2 DoF Joystick For Racket Sports eGame that Can Mimic Realistic Feedback

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Abstract— **This paper presents a novel two-degree-of-freedom (2-DoF) joystick designed for virtual racket sports that integrates haptic feedback to mimic realistic physical sensations. The device incorporates two DC motors capable of generating directional force feedback, simulating ball impact, textured surfaces, and collision boundaries. A pilot study involving six participants was conducted to evaluate the effect of haptic feedback on user performance and experience in a virtual tennis environment. Results showed that haptic feedback enhanced users' confidence and task performance compared to visual feedback alone. Constant force feedback demonstrated the highest user performance, while oscillating feedback, aimed at replicating realistic racket vibrations, provided moderate improvements. The findings suggest that incorporating haptic cues significantly improves immersion and user interaction in virtual sports environments. Future work will focus on increasing motor output and refining the feedback mechanisms to deliver stronger, more distinguishable sensations, bringing virtual sports experiences closer to reality.**

I. INTRODUCTION

In recent years, the interest in incorporating haptic feedback into virtual environments (VEs) has grown steadily, as developers look for ways to make virtual interactions feel more natural and engaging. Although standard VR setups often rely heavily on visuals and audio, these sensory channels alone are not enough to fully capture the sensation of interacting with real objects. This is where haptic feedback—ranging from subtle vibrations to controlled forces. By letting users actually feel what is happening in the virtual world, we can create experiences that are not only more immersive, but also closer to everyday physical interactions [1].

Sports simulations like tennis or table tennis offer a prime example of why this matters. Visuals and sound effects can show you where the ball is landed or how hard it is hit, but cannot convey the tug on your arm when you swing a racket or the friction of the court surface underneathfoot. Without haptics, these games risk feeling flat and disconnected from the physical skills they're trying to simulate. Realistic force and texture feedback can influence how deeply a player gets drawn into the game and how they adjust their technique over time. As VR applications continue to diversify—from entertainment to sports training—a more complete range of tactile sensations can make the difference between a novelty and a genuinely useful tool.

However, adding these layers of realism is far from straightforward. Many existing VR controllers rely on vibration motors to hint at an interaction, but this sort of one-size-fits-all approach rarely captures the complexity of dynamic, fast-paced sports movements. The result is that, while we can simulate some feedback, we often fail to recreate the full range of forces and textures that define real gameplay. Moving beyond simple vibrations requires us to tackle some tough engineering questions. How can we pack multiple forms of actuation into a device that remains comfortable and easy to use? How do we represent complex, rapidly changing forces without making the device too large, unwieldy, or expensive?

II. BACKGROUND

Early research into VR haptics usually started small, using basic vibrations to signal simple events. This approach helped establish that adding touch-like feedback could improve user engagement, but it didn't take long for researchers to realize that more nuanced cues were needed. Sports simulations, especially racket-based ones, presented new challenges: the moment a ball hits a racket isn't just a buzz or a beep, it's a directionally oriented force that varies in magnitude, angle, and timing.

Noguchi et al. [2] experimented with introducing short force cues—sometimes referred to as "hit-stop"—at the precise moment of impact in virtual tennis. Instead of just hearing a ball bounce, players got a brief, physical jolt that reinforced the illusion of a real collision. Tsai et al. [3] took this idea further with the "AirRacket" system, which offered directional force feedback. Rather than a general cue, players could sense not only that they'd hit the ball, but also get a feel for where it came from and how hard it struck.

The placement of force feedback can also matter. Oh et al. [4] looked into location-based electrotactile feedback for virtual table tennis. By stimulating specific areas on a virtual racket interface, they helped players pinpoint where the ball was making contact. This more precise feedback can be crucial for skill development, since knowing exactly where you're hitting can guide you to adjust your technique.

Surface texture introduces another layer of complexity. In real tennis or table tennis, the feel of the court—its friction, hardness, or slipperiness—can shape how players move and strategize. While some researchers have turned to pseudo-haptics to create the illusion of texture through changes in visuals and sound [5], these tricks can only go so far.

