UC UNIVERSITY OF CANTERBURY

Gyroscope induced force feedback for ball impact simulation in exergames

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ABSTRACT

A haptic feedback device for simulating batting sport haptics was designed using the resultant gyroscopic effect from rapidly reorienting spinning flywheels and integrated into a custom cricket themed virtual reality exergame. The device was capable of producing impact vibrations and a 0.1 N m torque. A within-subjects user study conducted on 16 participants, and player presence was evaluated using the Presence Questionnaire. The results of the user study were statistically insignificant due to a small sample size ($p=0.153$), and we were unable to reject the null hypothesis, but visual data analysis was used to identify trends that supported our hypothesis that increase haptic feedback fidelity increases presence in virtual reality batting sports exergames. Due to the statistical insignificance of these results, further research should be conducted to confirm these findings.

AKNOWLEDGEMENTS

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CONTENTS

ABBREVIATIONS

VR	Virtual Reality
VE	Virtual Environment
FFD	Force Feedback Device
HFF	Haptic Feedback Fidelity
HFD	Haptic Feedback Device
PQ	Presence Questionnaire
ITQ	Immersive Tendency Questionnaire
CMG	Control Moment Gyroscope
BLDC	BrushLess DC motor
ANOVA	Analysis Of Variance

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1 INTRODUCTION

Virtual Reality (VR) provides immersive experiences across a variety of fields, including education, entertainment, medicine, data visualisation, and more[1]. It is a technology that intercepts and replaces sensory stimuli that are used to ascertain information about one's present environment. By replacing environmental information such as light and sound, VR can trick its users into feeling present in a Virtual Environment (VE) and become engaged in the experience. Modern immersive VR devices do this by presenting user's sensory systems with information that the VE would produce if the user were truly in that environment: visual sensory input (i.e. sight) is replaced by using high resolution displays to provide the eyes with images of the VE instead of their true surroundings, and auditory sensory input (i.e. hearing) is replaced or augmented by using headphones or speakers to provide the ears with sounds of the VE.

Of course, the human sensory experience is not limited to sight and hearing. Another set of sensory inputs important to understanding one's environment are tactile and kinaesthetic haptics, more commonly known as the sense of touch. When one physically interacts with their environment, they expect to receive haptic feedback as a response [2]. To clarify, haptic feedback is the combination of two sensory inputs: tactile haptics and kinaesthetic haptics. Tactile haptics are sensations experienced through the skin, including texture, temperature, and vibration. Kinaesthetic haptics are sensations of force, felt through sensory cells located at the end of the tendons or between the muscle strands. [3] When it comes to simulating the sense of touch in a VE, current commercial and consumer technology is limited to the tactile sensation of vibration, and sensations of heat, force, and weight are often ignored.

One application of VR is the facilitation of immersive exergames, also known as exertion games or active games. Exergames are video games that require the user to use physical bodily movement to play and they have applications in recreation, professional sports training, education, rehabilitation, and more [4]–[6]. Exergames can take the form of sports simulations, wherein there may be several haptic stimuli the VE would be expected to produce. A particular example of this is for ball sports. In every ball sport where the player interacts with a ball, the player should expect to receive some haptic feedback from the ball. Whether it be the texture of a netball on the players hands when they catch it, the vibration of the hockey stick as they scoop the hockey ball, the reactionary force of a basketball as they dribble it, or the impact force on the cricket bat as they strike the incoming cricket ball. To maximise realism when simulating sports in a VE, these haptic sensations should also be simulated.

Ball sports involving bats, sticks, and rackets lend themselves to having their haptic behaviour simulated more easily, naturally, and thoroughly as they already require the player to hold some sort of device to interact with the ball. Where a player playing a game of tennis would hold a tennis racket, a player in an immersive tennis exergame could hold a haptic feedback device in its place. For the sake of brevity, sports involving rackets, sticks, and bats shall be referred to as batting sports in this thesis.

1.1 Motivation

Batting sports haptics simulations have been a popular topic of research in the past, with haptic simulations of tennis [7], [8], table tennis [9], cricket [10], air hockey [11], though they commonly only provide reciprocating vibrations as the haptic response. In contrast, in real batting sports, a user experiences a kinaesthetic haptic response in addition to the tactile haptic response of vibration, as striking a ball in a batting sport will provide a unidirectional reactionary force, in a direction opposing the direction of the force the bat applied to the ball, as stated by Newton's third law of motion. This is a directional response that cannot be provided by the examples above that only provide the tactile haptic feedback of vibration. However, there do exist haptic feedback devices capable of simulating directional force feedback such as the PHANToM OMNI haptic device [12] used in Kusunose et al.'s research simulating air hockey haptics [11]. The PHANToM however is a grounded device, and as such it must be mechanically coupled to a stationary surface, preventing such a device from providing the flexibility of motion required in other batting sports such as baseball or badminton. Ungrounded Force Feedback Devices (FFDs) have been developed [13], but their high response times makes them unsuitable for simulating the snappy impact of hitting a ball, or they require large air compressors and pressure tanks [14].

Physical exercise provides significant health benefits, mitigates health risks, and is associated with delaying the onset of 40 chronic diseases [15], [16]. Conversely, insufficient exercise has significant detrimental health impacts, is responsible for up to 5 million deaths annually, and increases risk of death by 20 to 30% when compared to people who are sufficiently active [17]–[19]. Globally, 28.5% of the adult population is insufficiently active, though this percentage is larger and increasing in high income countries, increasing from 31.6% in 2001 to 36.8% in 2016 [20]. One contributing factor to this increase in inactivity is an increase in recreational sedentary activities, such as watching television or playing video games [15]. With over 3 billion global consumers of computer games [21], there exists an opportunity to leverage the popularity of video games for increased physical activity through exergames [22]–[24]. Exergames have seen commercial success and large adoption rates in the past in games such as Nintendo's Wii Sports and Microsoft's Kinect Sports Rivals [25].

An effort can be made to make exergames more appealing to a larger population by making them more engaging. Engagement is a complex psychological phenomenon determined by several sub phenomena, namely involvement, focused attention, immersion, flow, and presence [26]. Presence in a VE is affected not only by the fidelity of the sensory information it provides, but also on how well the VE's behaviour matches its expected behaviour, or in other words, how realistic it is [27]. Therefore, making realistic exergame experiences that promote presence and engagement is an important endeavour.

1.2 Research questions

This thesis aims to document the development of a haptic feedback device capable of simulating unidirectional forces experienced in batting sports, and to evaluate its effect on player presence in an immersive batting sport.

Through such research, answers the following research question and sub questions are sought:

Q1 – How can a device capable of simulating different levels of haptic feedback be designed for virtual reality batting sports?

> Q1.1 – What are different levels of haptic feedback for virtual reality batting sports?
>
> To measure presence against realistic haptic feedback, it is necessary to be able to control the level of realism of the feedback, referred to here as Haptic Feedback Fidelity (HFF)

Q1.2 – How do different do different levels of haptic feedback affect player presence in virtual reality batting sports?

With the goal of developing a haptic feedback device to increase player presence, we would like to validate if such a device does in fact affect player presence in a VE, and if so, how?

To answer this question, the following hypothesis is presented:

H: higher levels of haptic feedback fidelity result in higher levels of player presence

The corresponding null hypothesis to be rejected is presented:

H_0: Different levels of haptic feedback fidelity have no effect on player presence

1.3 Thesis structure

Chapter 2 (Literature review) reviews previous research and identifies their strengths to learn from and weaknesses to build upon. Research reviewed is on the topics of haptic feedback devices, exergames, and presence evaluation.

