and (b) preference. (*) denotes p<.01 and (**) denotes p<.05.

was very different from vibration, which is common in commercial racket sports games, and the propulsion force adds to the realism and enjoyment of the experience." (P2)

Participants also reported three limitations:

(1) *Insufficient force variation*: "Propulsion force for all hits felt similar," (P4) and "force magnitude for tennis didn't change at all." (P11)
(2) *Directional force too weak for tennis*: "Propulsion felt more realistic but was still weaker than actual tennis."(P5) "Air jet force could not be felt as much when swinging the racket stronger."(P6) "Propulsion force makes the whole experience more present, but still different from the real ones since it's weaker than actual tennis." (P9)
(3) *Directional force too strong for ping-pong*: participants reported that "the force feedback from air jet was stronger than expected." (P7) "making the experience less realistic." (P3,P10)

To address these concerns, we explored perceptual designs to increase the maximum perceived force magnitude, and to provide a larger effective and perceived dynamic range.

5 STUDY: PERCEIVED IMPACT FORCE MAGNITUDE VS. DURATION

During the early development and testing of AirRacket, we discovered that forces of the same magnitude would consistently feel stronger when the duration was longer. To validate and quantify how duration affect perceived impact force magnitude, we used the magnitude estimation methodology with unipolar scale [23] based on Marks et al. [43].

The range of duration we sampled started at the shortest duration of the system, 50ms, and increased in 100ms steps, until it felt too long to be realistic as a ball impact, which was 350ms. The range of force magnitude we sampled started at 0.5N, and increased in 0.5N steps, up to 2.5N. For the baseline stimuli, we used the median values of 50, 150, 250, 350ms and 0.5, 1.0, 1.5, 2.0. 2.5N, which was 200ms at 1.5N. Because racket sports have a wide range of racket lengths, we collected data using both a short (20cm) and long (60cm) air propulsion force feedback devices that corresponded to the typical lengths of ping-pong paddles and tennis rackets.

5.1 Procedure, Tasks, and Participants

Participants were asked to sit on an armchair comfortably while holding a racket. To minimize audio and visual distraction, participants wore eye masks and noise-canceling headphones playing white noise.

The study consists of two sessions corresponding to the two device lengths. For each session, there are three repeated blocks, where in each block a participant is asked to estimate the force magnitude of 20 unique impact events (i.e. 4 durations x 5 force magnitudes). Therefore, each participant experienced a total of: 2 device lengths x 4 durations x 5 magnitudes x 3 blocks = 120 trials. The study used a within-subject design with the ordering of device length counter-balanced, and the ordering of impact events shuffled.

To estimate the perceived magnitude for each impact event, participants first experienced the baseline stimuli and rated it with a number that they felt best represented the force magnitude of that baseline impact. For the remainder of the impact events, participants first experienced the baseline impact followed by the impact they were to rate. They were then asked to estimate the relative force magnitude between the two impact events. The impact events could be repeated as requested by participants. After finishing both sessions, qualitative feedback was then collected.

We recruited 12 participants (9 male, 3 female), all right-handed, ages 21 to 26 (mean=22.5, SD=1.8). For prior haptic experience, 9 participants had experience with VR controllers and all had experience with game console controllers.

Table 2: Average normalized magnitude estimation of different force durations with impact force rendered on the long moment arm (60cm) and short moment arm (20cm) across 12 participants, and their average (AVG) across 5 force magnitude settings.

	Long Moment Arm					
Force	0.5N	1.0N	1.5N	2.0N	2.5N	**Avg**
50ms	40.8%	33.8%	27.4%	31.6%	32.9%	**33.3%**
150ms	89.5%	82.4%	99.6%	97.7%	101.3%	**94.1%**
250ms	122.0%	129.6%	122.9%	122.0%	126.5%	**124.6%**
350ms	130.4%	146.6%	143.9%	142.3%	130.5%	**138.7%**
	Short Moment Arm					
Force	0.5N	1.0N	1.5N	2.0N	2.5N	**Avg**
50ms	63.3%	56.2%	62.0%	79.6%	71.9%	**66.6%**
150ms	104.7%	103.7%	102.7%	103.3%	104.4%	**103.8%**
250ms	112.0%	115.5%	112.0%	107.7%	108.0%	**111.0%**
350ms	120.0%	124.6%	123.4%	109.4%	115.7%	**118.6%**

* : P<0.05 ** : P < 0.01 *** : P < 0.001

5.2 Results and Discussion

For each participant, We normalized the data with the arithmetic mean within each force setting. We then computed the geometric mean of estimated magnitude across all participants as suggested by [31]. The result is shown in Figure 9 and Table 3.