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Ratschat et al. [6] emphasize that training scenarios often demand reliable, repeatable force feedback. Real mechanical actuation, rather than perceptual tricks, generally offers more consistent and meaningful cues.

As haptic systems became more advanced, researchers started blending multiple approaches. Rather than relying solely on vibration, directional forces, or electrotactile stimulation, some have experimented with combining different methods. For example, Leete Hayden [7] explored gyroscopic feedback to simulate rotational forces that occur during a swing, adding yet another dimension of realism. Tang et al. [8] pointed out that while these complex systems show promise, making them practical—affordable, comfortable, and simple enough to use—remains a challenge.

Our contribution to this evolving field focuses on developing a two-degree-of-freedom (2-DoF) joystick that's specifically designed for virtual tennis or table tennis. In our project, we use two DC motors to produce directional force cues that can simulate the sensation of a ball striking a racket. Beyond that, we aim to recreate subtle surface textures, giving players the sense that they're interacting with more than just a flat, frictionless world. By concentrating on both the impact forces and the textures under the player's control surface, our approach could bring virtual sports one step closer to feeling as tactile and responsive as the real thing.

III. DESIGN

A. Device Design

A 2-DoF joystick device uses two shafts to control x- and y-axis translation separately (Fig. 1). Each shaft features a magnet on one end, which is read by magnetic rotation (MR) sensors. These sensors detect the rotational displacement caused by the joystick's translational movement, converting it into precise digital signals for processing. This arrangement(Fig. 2)(Fig. 3) ensures high-resolution tracking of user input, offering seamless interaction and accurate positional feedback.

The other end of each shaft is equipped with a 12V DC motor (RF370CA-15370) that provides haptic feedback. The device is built on a robust and modular structure to house and stabilize the shafts. This design ensures durability and compactness while allowing for smooth motion.

Additionally, the electronics are seamlessly integrated with the Hapkit microcontroller, which is based on Arduino UNO. The microcontroller processes sensor data and controls the motors. The motors are connected to the Motor Power Pins of the Hapkit. One of the MR sensors is directly soldered to the Hapkit board, while the other MR sensor is attached directly to the housing wall, aligned with the corresponding magnet.

B. Game Design

The current virtual tennis game provides a dynamic 2D experience, where the user competes against an AI opponent. The game(Fig. 4) is implemented in Processing, with MR sensors and motors enabling precise control and immersive haptic feedback. The player starts at the center of their half of the court, restricted to movement within this area to prevent out-of-bounds play. Using the joystick, the player can move in all directions, including diagonally, to hit the ball and strategize their gameplay. The AI opponent tracks the ball's vertical movement to simulate intelligent gameplay, creating a challenging and engaging match.