Chapter 3 (Methodology) Documents the design and development of a Haptic Feedback device (HFD), a user study for evaluating the HFD's effect on player presence, and an immersive batting sport exergame for conducting the user study with.

Chapter 4 (Results) presents the results of the user study and device development.

Chapter 5 (Discussion) discusses results of the user study and device and the limitations of the research.

Chapter 6 (Conclusion) Closes the thesis and sets up what further research could be conducted from the findings of this work.

2 LITERATURE REVIEW

To answer the research questions, existing research from relevant fields are explored. For question Q1, research regarding existing methods for force feedback are explored, and each implantation has its merits and weaknesses discussed to inform the design of our device.

2.1 Torque-based force feedback mechanisms

When a batting sports player hits a ball at the end of their bat, the bat acts as a lever with the player's hand being the fulcrum, as illustrated in Figure 1. The force transferred from the ball to the bat also transmits a torque to the players hand, with the torque τ given by Equation (1)

$$\tau = Fd \tag{1}$$

Where F = the force the ball is transferring to the bat in Newtons and d = the distance from the hand to the impact point on the bat in meters. Therefore, a realistic ball impact simulator should transfer both a unidirectional linear force and unidirectional rotational torque to the user's hand.

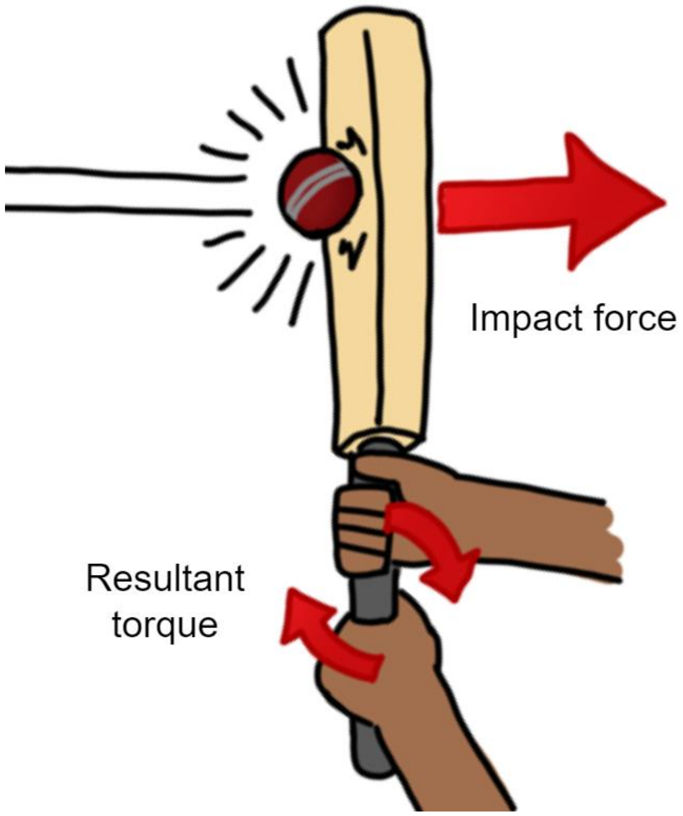


Figure 1: The linear impact force of a ball on a bat causing a rotational torque on the hands of the player.

FFDs are haptic devices that specifically provide kinaesthetic haptic feedback. There has been plenty of research investigating different mechanical methods of providing force feedback, yet the field itself is still having regular novel approaches introduced and is far from saturation.

Several FFDs provide not a linear force feedback, but rather a rotational torque feedback. An example of such a device is the work by Eizad et al.[28] wherein a set of reaction wheels were implemented to provide balancing cues to the user. The reaction wheels were attached to the user's back, as shown in Figure 2.

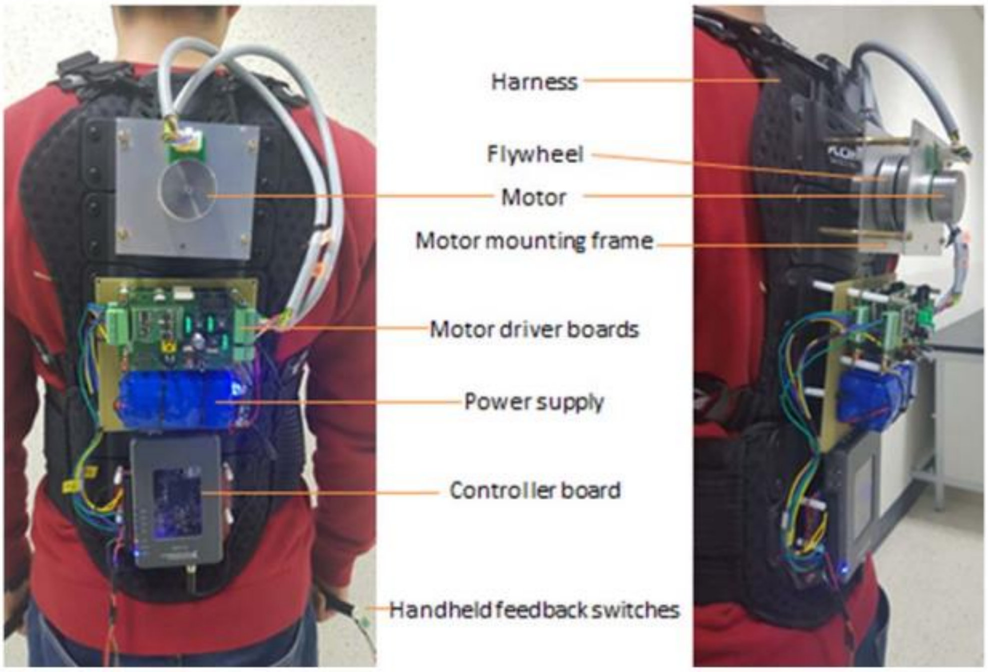


Figure 2: The reaction wheel FFD by Eizad et al. [28].

Reaction wheels work by accelerating or decelerating a flywheel to provide a reactionary torque to another body. In the case of Eizad et al.'s work, the flywheel's mounted to the user's back provide left and right leaning torques to the user. The flywheels are accelerated and then decelerated over a period of about 0.8 seconds, resulting in a directional impulse in one directly, immediately followed by an impulse in the opposite direction, as shown in Figure 4: The resultant forces from the flywheels in Eizad et al.'s [28] work.. While these impulses in rapid succession are in opposite directions, Eizad et al. found that the users were still able to recognise which direction the feedback was intended to convey.

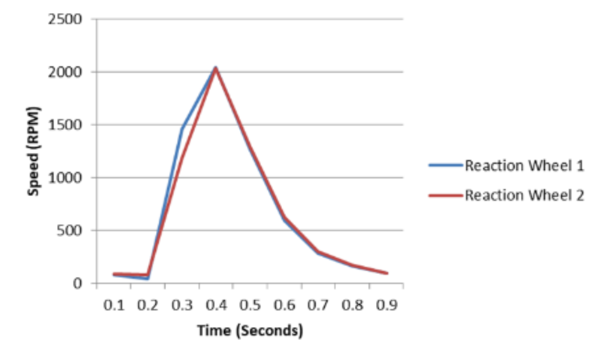


Figure 3: The rotational speed of the flywheels in Eizad et al.'s [28] work.