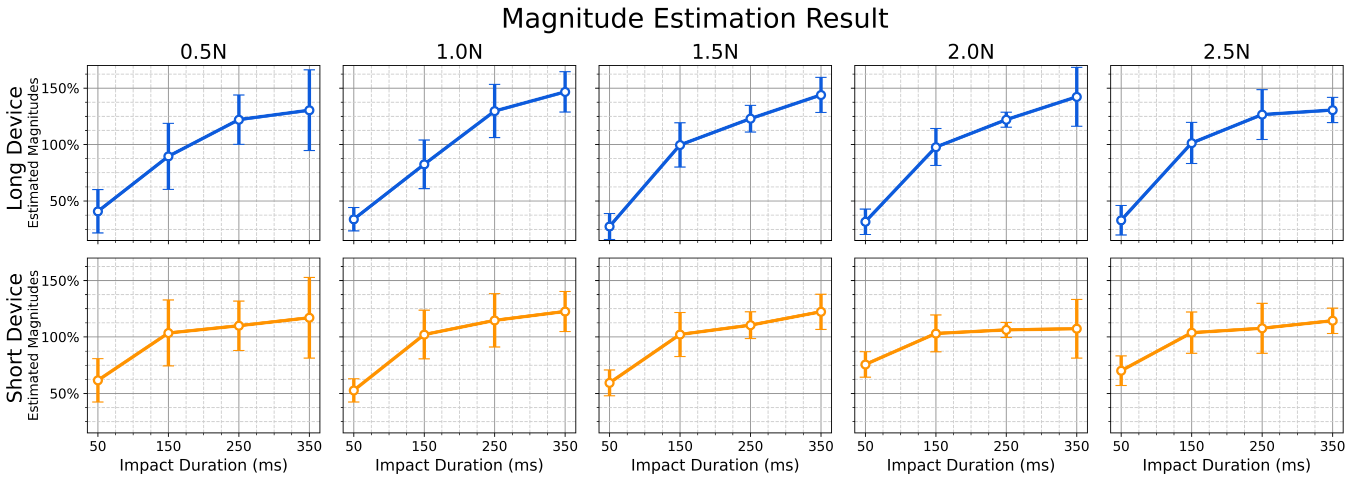

Figure 9: Averages and standard deviations for normalized magnitude estimation of different force durations with impact force rendered on the long device length (60cm) and the short device length (20cm).

Participants reported significantly higher perceived force magnitude as force duration increased. For example, the perceived magnitude of the 350ms force duration ranged from 1.37x to 5.25x (average 2.57x) compared to 50ms duration. One-way ANOVA (df = 11) and paired-sample t-test (df = 11) with Bonferroni correction showed that the increase in perceived impact magnitude is statistically significant (p<.01) for all 5 force magnitudes and both long and short devices, as shown in Table 2.

Furthermore, the perceived increase was significantly higher (p<.01) for long vs. short devices for all durations (e.g. 138.7% vs. 118.6% for 350ms). For absolute comparison among different force settings, we also provide result normalized with the grand arithmetic mean across all force settings for each participants in Appendix A. This perceptual illusion increases the maximum perceived impact force magnitude of existing technologies, for virtual experiences that can have varying impact duration. Also, because the illusion does not require visual feedback, it could potentially be combined with visuo-haptic techniques to further increase the perceived force magnitude.

6 STUDY: RANGE OF ACCEPTABLE IMPACT DURATION FOR VIRTUAL RACKET SPORTS

In order to apply the perceptual illusion we discovered to racket sports, we designed another within-subject experiment to collect the range of acceptable duration for a realistic impact experience, as well as the most realistic duration.

6.1 Procedure, Tasks, and Participants

Our procedure was based on the method of adjustment from psychophysical techniques which have been used extensively for perception studies [31] and are suited for studies with a large number of conditions. The methodology had users adjust impulse duration to match each of the following criteria:

(1) The longest acceptable duration for a realistic impulse experience.
(2) The shortest acceptable duration for a realistic impulse experience.
(3) And the duration with the most realistic impulse experience.