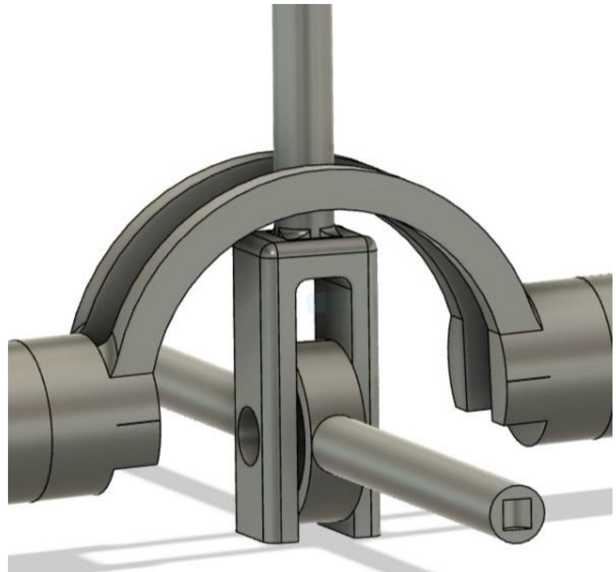

Fig. 1. 2 DoF joystick mechanism

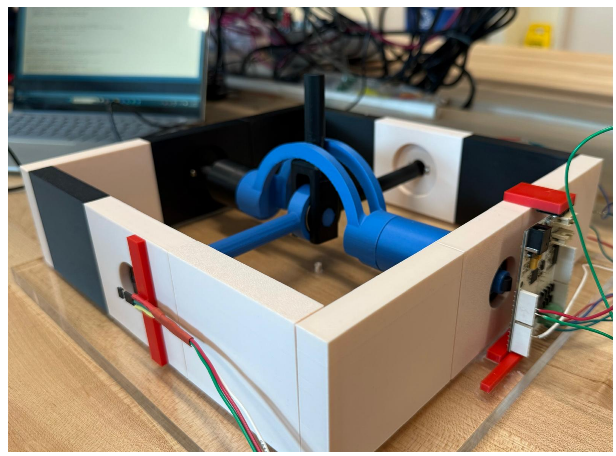

Fig. 2. 2 DoF joystick mechanism Isometric view 1

The player-controlled racket and the AI-controlled opponent's racket are represented as simple rectangles. The player's racket moves based on MR sensor inputs, which are mapped to on-screen coordinates using the map() function. This mapping ensures the racket's position accurately reflects joystick movements within defined boundaries. The AI racket's position is dynamically adjusted to follow the ball's vertical motion, constrained to its side of the court for fair gameplay.

The ball, depicted as a small red circle, is central to the game's dynamics. It is drawn using the ellipse() function and its position updates in real time based on its velocity

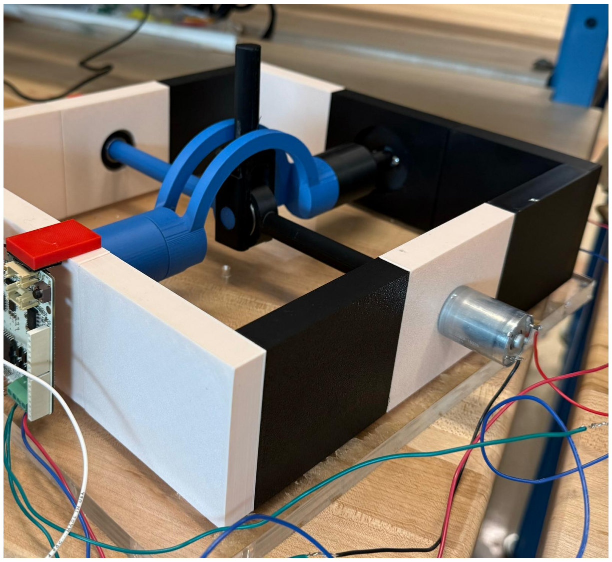

Fig. 3. 2 DoF joystick mechanism Isometric view 2

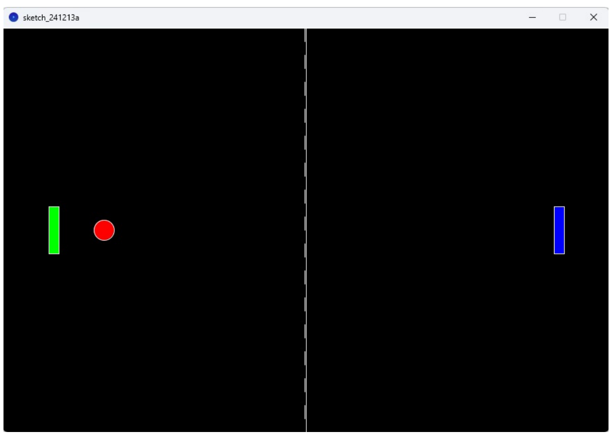

Fig. 4. Game interface on processing

components. The ballX and ballY coordinates increment each frame, ensuring the ball moves smoothly across the court. This continuous rendering creates a fluid experience for players.