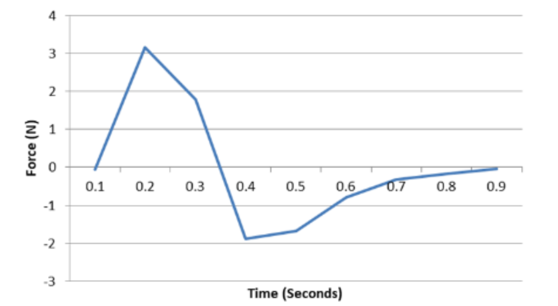


Figure 4: The resultant forces from the flywheels in Eizad et al.'s [28] work.

The amount of reactionary torque τ produced by a reaction wheel is given by Equation (2),

$$\tau = I\alpha \tag{2}$$

where I = the flywheel's moment of inertia about its axis of rotation in $\mathrm{kg \cdot m^2}$ and α = the flywheel's rotational acceleration in $\mathrm{rad \cdot s^{-1}}$. As the acceleration and deceleration of the of the flywheels were of similar magnitudes, as discernible by the similar upwards and downwards slopes in Figure 3, the two resultant force peaks were of similar magnitude as shown in Figure 4. The reactionary torque of a reaction wheel is given by the time derivative of its angular velocity, and so with more careful control of when the reaction wheel is accelerated or decelerated, more controlled torque impulse can be generated (Figure 5). Amemiya et al. demonstrates this with their work [29] in which they investigate asymmetrical acceleration and deceleration of a flywheel for use in a kinaesthetic haptic device. They find that a reaction wheel can be brought up to a high speed slowly enough that the reaction force is below the human threshold for perception of torque (about 0.02Nm) and then rapidly decelerated to create a torque impulse.

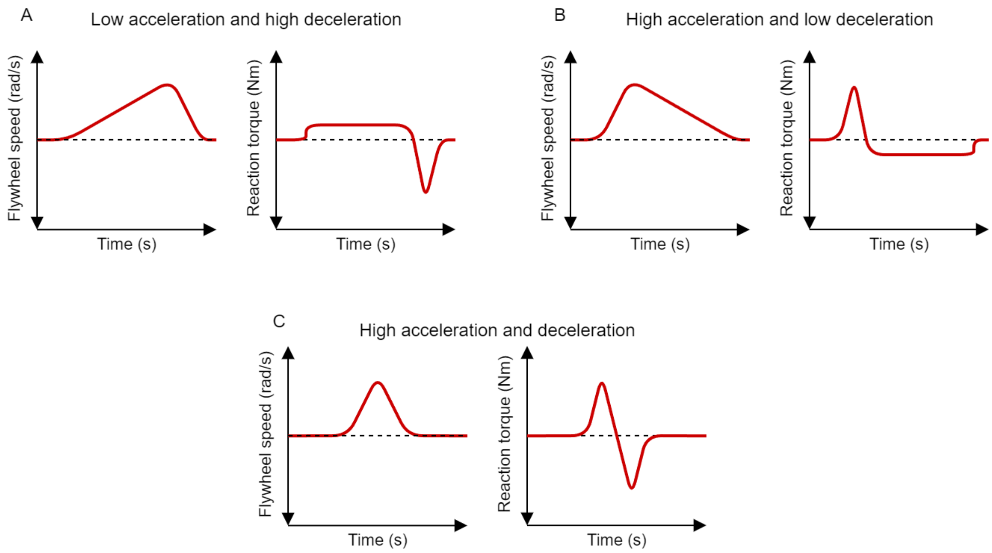


Figure 5: General relationships between flywheel speed and reaction torque CRICK

Cubli [30] (Pictured in Figure 6) is a self-balancing cube that uses a similar mechanism at higher speeds to produce large enough impulse to lift off the of the ground. It first spins up a flywheel to just under 380 RPM and brings it to a near instantaneous stop by applying a brake, generating a torque impulse large enough to causing it to jump up onto its corner.

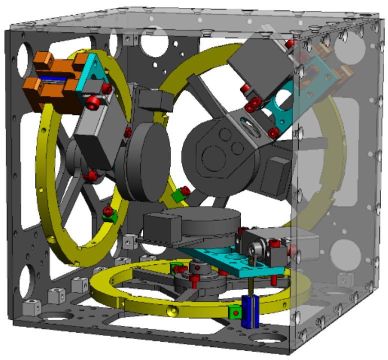


Figure 6: Cubli, a cube that uses reaction wheels for balance and impulse generation. Image from Gajamohan et al. [28].

While the Cubli can generate torque impulses on demand, it must first be in a state where its relevant flywheel is spinning at a high speed, which makes it prone to unwanted gyroscopic reaction forces if rotated about any axis not parallel to its axis of angular momentum.

When a flywheel spins, it has angular momentum $\vec{L}$, given by the Equation (3):

$$\vec{L} = \vec{\omega} I \quad (3)$$

Where $\vec{\omega}$ = the flywheel's rotational velocity, and I = the flywheel's rotational inertia about its axis of rotation. Unwanted gyroscopic forces occur when trying to reorient a spinning flywheel because of conservation of angular momentum. In Figure 7, A spinning flywheel with angular momentum $\vec{L}_0$ is in orientation A. For it to be rotated from orientation A to orientation B, it must have a torque applied about the axis of $\Delta\vec{L}$. Therefore, if it were rotated by an external force, for example a person holding a device with a flywheel, that person would then feel an unintuitive and unexpected reactionary torque about this $\Delta\vec{L}$ axis. Amemiya et al. also explored instead accelerating the flywheel rapidly and decelerating it slowly, reducing the amount of time the flywheel spent at high speeds. This however reduced the maximum amount of torque that could be produced as applying brakes was more effective at velocity change than a powered acceleration.

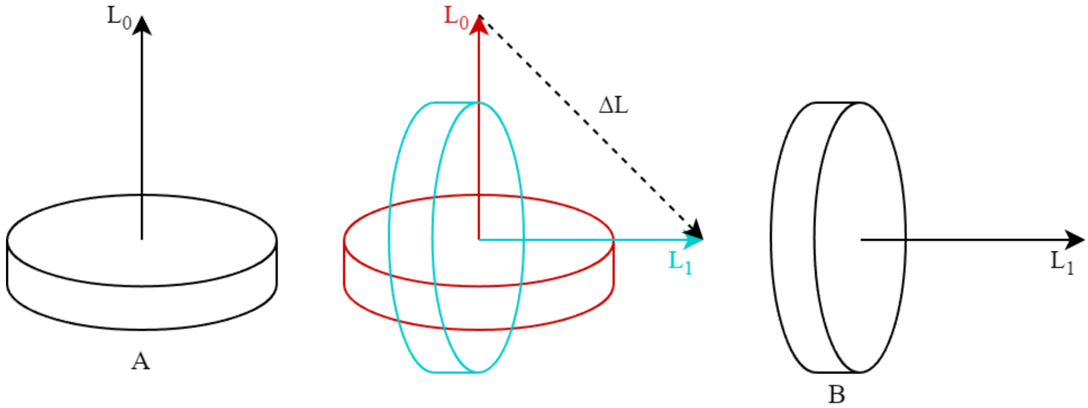


Figure 7: A spinning flywheel being reoriented, requiring a torque about $\Delta\vec{L}$ to change the angular momentum.

While this may be an unintended side effect of a reaction wheel-based systems, other research papers have used this effect in a controlled manner to create intentional directional torque. Such devices are called Control Moment Gyroscopes (CMGs).