The tasks in VR were based on the same setup as our haptic experience study with the physics model in Section 4, except we used two target zones for all three sports (removing the nearest target zone for tennis) and only the medium serving speed in Table 1 for each sport. The number of conditions were: 3 racket sports x 2 target distances (neaw/far) x 3 criteria for duration data = 18. We counter-balanced the ordering of the two target distances and duration conditions by a balanced Latin square and had participants rest for 3 minutes between each condition.

At the beginning of each condition, participants first experienced the full range of impulse durations from 40-500ms while hitting the balls. Participants were then asked to perform a flat drive for each hit, after which they adjusted the impulse duration using a VIVE controller held in their non-dominant hand to the best perceived fit for the criteria. The duration was adjustable between 40-500ms with 10ms stepping, and the starting duration was set to the median of the range which was 270ms. The force magnitude was constant at 1N for ping-pong, and the system max for badminton and tennis.

Participants. We recruited 12 participants (8 male, 4 female), all-right handed, ages 19-24 (mean=20.83, SD=1.46), with a wide range of VR experience: 4 used VR more than once a week, 3 monthly, 3 about once a year, and 2 never. For prior haptic experience, 9 participants had experience with VR controllers and 11 with game console controllers. The distribution among *beginner:intermediate:expert* was 7:4:1 for ping-pong, 7:2:3 for badminton, and 11:1:0 for tennis.

6.2 Results and Discussion

Table 3 summarizes the average durations chosen by users for the shortest acceptable, most realistic, and longest acceptable duration for a realistic impulse for near and far targets. Participants chose

Table 3: Average duration (with standard error) across users from the Impact Duration Study, showing the shortest acceptable duration (Shortest), most realistic duration, and longest acceptable duration (Longest) chosen for realistic impact experience for near and far targets for ping-pong, badminton, and tennis.

	Ping-pong			Badminton			Tennis		
Duration Type	Shortest	Most Realistic	Longest	Shortest	Most Realistic	Longest	Shortest	Most Realistic	Longest
Near targets	43 (1.6)	88 (15.8)	173 (19.6)	45 (2.9)	73 (11.2)	134 (19.8)	85 (22.2)	218 (26.3)	322 (32.4)
Far targets	49 (4.2)	139 (19.1)	202 (19.4)	56 (4.7)	113 (10.4)	187 (13.1)	101 (26)	282 (25.1)	351 (32)
Average	**46ms**	**114ms**	**188ms**	**51ms**	**93ms**	**161ms**	**93ms**	**250ms**	**337ms**

significantly longer duration for far vs. near targets for all three sports (paired-sample t-test , df = 11, p<0.01 for all), by a factor of 29-58%. This increase in duration is consistent with our discovery as participants expected a stronger perceived magnitude for farther targets.

Qualitative Feedback. Participants reported that "for badminton, when the duration is longer, the force felt stronger. For ping-pong, I didn't really feel the difference between different durations" (P11). "I felt that when hitting stronger, the duration time should be longer, even though it sometimes felt longer than reality" (P8). Participants also explained their approach for finding the most realistic duration for different distances: "I set the threshold to either the maximum or minimum then continued to adjust until finding the most realistic threshold." (P1, ping-pong expert)

Discussion. The most realistic duration for the three sports were all longer than the real-world impact of 5ms. The average of the most realistic durations for near and far targets were 15-44x and 23-56x of the real-world impact. This drastic difference may arise when haptic systems have considerable limitations vs. real-world physics, which is common for reasons such as technology limitation (e.g. propellers/air jets are 2 orders of magnitude weaker than rackets sports), safety, and design tradeoffs (e.g. choosing light-weight actuators to improve portability). This suggests that the optimal user experience would be perceptual designs that could potentially deviate significantly from the physics-based model.

7 PERCEPTUAL DESIGNS OF FORCE MAPPING MODELS

In our haptic experience evaluation study with a physics-based model, we used a force mapping model based on physics modeling for force magnitude. When the modeled impact force exceeded the system maximum output, we rendered force feedback at the system maximum magnitude. To understand the effective dynamic range of this model, we analyzed the log from the study. For ping-pong, 64% of impacts exceeded the maximum. For badminton and tennis, all impacts exceeded the system maximum, resulting in constant force feedback at the maximum magnitude which gave an effective dynamic range of 0. A straightforward approach to reproduce the physics would result in a limited dynamic range which was also evident from users' qualitative feedback.