C. Ball Collision Dynamics

The interaction between the ball and the rackets is governed by a straightforward bounding box collision detection system. This logic, implemented in the checkBallRacketCollision() function, compares the ball's position with the coordinates of the rackets. When the ball intersects the player's racket, its X velocity reverses, simulating the rebound of a tennis stroke. Additionally, a small random offset is added to the ball's Y velocity, introducing variability in its trajectory for more engaging gameplay. The AI racket collision logic is similar, ensuring the ball bounces back while remaining constrained to its court side. The collision detection system provides the foundation for a dynamic and competitive interaction between the player and the AI opponent.

D. Haptics Feedback Mechanisms

This device has three feedback mechanisms, all delivered by the 2 motor attached to the joystick shafts.

1) Racket-Ball Haptic Feedback: To mimic the realistic sensation of hitting a ball with a decaying oscillating function is used to rotate the motor to create the decaying vibration.

$$F(t) = F_0 e^{-\beta t} \cos(\omega t) \tag{1}$$

Here, F0 represents the initial impact force, controls vibration decay, and defines oscillation frequency. This dynamic force is delivered through a motor, creating a realistic post-impact vibration that decays over time.

2) Surface Texture Feedback: When the user moves across the virtual environment, the user will feel a surface texture that is intended to mimic a tennis court feel.

$$F(x) = k \cdot dx_f \sin(n \cdot \pi \cdot x) \tag{2}$$

Here, F(x) represents the force feedback at a specific position x, representing the tactile sensation of the surface texture, k is the scaling coefficient that adjusts the intensity of the force feedback, dxf is the filtered velocity component of the player's movement along the surface, n defines the frequency of the sinusoidal bumps or texture patterns, and x is the position of the player along the court, used to calculate the feedback based on location.

3) Boundary Feedback: When the user racket collides with the user court boundaries the user will experience a motor force in the opposite direction basically push the user away from the wall.

IV. Study

We have performed a user study to investigate the impact of the haptic feedback with different signal levels on users' task performance during a virtual task based on interactions with ball.

TABLE I
QUALITATRIVE QUESTIONNAIRE

Par	Question	Mean	STD
Q1	I felt confident about the ball contact in the presence of haptic feedback	6.5	0.76
Q2	I had the feeling of performing better while receiving feedback from the joystick	6.16	0.69
Q3	I had the feeling of performing worse while receiving only the visual feedback	5.83	0.69
Q4	I felt more tired while receiving constant force haptic feedback	2	1
Q5	I felt more tired while receiving oscillating haptic feedback	2.33	0.94
Q6	I felt better without any haptic feedback	1.66	0.75

A. Experimental Setup

We conducted an experiment with 6 participants to test the user performance and user experience. The participants interacted with the virtual environment using the device under three different conditions, (i)No haptic feedback (ii) Haptic feedback with constant force, (iii)Oscillating haptic feedback mimicking the vibration of a racket when the user makes contact with the ball in the virtual environment. Before starting the experiment the subject was instructed on the rules of the Virtual environment. During the experiment, the participant was asked to only concentrate on the screen while moving the joystick to control the user racket position in the virtual environment.

Before conducting the experiment all the participants were allowed to get used to the device in all 3 cases for 2 minutes each to familiarize the participants with the setup. Each user was given three tries under each feedback condition, totaling nine tries, and the average number of correct racket-ball contacts for each condition was recorded. This should indicate the effect of haptic feedback on user performance. Each rally without missing the ball is considered as an attempt, and once the participant misses the ball the attempt comes to an end. A one-minute mandatory pause between each attempt was given to ensure sufficient rest for the participants. After the experiment, the participants were asked to fill out a 7-point Likert-Scale questionnaire(1: strongly disagree; 7: strongly agree) to evaluate the user experience.

B. Results

Fig.5 shows the average successful racket-ball contacts recorded for each condition in the study. The quantitative results suggest that the presence of haptic feedback has slightly better user performance than during the absence of haptic response, since the average number of correct ball hits per attempt is higher(highest for feedback with constant force) for conditions with force feedback. The qualitative questionnaire(Table.1) also reflects the same. According to the questionnaire, the participants strongly agree that the presence of haptic feedback made them confident during the experiment.