Winfree et al. developed a handheld haptic device using a single large flywheel for a CMG, called the iTorqU 2.0 [31], pictured in Figure 8. With this device, they could reorient a flywheel to produce significant torques of nearly 1,200 N mm. The magnitude of torque it can produce is dictated by the speed and inertia of the flywheel, and the speed at which the flywheel can be rotated.

Figure 8: The iTorqU 2.0 haptic feedback device from Winfree et al. [31].

The iTorqU featured a dual gimbal design, allowing the flywheel to be reoriented in almost any direction (subject to limitations of gimbal lock) at the cost of additional weight. This dual gimbal design, combined with an accelerometer to measure the orientation of the device, allowed the device to actively control the orientation of the flywheel to remain fixed in space, even as the user moved and rotated the device from underneath it, removing a large amount of the unwanted gyroscopic effects that simpler flywheel-based designs suffer from.

Antolini et al. [32] proposed a haptic device design using two flywheels in a "scissor pair" to cancel out certain unwanted gyroscopic effects without the need of active accelerometer based control. This works by having two flywheels in mirrored orientations, such that their summed angular momentum is $\vec{0}$, therefore the system as a whole does not produce any net gyroscopic effects when moved through space in this configuration, as illustrated by $\overrightarrow{L_0}$ in Figure 9.

This scissor pair gyroscopic design also ensures that when reorienting the flywheels, if the flywheels remain mirrored about some plane M, the reactionary torque produced by them is constrained to a single direction that both lies upon the plane M and is perpendicular to the axis of reorientation, as illustrated in Figure 9. This contrasts a single flywheel CMG, where direction of torque is perpendicular to the axis of reorientation and the flywheel's current axis of spin.

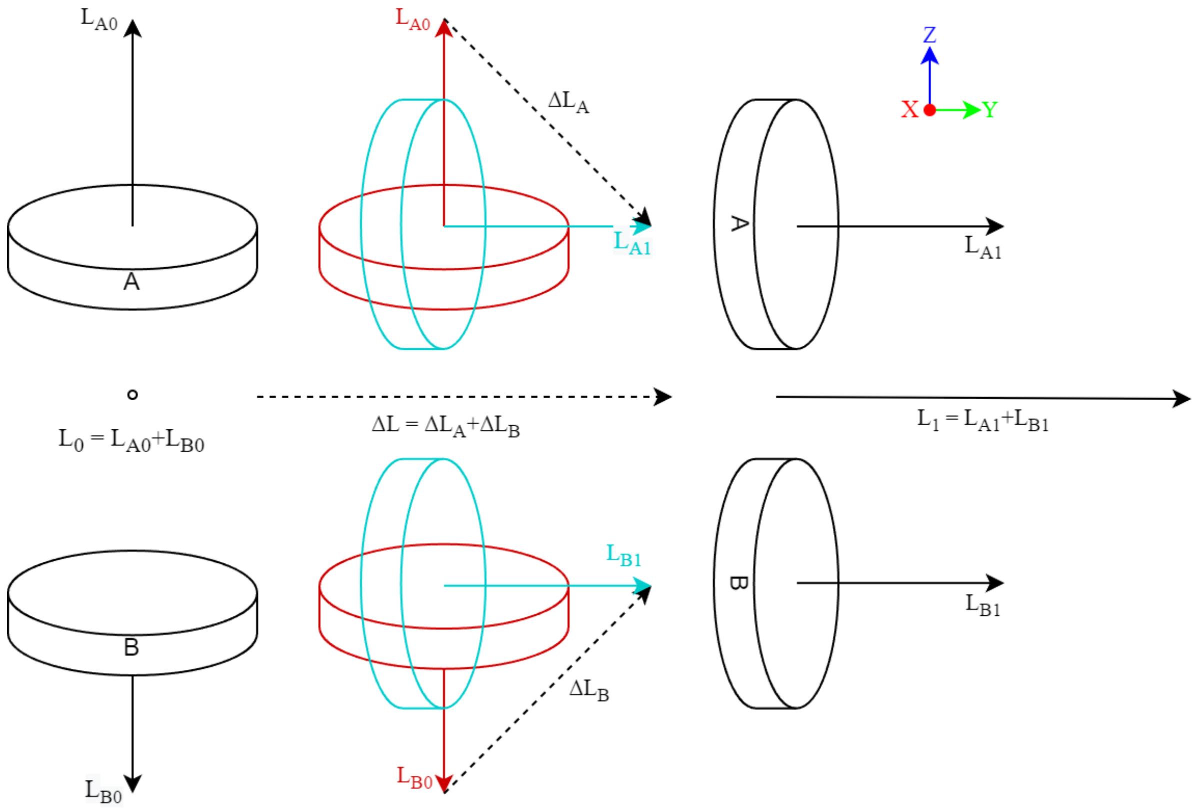


Figure 9: Scissor paired CMG made with two flywheels A and B mirrored about the XZ plane. The angular momentum vectors $\overrightarrow{L_{A0}}$ and $\overrightarrow{L_{B0}}$ sum to $\vec{0}$. Additionally, when reorienting the flywheels about the X axis, the Z axis components of $\Delta\overrightarrow{L_A}$ and $\Delta\overrightarrow{L_B}$ cancel each other out, resulting in a total change in angular momentum (and therefore resulting torque) that lies only upon the Y axis.

Walker et al. [33] implemented this mechanism into a haptic device pictured in Figure 10.

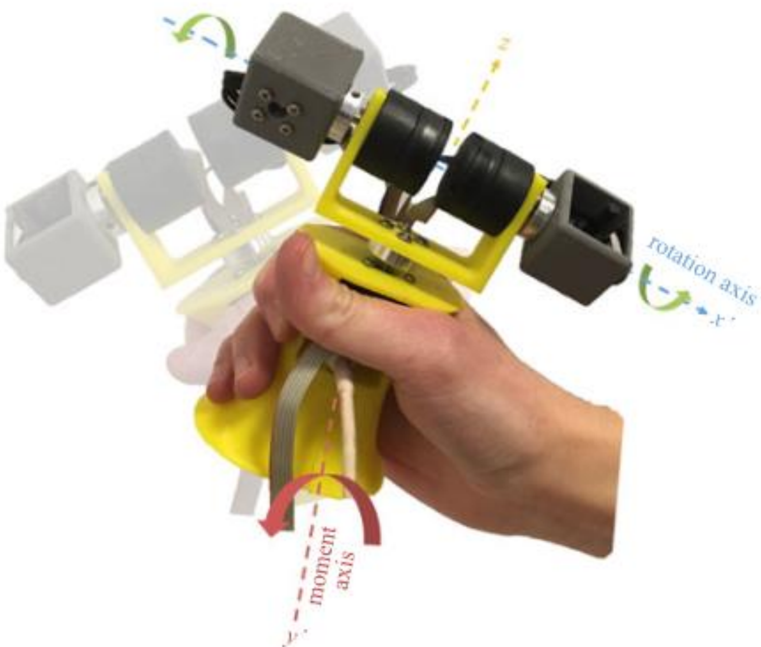


Figure 10: Walker et al.'s [33] haptic device using a scissor pair CMG.