7.1 Force Mapping Models

To expand the effective and perceived dynamic range of force feedback, we explored duration scaling and force magnitude scaling, and designed three additional force mapping models for a total of four models, as shown in Figure 10:

- *Baseline*: the same physics-based model as in Section 4, its effective dynamic range of force magnitude is between the minimum impact magnitude and the system's maximum magnitude.
- *Scaled*: the magnitude is linearly scaled to the user's personal maximum impact force (measured in the practice sessions) from the minimum user detectable force (i.e. ADT) with the duration being constant. This fully utilizes the dynamic range of the system output, and is specific to each user.
- *Max+Duration*: constant, maximum force magnitude with varying duration, shown in Figure 10c. To define the mapping between duration and expected force, we linearly interpolate duration starting from the average shortest acceptable duration in Table 3 at minimum force, to the average longest acceptable duration in Table 3 at the user's maximum impact force.
- *Scaled+Duration*: combining two concepts together, scaled force magnitude with varying duration, shown in Figure 10d. This is the first exploration of multi-variate scaling to improve the perceptual design of force feedback.

7.2 Minimum Perceivable Force in Force Mapping

To ensure all our designed feedback patterns were perceptible to users and determine the proper minimum force for the above mappings, we conducted a psychophysical Absolute Detection Threshold (ADT) study.

We recruited 24 participants (8 male, 15 female, 1 non-binary) ages 19 to 54 (average 23.7, SD=8.8) which included 12 returning users from the study in Section 4 (the rest of the user studies all had complete different users, for a total of 72 unique participants). We followed a standard, adaptive method of limits procedure with a two-down one-up staircase [31, 37] where our initial magnitude was 0.5N with an initial step size of 0.1N. The step size was halved after the first reversal and stopped at the seventh reversal, similar to the ADT study procedure in HeadBlaster [39]. Each of the three sports were repeatedly measured for 3 trials (for a total of 9 staircases). Participants were asked to hold each device in a stationary posture corresponding to the posture for the sport. Our results showed that

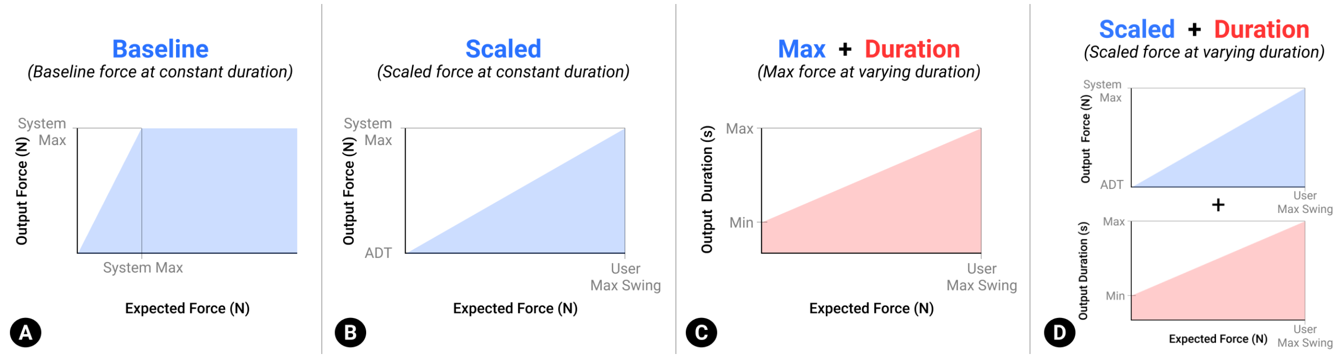

Figure 10: Our four types of force mapping models: a) *Baseline*: based on physics modelling, and clipped at the system maximum, b) *Scaled*: scaled force magnitude with constant duration, c) *Max+Duration*: constant, maximum force magnitude with varying duration, d) *Scaled+Duration*: scaled force magnitude with varying duration.

ADT was similar across three sports at 0.183N, 0.169N, 0.178N for ping-pong, badminton, and tennis, respectively. The ADT is used as the minimum force magnitude (ie. floor) for the additional force mapping models.

8 STUDY: USER EXPERIENCE EVALUATION OF PERCEPTUAL DESIGNS

Our experiment was a within-subject design with a single independent variable of four types of force mapping models: *Baseline*, *Scaled*, *Max+Duration*, and *Scaled+Duration*, as shown in Figure 10.