C. Discussion

The results indicate that haptic feedback positively influenced user performance compared to the absence of feedback. The average number of successful racket-ball contacts was highest when using constant force feedback, followed by oscillating feedback, and lowest with no haptic feedback. These findings suggest that providing users with tactile cues enhances their ability to interact with virtual objects, likely by improving their sense of timing and precision during the task. Interestingly, the oscillating feedback, which aimed to simulate the real-world vibration of a racket upon ball contact, did not outperform constant force feedback. While it did improve performance compared to no feedback, its effect was slightly less pronounced than constant force feedback. This discrepancy could be attributed to the complexity of oscillating feedback, which might require longer adaptation times or more precise tuning to maximize its effectiveness. The qualitative questionnaire further supports the benefits of haptic feedback. Participants reported high confidence (mean = 6.5) and perceived better performance (mean = 6.16) when using haptic feedback. Additionally, participants strongly agreed that they performed worst with only visual feedback (mean = 5.83). These responses highlight the importance of multimodal feedback, with haptic cues providing critical reinforcement that complements visual information.

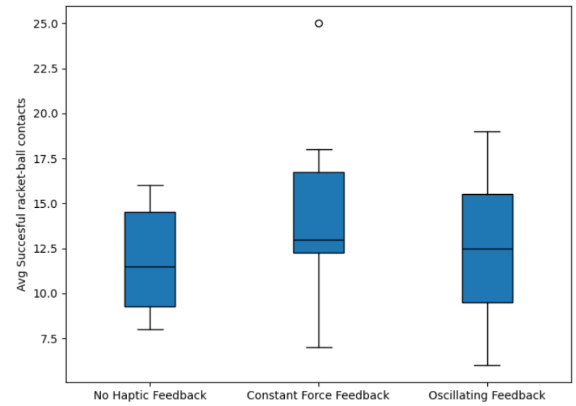

Fig. 5. Box Plot Average Correct Racket-Ball contacts in the study

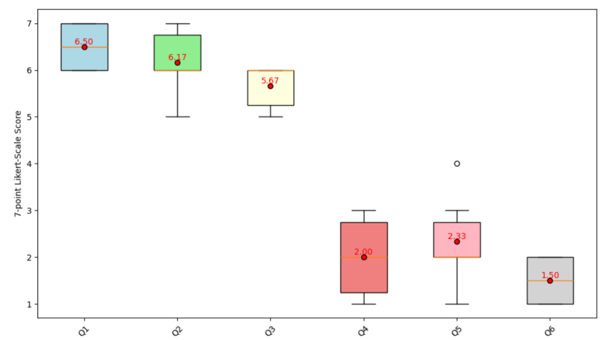

Fig. 6. Box Plot of the Qualitative Questionnaire Results

D. Full-Length Study

This Pilot study has several limitations. The sample size was small (N = 6), which may limit the generalizability of the results. Additionally, the experimental setup was relatively controlled, with experimment focusing solely on the racket-ball interactions. Future studies could involve more participants and explore diverse tasks, environments, and user groups to validate these findings. The future study should analyze the effects all the three feedback mechanisms in the haptic device and different possible conditions for these mechanisms on the user performance. The user performance indicators used to analyze in the study will include error rate, movement accuracy, movement time, user fatigue, etc,. to extensively analyze the device.

V. DISCUSSION

A. Limitations

The current haptic device's motor output is insufficient to generate feedback of realistic amplitude, making it challenging to distinguish between ball-hit feedback, textured surface feedback, and boundary feedback. Additionally, the direct connection of the motors to the shafts results in minimal torque output, limiting the device's ability to accelerate heavier loads effectively.

Operating the virtual interface on Processing introduces further limitations. The environment may occasionally freeze or crash when the device records erratic position values. These inaccuracies can arise from rapid user movements that exceed the tracking capabilities of the MR sensors or from imprecise sensor readings. Moreover, the device occasionally reaches its physical boundaries even when the virtual environment does not impose such limits, causing a mismatch between physical and virtual feedback.