After this device changes flywheel tilt configuration and produces a torque, it must then return to its idle position to retain the benefit of having a net zero angular momentum and generates a corresponding reversed torque upon reversal of the flywheels' tilt. To keep the haptic feedback perceived as unidirectional, they used asymmetrical pulse durations for the moving and resetting of the flywheels to keep the return torque less noticeable, similarly to Amemiya et al. They also noted that the power of the torque impulses was limited by the tracking speed of the motors that actuated the flywheels.

All these haptic feedback approaches have been for producing ungrounded torques, but there is also substantial research on linear force production.

2.2 Linear force-based force feedback mechanisms

Externally grounded FFDs use some physical linkage between the user and a static body such as the ground or a table to apply strong directional forces to the user. The PHANToM OMNI is a grounded FFD, pictured in Figure 11. It its base is rigidly connected to a table or desk and is connected to a stylus like interface through a series of actuated linkages. The grounded design enables it to produce direction forces by pushing back against the table, of magnitudes up to 3.3N [12]. This grounded feedback device also has a fast response time and does not produce any unintentional forces while the user operates within its operational space, allowing it to produce sensations of touching a physical object with the stylus, and even tracing along its virtually textured surface. The weakness of this device, and all grounded devices, is that as they require a linkage to some static body, they severely limit the flexibility of motion to the user.

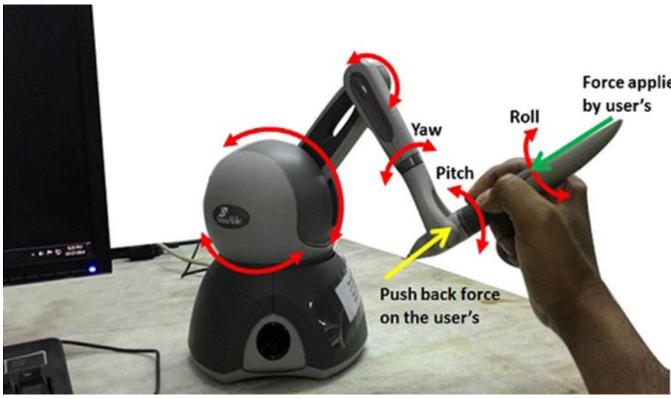


Figure 11: The PHANToM OMNI FFD. Image from Gajamohan et al. [34].

Body grounded devices build upon this technology and overcome spatial limitation by connecting the device to other stable parts of the user's body. Tsia et al. [35] developed a body grounded FFD capable of delivering both resistive forces and impact forces to the hand of the user, shown in Figure 12. This device produced force impulses on the user's hand by tensioning an elastic band connecting the user's hand and forearm. In its idle/winding state, the tension of the elastic band was transferred to a motorised gate, preventing the user from feeling it the force until needed. To produce a force impulse, the gate was lifted, immediately transferring all the tension force to the user's hand, pulling it back. Additionally, there was a retractable wire between the elastic band and the hand with a motorised brake, allowing the device to produce resistive forces to the hand by adjusting the brake force. Being body grounded, every force this device applies to the hand is oppositely applied to the part of the body to which it is grounded. Additionally, a pulling sensation is not exactly equal to a pushing sensation; if the user is holding an object and their hand is accelerated back by the elastic band, the inertia of the held object will apply a resistive force in the opposite direction, as if the object is pulling away from the hand.

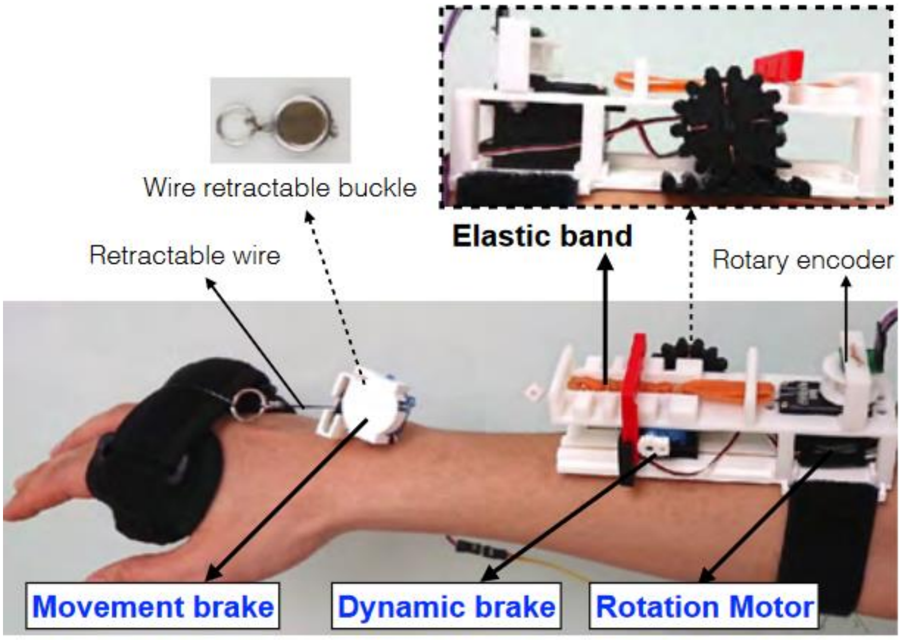


Figure 12: The ElasticVR haptic feedback device by Tsia et al. [35].

Wang et al. [36] developed the JetController, a FFD that used compressed air jets to generate thrust forces. Five nozzles were connected to a compressed air supply, each connected to their own electronically controlled pressure regulators and high-speed valves. Their device could produce both short impulses and long duration forces by adjusting the period the valves were open for. They could also adjust the force each nozzle produced by adjusting the pressure regulators connected to each nozzle, allowing up to a maximum of 4.0N of force feedback. Its fast response time also made it suitable for simulating rapid haptic events, such as those produce by an automatic weapon in a video game. While the handheld device had a total weight of 360g (202g controller weight + 158g nozzle + hose system), the pneumatic control system weighed 4.8kg.

Figure 13: The JetController by Wang et al.[36].

Similarly, Gong et al. [37] developed Jetto, a smartwatch haptic system using compressed air. This device also needed an external air compressor to run for extended durations, or a CO2 cartridge could be used for portability, but limited the total force output duration to just 5 seconds.

Heo et al. [13] developed a device named Thor's Hammer, pictured in Figure 14, another air propelled haptic device that had no need for compressed air supplies. Instead, this device used electrically driven propellors to generate up to 4.0 N of continuous thrust. Due to the time required to accelerate the propellors to generate a force, the device had a general response latency of 300ms, making it less suitable for some interactions, such as hitting a rigid surface. Other propellor based devices [38]–[40] have similar limitations.

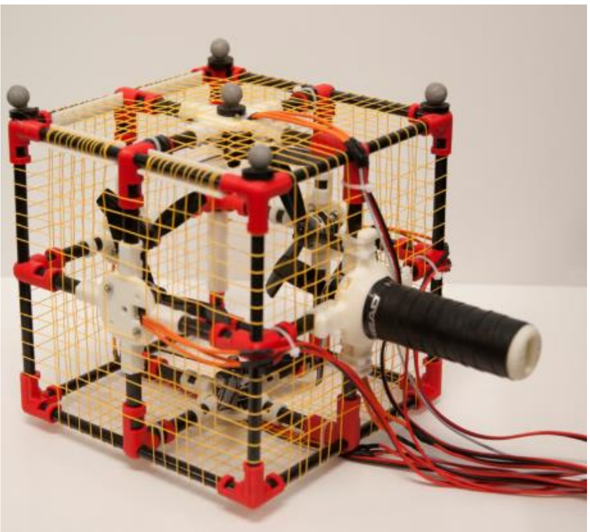


Figure 14: Thor's Hammer by Heo et al. [13].