8.1 Procedure, Tasks, and Participants

We used the same study procedure as the previous haptic experience study in Section 4, with an added step at the beginning of each sport to measure each participant's maximum swing speed and force for use in magnitude scaling. Each session consisted of participants using the four force mapping models, for 3 minutes each, with a 3 minute break in between when we collected participant responses. We had the same number of balls and targets for each condition; the targets were presented in shuffled order. We counter-balanced the order of the three racket sports and the four force mapping models by a balanced Latin square.

Participants. We recruited 24 participants (11 male, 13 female), one left-handed, ages 18 to 30 (average=20.6, SD=2.4), with a wide range of VR experience: 1 used VR more than once a week, 4 once every three months, 10 about once a year, and 9 never. For prior haptic experience, 12 participants had experience with VR controllers and 23 had experience with game console controllers. The distribution among *beginner:intermediate:expert* was 14:9:1 for ping-pong, 12:12:0 for badminton, and 20:4:0 for tennis.

8.2 Results and Discussion

Realism. Figure 11a shows participants' average ratings of realism for each force mapping model on a 7-point Likert-scale. The Scale+Duration model received the highest average ratings for all three sports: 5.00, 5.38, and 4.71.

Friedman test (df = 23) showed significant difference among the four force mapping models for ping-pong and badminton (p<.05 for both). Two-tailed Wilcoxon matched-pairs signed-rank test (df = 23) with Bonferroni correction showed significant improvement with large effect size (Wilcoxon r > 0.5) for ping-pong using Scaled+Duration vs. baseline and vs. Max+Duration (5.00 vs. 4.21, p<.05 for both, r = 0.65 and 0.52, respectively). For badminton, Scaled+Duration showed significant improvement vs. all other models (p<.05 and r > 0.5 for all).

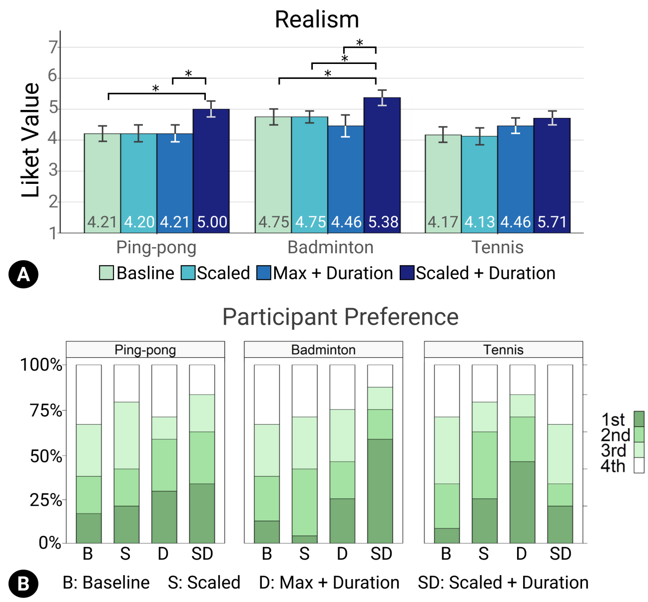

Figure 11: Force Mapping Model Evaluation Results: A) The average likert points of each force mapping models for sense of realism. B) Participants' preference rankings for each mapping methods in three racket sports.

Preference. Figure 11b shows overall preference for participants' preferred models regarding duration scaling vs. the baseline model. For ping-pong and badminton, the most preferred model was Scaled+Duration, with 33% and 58% of participants, respectively. For tennis, the most preferred was Max+Duration, with 46% of participants.

Friedman test (df = 23) showed a significant difference among the preferences for the four models for badminton (p<.05), and Wilcoxon signed-rank test with Bonferroni correction (df = 23) then showed a significant difference between the preferences for Scaled+Duration vs. baseline as well as vs. Scaled (p<.05 for both).

Qualitative Feedback. Participants reported that "Scaled+Duration provided more variation when hitting the ball compared to the Scaled model." (P10) "For badminton, the feedback from Scaled+Duration was quite good." (P21) "I liked both Scaled+Duration and Max+Duration. For ping-pong, I think Scaled+Duration was more realistic." (P11) "For tennis, the stronger the force, the more realistic it felt, so Max+Duration was best. For ping-pong, the baseline model was too strong, which made it less realistic."(P21)

Discussion. These results showed that given the exact same system limitations, perceptual design, and especially multi-variate perceptual design, can significantly improve the user experience vs. the baseline, physics-based model with large effect sizes. Scaled+Duration provided the largest perceived dynamic range, which worked well for ping-pong and badminton that benefited from finer and more distinguishable feedback in the gameplay. Because force magnitude of tennis always far exceeded the output of the system, scaling magnitude caused light hits to be scaled down to be too weak. Thus, Max+Duration is likely to work better for experiences that are consistently far above the system capability.