B. Future Improvements

Future improvements to the haptic device should focus on enhancing motor output to deliver stronger and more realistic feedback amplitudes, allowing for better differentiation between ball-hitting and boundary interactions. Upgrading the motor system to include higher torque capabilities would enable the device to handle heavier loads and accelerate more effectively, improving overall performance. This can be done by using higher capacity motors, incorporating gear system to increase torque output, and using motor drivers for smoother motor speed and direction regulation to differentiate between different feedback.

To address issues with the virtual interface, transitioning to a more robust platform or optimizing the current Processing-based setup could mitigate crashes and freezing. Additionally, integrating advanced sensors with higher accuracy and faster response times would reduce erratic position readings caused by rapid user movements. Incorporating a mechanism to better synchronize the device's physical boundaries with the virtual environment would further ensure seamless interaction and enhance user experience.

VI. CONCLUSION

We proposed using a 2D-o-f joystick with oscillating force feedback to simulate the impact sensation of a racket hitting a ball, aiming to replicate a realistic hitting experience. By utilizing both x and y-axis motors in unison, we created a method where the y-axis motor mimics a decaying oscillating force, while the x-axis motor generates high-intensity rotation opposite to the ball's movement, resulting in more realistic haptic feedback. Additionally, textured surface and boundary feedback were controlled by the two motors.

However, the current design faced challenges in differentiating between feedback mechanisms due to the limitations of the motors. The pilot study showed that haptic feedback slightly improved user performance and significantly enhanced user experience, suggesting that further refinement of the feedback mechanism and device design could provide even greater benefits. Future improvements will focus on overcoming these limitations to enhance the racket-hitting sensation in virtual environments.

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REFERENCES

[1] M. Orozco, J. Silva, E. Petriu, and A. El Saddik, "The role of haptics in games," in Haptics Rendering and Applications, Jan. 2012. DOI: 10.5772/32809.

[2] S. Noguchi, K. Matsumoto, Y. Ban, and T. Narumi, "Realistic impact perception in multi-user VR tennis: Enhancing UX through hit-stop and modification of others' movement," in Proc. SA '24: SIGGRAPH Asia 2024 Emerging Technologies, Nov. 2024. DOI: 10.1145/3681755.3688941.

[3] C.-Y. Tsai, I.-L. Tsai, C.-J. Lai, D. Chow, L. Wei, L.-P. Cheng, and M. Y. Chen, "AirRacket: Perceptual design of ungrounded, directional force feedback to improve virtual racket sports experiences," in Proc. CHI '22: 2022 CHI Conf. Human Factors Comput. Syst., Apr. 2022, Art. no. 185, pp. 1–15. DOI: 10.1145/3491102.3502034.

[4] S. Oh, B.-J. Yoon, and H. Park, "Location-based electrotactile feedback localizes hitting point in virtual-reality table tennis game," Biomed. Eng. Lett., vol. 14, no. 2, Feb. 2024. DOI: 10.1007/s13534-024-00354-7.

[5] Y. Hirao, A. Lécuyer, and T. M. Takala, "Comparing motion-based versus controller-based pseudo-haptic weight sensations in VR," in Proc. IEEE Conf. Virtual Reality 3D User Interfaces Abstracts Workshops (VRW), Mar. 2020. DOI: 10.1109/VRW50115.2020.00069.

[6] A. Ratschat, B. M. van Rooij, J. Luijten, and L. Marchal-Crespo, "Evaluating tactile feedback in addition to kinesthetic feedback for haptic shape rendering: A pilot study," Front. Robot. AI, vol. 11, Apr. 2024. DOI: 10.3389/frobt.2024.1298537.

[7] H. Leete, "Gyroscope-induced force feedback for ball impact simulation in exergames," M.S. thesis, Discipline of Human Interface Technol., Univ. Canterbury, Christchurch, New Zealand, 2022.

[8] Y. Tang et al., "Advancing haptic interfaces for immersive experiences in the metaverse," Device, vol. 2, no. 6, Jun. 2024, Art. no. 100365. DOI: 10.1016/j.device.2024.100365.