While air-based devices produce forces by pushing against air, linear mass acceleration devices produce forces by pushing against rigid or weighted bodies. For ungrounded devices, these bodies must be contained internally (or be permanently ejected).

F. W. Teck [8] developed a haptic device for simulating tennis force and torque impacts by actuating solenoids, as shown in Figure 15. Solenoids above the hand were actuated in one direction, while a solenoid below the hand was actuated in the opposite direction simultaneously. The alternate directions between solenoids resulted in a torque about the user's hand, while the three-solenoid design meant there was also a linear force in one direction. Solenoids generate significant force both in acceleration and deceleration in rapid succession, and so were not able to generate unidirectional force.

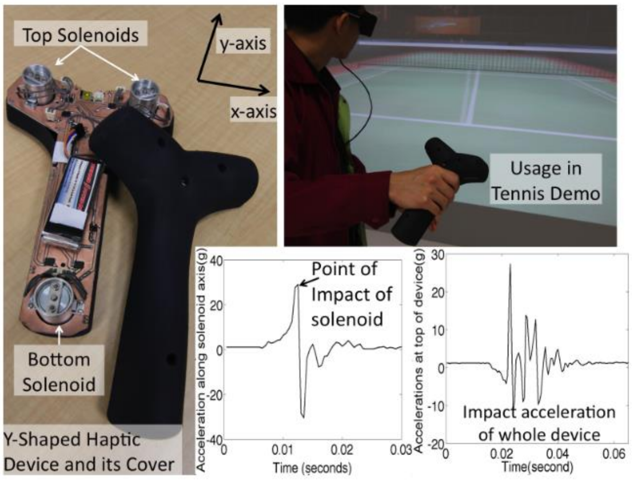


Figure 15: A tennis racket simulator by F. W. Teck [8].

A variety of implementation methods for force feedback have been explored, each with their own merits and weaknesses. The gyroscopic FFDs [32], [33] and reaction wheel based devices [28]–[30] produce ungrounded torques by changing their internal angular momentum, and can mitigate return forces to make their feedback unidirectional with asymmetrical actuation periods. Linear actuation based devices produce quick snapping forces but cause more vibration than unidirectional force [8]. Compressed air powered devices [14], [36], [37], [41] and propelled air devices [13], [38]–[40] also provided ungrounded unidirectional forces free of extraneous return forces, but compressed air devices need large external air compres0073ors and pressure tanks, and propelled air devices have a slow response time as the propellors take time to get up to operational speed, and provide persistent forces as opposed to fast impulses.

The explored gyroscopic FFDs also provide somewhat persistent forces over the period of 100-1000s of milliseconds, but this limitation could possibly be overcome by having the flywheels reorient faster. A suitable method for doing so is by using a tensioned quick release mechanism, similar to that in Tsai et al.'s work [35].

2.3 Exergames

Exergames, also known as exertion games or active games, are a genre of video game that require the player to exert skeletal muscles resulting in physical fatigue. This definition differentiates them from traditional non-exertion games that often require user input through only a keyboard and mouse or gamepad [4]. The common motivation for exergames is to drive physical activity through play [4], [7], [42]–[46]. The history of exergames began in 1980 [47] with the Atari Joyboard, a simple balance board enabling directional input to the Atari 20660 game console. Since then, exergames and their input methods have become more sophisticated and have recently become a more common topic of research [48].

Exergames present scenarios of varying levels of realism, some are immersive first person simulations like Virtual Tennis [8] and PaperDude [49], where the player's bodily movements are directly applied to a first person avatar; others abstract the user's motion more by having them control virtual agents in third person such as Nintendo's Wii Sports, and may have more abstract motion input mapping such as in Balloon Burst[50].

In PaperDude by Bolton et al. [49], the player sits on an exercise bike wearing a VR)headset, and is presented with a virtual bicycle. A Microsoft Kinect sensor is used to capture upper body motion of the player. In the virtual environment, the player's pedal action on the exercise bike is directly mapped to the virtual character's travel speed on the virtual bicycle, and the player's arm and torso movement is mapped directly onto the character's arm motion, allowing the user to throw virtual newspapers in game by simply making throwing gestures in their physical environment. The system provides an immersive exergaming experience, though Bolton et al. notes that the immersion is limited by the lack of force feedback.

An example of an exergame that abstracts the user's input motion is found in Balloon Burst: an exergame by Stach and Graham [50] investigating the effects of haptic feedback in exergames. In Balloon Burst, two players seated on recumbent exercise bikes compete for the highest score. The players use Xbox gamepads to pop on screen balloons to score points, using the exercise bike pedalling speed to make balloons appear faster. Abstracting user motion input, however, provides a less realistic interface with the VE, and so for this research is to be avoided.

2.4 Haptics in exergames

Stach and Graham [50] produced one of the first papers relating exergames and haptic feedback in an investigation of how haptic feedback can improve three specific aspects of exergaming. These aspects were balance: using haptic feedback to mediate the effort players must spend, enabling players of different skill or fitness levels to play with each other; safe and healthy interaction: using haptic feedback to provide cues when exertion limits have been reached; and presence: how haptics increases the enjoyment of an exergame by increasing the player's perceived presence in the virtual world. They found that haptics can provide a richer exergaming experience and presented a set of design principles for future exergame designs, one of which being that the haptic feedback should have a clear link to the physical situation in the game environment.

Adamocich et al. [51] used exergames in VR for post stroke hand rehabilitation, using a Rutgers Master II [52] force feedback glove that allowed for a controlled haptic response, tuned to the patient's needs. Their outcomes suggested that their VR haptic system may be useful to augment specific rehabilitation programs, though they did not individually study the isolated effect of the haptic component of their system.

Shaw et al. [53] studied the effects of haptic and auditory feedback on motivation and immersion within an exergame on an exercise bike. Their study featured five feedback conditions: no feedback, haptic feedback via a fan blowing air, haptic via digitally controlled resistance of bicycle pedals, auditory feedback, and a combination of all three. They found that each feedback method increased user immersion independently, and when combined increased immersion further than any single feedback method.

Haptic feedback in exergames has also been used as a supplementary communication medium between the game and the user in Morellu et al.'s [7] VI-Tennis, an exergame for the visually impaired. The game is modelled after Wii Sports tennis where the user performs swiping gestures with a motion controller to perform forehand and backhand shots in game. The game gives audio and tactile cues for events in the game, e.g. When the ball is served, bounces, hit, returned, etc. Two versions of the game where studied, one with audio and haptic feedback, and one with only audio feedback. The haptic feedback version was more enjoyed by the test users and produced significantly higher user scores than the strictly audio feedback version.

The results of these papers show that haptic feedback has a significant positive impact on user experience, and that when implementing haptic feedback in an exergame, having a clear causal link between the game world and the haptic feedback is important for user engagement and presence [50].

3 METHODOLOGY

3.1 Device design considerations

To decide on what force feedback implementation to pursue for the design of the HFD, mechanisms from the literature review were analysed for merits and weaknesses under the context of providing realistic batting sport haptic feedback.