9 DISCUSSION AND FUTURE WORK

In this section, we address some of the additional findings, limitations, and future research directions AirRacket may lead to.

9.1 Combining with Visuo-haptic Techniques to Increase Perceived Force Magnitude

Compared to prior visuo-haptic approaches, the haptic illusion we discovered is unique in that it does not require visual feedback. Therefore, it may work especially well in combination with a wide range of visuo-haptic techniques that also increase perceived force magnitude. For example, the range of impact duration for tennis covers the duration of the stop-motion visual effect technique (300ms) [5]. It would be straightforward to combine both illusions to explore their effects. In addition, the technique of applying force feedback in advance of the expected impact [32] could be combined with our discovery for racket sports with racket motion prediction and ball trajectory prediction.

9.2 Impact Force Feedback on User Performance

Haptic information is crucial for dynamic interaction in the real world [71] such as bouncing a ball on a racket surface [63]. For racket sports, increasing the dynamic range of haptic feedback could help with predicting the trajectory [61] and also make it easier for user to learn the dynamics of the system [71]. A few participants from the force mapping comparison study (Section 8) mentioned that different force models affected their ability to aim targets. For example, "better feeling of feedback intensity helped me adjust the swinging speed for the next ball" (p13). We are exploring how techniques that can further expand the perceived dynamic range can help improve virtual racket sports performance.

9.3 Perceptual Design for Other Applications

Impact sensation is common in everyday and VR experiences such as egocentric impact (e.g. being hit in boxing), percussion (e.g. drumming), recoil (e.g. firing a weapon), kicking a football, etc. Most scenarios also have the design challenge that the system capability is dramatically weaker than the real-world impact force. For example, kicking/catching a football can exceed 2000N, which is 3 orders of magnitude larger than any foreseeable force feedback technologies. While our paper focuses on racket sports, the haptic illusion we discovered, our design process, and the lessons learned can help improve the design for other experiences. For each application scenario, the haptic designer can determine the range of acceptable durations for a realistic impact experience, then explore how force mapping models with different scaling can be applied. Combining both scaling techniques provides the largest perceived dynamic range while Max+Duration is likely more entertaining with stronger force feedback and also better suited for experiences that consistently require large force magnitudes (e.g. kicking/catching football).

9.4 Further Findings on Perceived Impact Magnitude vs. Duration

Prior studies have investigated stimuli duration vs. perceived intensity for visual perception (brightness) [6, 16] and auditory perception (loudness) [34, 64], and have found power function relationships between them.

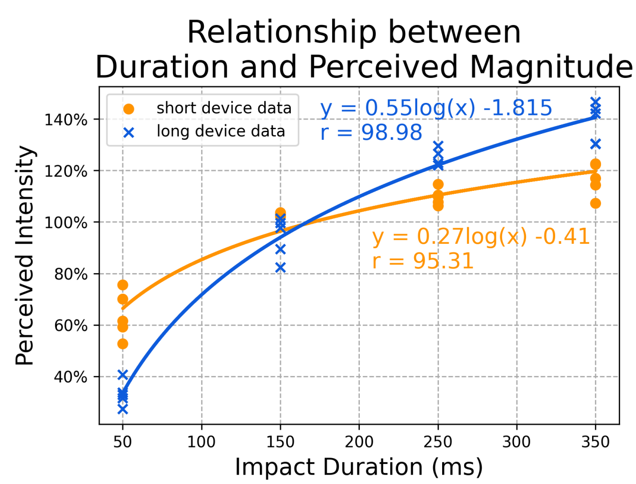

Figure 12: Regression analysis showing force duration vs. perceived intensity from our magnitude estimation study follows the power law.

Regression analysis of our force duration vs. perceived force magnitude study results (Section 5) also showed power law relationship [65], where the effect of perceived difference decays as absolute stimuli increases. The results of simple linear regression after logarithmic transformation on duration, suggested by [23], are shown in Figure 12 for the long moment arm device (r-value =

98.98, p-value < 0.0001) and for the short device (r-value = 95.31, p-value < 0.0001).

Combined with prior findings, our observation might indicate a more general phenomenon of perception, where the perceived intensity for a stimulus is affected by its overall dynamics.

9.5 Handheld Device Designs

Although the badminton device we used for the user studies weighed similar to recreational and training rackets, competition-level rackets are in the 80-110g range. We have since optimized and open-sourced our badminton racket design to eliminate the shaft connector, which helped reduce its weight from 157g to 107g.

In this paper, we used a separate device for each sport to provide more realistic weight distribution and wielding sensation. We are exploring shape-changing device designs [59, 76] that support varying moment arm length to support multiple sports. In addition, we are exploring combining vibration feedback patterns in the handle to better simulate impact on different parts of the racket's string surface which would also affect moment arm perception [49].

Furthermore, while horizontal forces is minimal for badminton, it is more noticeable for sports like tennis when performing a slice shot. Motorized nozzles to generate force in direction of angled impact could support horizontal component forces to further improve the experience. We are exploring such designs for sports which the added device weight to rackets is acceptable.

10 CONCLUSION

We have presented the perceptual modeling and design of ungrounded, directional force feedback for virtual racket sports. Using compressed air propulsion jets, we demonstrated that directional impact forces significantly improved user experience vs. vibrotactile feedback for ping-pong, badminton, and tennis. To address the limited force magnitude of ungrounded force feedback technologies, we discovered and quantified the novel illusion that users perceive a larger impact force magnitude (2.57x) with longer impact duration (350ms vs 50ms). Through a series of formative, perceptual, and user experience studies with a total of 72 unique participants, we explored several perceptual designs using force magnitude scaling and duration scaling methods to expand the dynamic range of perceived force magnitude. User experience evaluation showed that perceptual designs can significantly improve realism and preference vs. physics-based design for ungrounded force feedback systems.

ACKNOWLEDGMENTS

This work is supported by the Ministry of Education (110L892805) and Ministry of Science and Technology of Taiwan (MOST 108-2628-E-002-006, MOST 107-2923-E-002-007, MOST 109-2218-E-011-011) and National Taiwan University. We thanks Mu-An Kuo for her amazing video-editing skill, and Pei-Wen Yu for the help of user study. Also, We thank participants and reviewers for their feedback, especially during the COVID-19 pandemic.

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A SUPPLEMENTARY DATA ON MAGNITUDE ESTIMATION

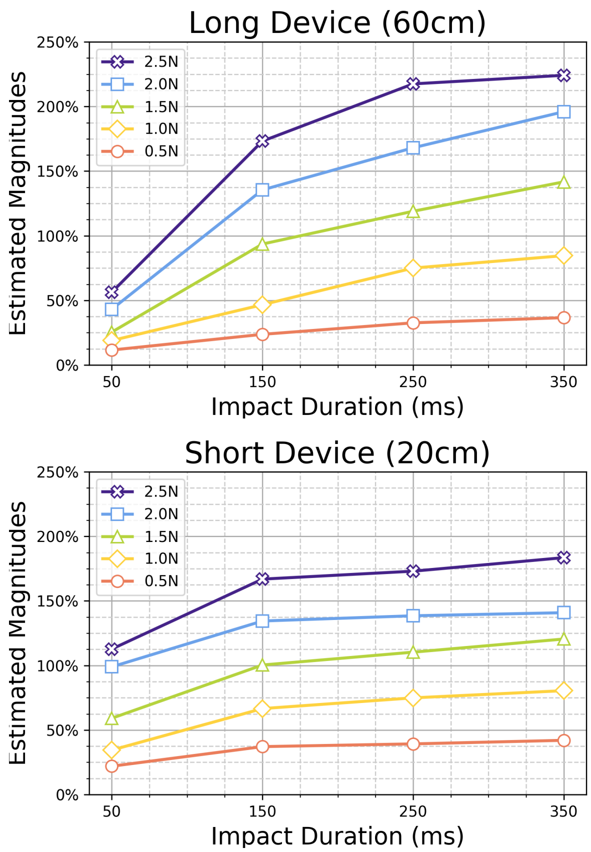

Figure 13: Result normalized with the grand arithmetic mean across all force settings for each participant.

B ICON CREDITS

Icons from the following source are used in Fig 4:

- Scuba tank icon made by Vectors Market.
- Air Compressor and pressure icon made by Smalllike.
- Valve icons made by Lauk from the Noun Project 2405965.