The main criteria for meeting this requirement were:

- Fast impulse generation. In a batting sport, a ball will be in contact with a bat for a very short duration, about 5ms for the example of tennis [54]. It would be less suitable to design a haptic device that applies forces for extended durations.
- Unidirectional impulse generation. When a ball hits a bat, it applies a force to the bat in a singular direction
- Passive haptic realism. When playing a batting sport, a player expects to feel a bat in their hands with a certain weight. Additionally, they expect force feedback to come from the bat in their hands.
- Mobility. The device should allow the player to move with a similar degree of freedom as the sport they are playing. This means the device should be ungrounded and not excessively heavy.

Externally grounded devices have limited operational spaces and making one the required size for a batting sport simulation would exceed available resource limitations.

Body grounded devices produce reactionary forces on other parts of the body, and as mentioned in Section 2.2 with ElasticVR [35], can cause the inertia of a hand held device to produce forces opposing that of the haptic device. Additionally, applying a force to the hand from another body part does not offer the same passive tactile haptics that holding a realistic batting equipment handle could provide.

Most existing haptic devices used for batting sports use linear mass accelerations such as vibration motors, which cannot generate unidirectional feedback, or solenoids, which produce similar acceleration and deceleration forces when actuated, disallowing the production of unidirectional forces. Unlike flywheels, this cannot be mitigated with asymmetrical acceleration and deceleration pulses, as the accelerated mass of the solenoid would need an excessively long passage to travel through which it could slowly change its high linear velocity, making such a design unsuitable for a mobile exergame.

Reaction wheel-based and gyroscopic-based devices can produce unidirectional impulses when using asymmetrical actuation periods. The magnitude of torque produced is proportionate to acceleration or braking speeds of flywheels for reaction wheel devices and proportionate to flywheel tilt speed for gyroscopic devices. Both device types fundamentally operate on the same principle of trying to change a flywheel's angular momentum to generate torque.

Air based devices can produce unidirectional pulses, but compressed air devices require heavy air compression and control equipment, and propellor based devices have too large a latency to be able to produce the fast impacts required for a batting sport exergame.

Comparing to our design criteria, compressed air, CMG, and reaction wheel mechanisms appeared to be the most suitable. Of these options, a scissor pair gyroscopic design was pursued, as a CMG for fast impulses had not previously been designed, and an opportunity for generating large torques by using springs to rapidly tilt the flywheels was present.

3.2 Device design

3.2.1 Mechanical design

The designed HFD operated using gyroscopic reaction forces as its torque generation method. The generated torque for this method is proportionate to flywheel tilt speed, so a high-speed tilt mechanism had to be designed to maximise torque production.

The tilt mechanism designed featured two stiff springs (Spring constant of 1.13 N/mm) to supply the force to tilt the flywheels. A carriage would compress the springs when pressed down by a plunger which was actuated by a 2mm pitch single start lead screw driven by an SM24240 stepper motor. The carriage was coupled to the flywheels in such a way that when the carriage moves, it rotates the flywheels, as illustrated in Figure 16. To allow the springs to tilt the flywheels at high speed with minimal delay, the carriage requires a quick release mechanism. For this purpose, solenoids were chosen over servo motors due to their fast actuation speed.

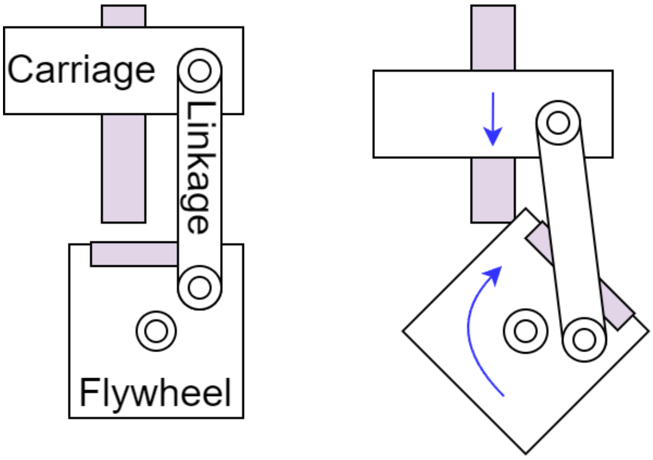


Figure 16: Linear to rotational linkage

To drive the flywheels, hobbyist brushless DC motors (BLDCs) were selected for their high speed. Two B2826/6 2200KV motors were used; their outer rotor design provided a higher rotational inertia than an alternative inner rotor design, allowing the motors' rotors themselves to better contribute to the total angular momentum of the flywheel assemblies.

To tilt the flywheels, flywheel assemblies were designed to both protect the flywheels from entanglement with loose wires/hair, and to function as a mechanical interface between the flywheel and linkage. An exploded diagram of a flywheel assembly is illustrated in Figure 17. The flywheels themselves were made of machined steel, with a guide hole for the BLDC spigot, three screw holes to allow it to be affixed to the flywheel, and a bore hold to fit a bearing on top. This bearing connected to the lid of the flywheel assembly to provide support to the flywheel during tilt. Each flywheel weighed 67g and had a rotational inertia about its spinning axis of 8201 g mm^2. Exact dimensions of the flywheels can be found in Appendix B.

Because the carriage rapidly accelerates when released by the solenoids, it also creates a set of opposing vertical force impulses: one downwards reactionary force as the carriage accelerates upwards, and an upwards impact force as the carriage strikes the plunger. As these two forces are in opposite directions, they do not cause a directional impulse, but a vibration in the HFD. By disabling the flywheel motors, this vibration effect can be isolated, and used as a lower fidelity haptic feedback mode, allowing the device to provide two distinct levels of HFF: the *Flywheel* mode, which has both torque and vibration feedback, and the *Clicking* mode, which has only vibration feedback.

Figure 17: exploded diagram of flywheel assembly (left), and shroud design (right).

The layout of the mechanism described went through four major design iterations, adjusting part placement to optimised space usage and reliability. An illustration of the final iteration's design can is shown in Figure 18. This design featured a guide rod on either side of the lead screw that kept the plunger and carriage orientated correctly. It had two solenoids positioned either side of the lead screw with a 90-degree offset, placed 0.5 mm away from the edge of the carriage to minimise required solenoid stroke, and therefore maximise the force the solenoids could apply to their own plungers. The plunger, carriage, main body (hub), flywheel shrouds, linkages, and all other structural components were all 3D printed using PLA, allowing for rapid iterative prototyping for each of the components. The sequence of actions the device performed to generate a torque impulse is illustrated in Table 1.

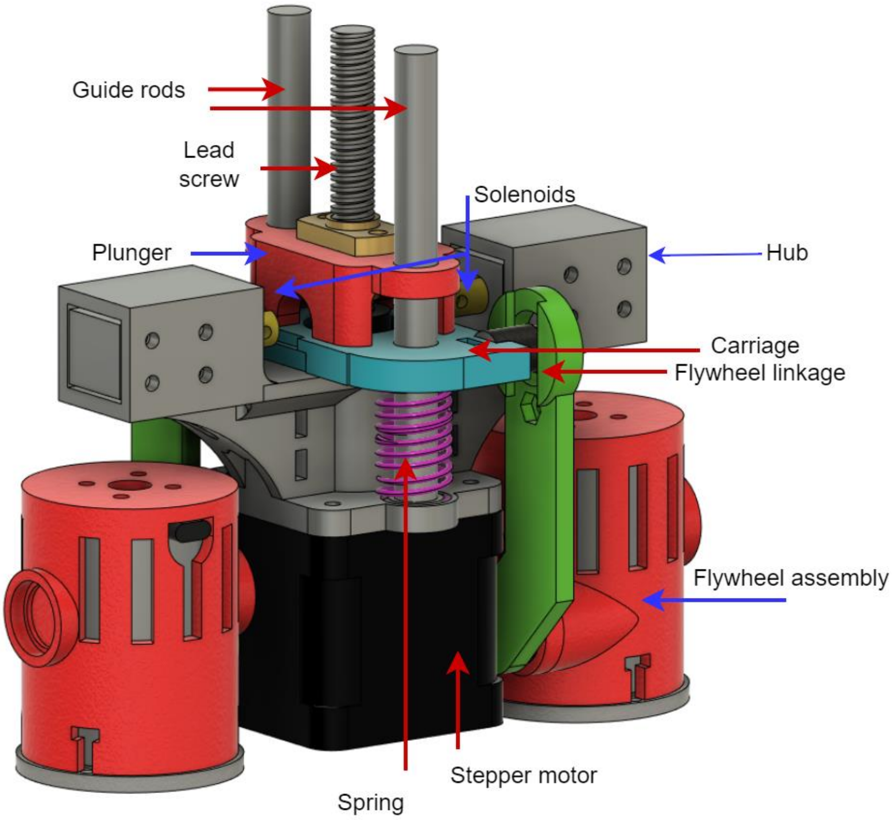
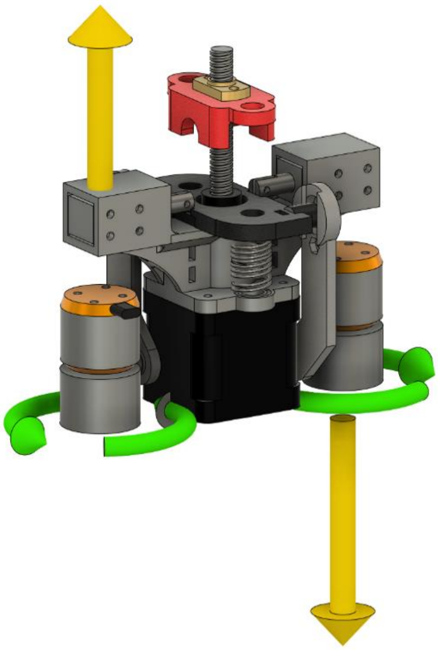
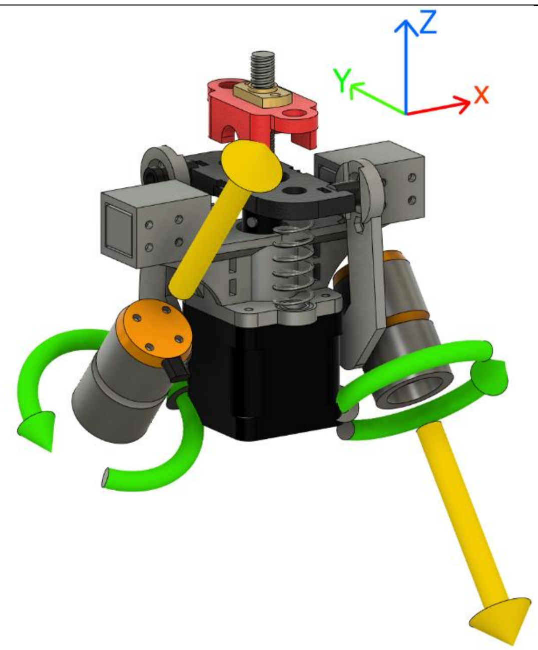
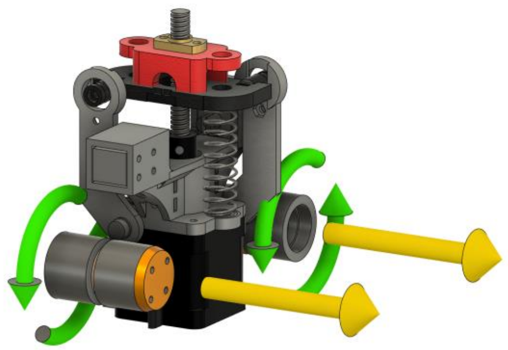
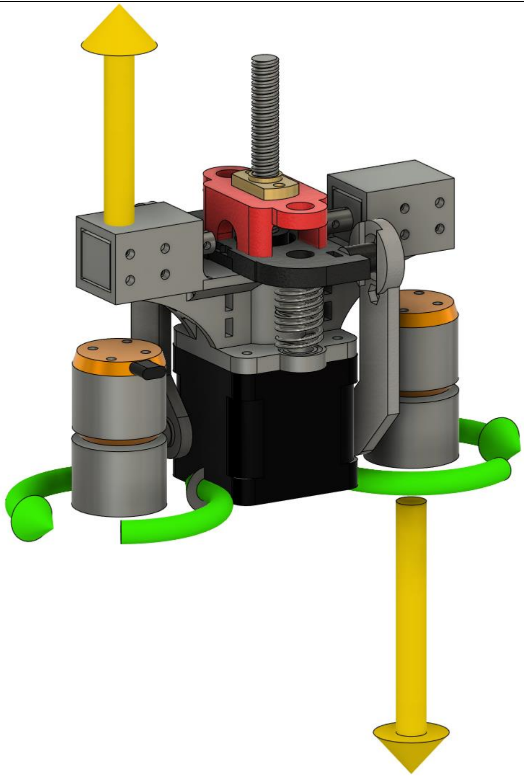
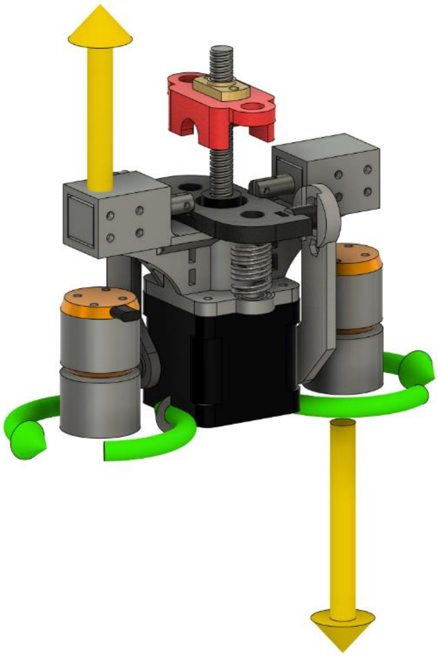


Figure 18: The main functional components of the haptic feedback mechanism. Other electrical and structural components are hidden.

Table 1: The haptic feedback sequence of the HFD.

	**Stage 1** The device is in the standby state, with flywheels spinning in opposite directions. The springs are fully compressed, the plunger is in the raised position, and the solenoids are extended. The circular green arrows in this diagram show the rotation direction of each flywheel assembly, while the yellow straight arrows represent the angular momentum pseudovectors of each flywheel assembly.

	**Stage 2** The solenoids are retracted, and the springs force the central carriage upwards, twisting the flywheel assemblies about the x axis. This is the transitory period during which the system's total angular momentum is being changed very quickly, producing a reaction torque, and takes place over 25ms.
	**Stage 3** The carriage reaches the plunger and stops moving. The flywheels are now aligned to have their angular momentum contributions fully summed together along the y axis instead of cancelled out.
	**Stage 4** The plunger drives the carriage back down into the standby position over the course of 1.0 second, recompressing the springs. This resetting movement is forty times slower than Stage 2, so though it does produce a reaction torque as it reorients the flywheels, it is of a magnitude forty times less; a negligible torque in comparison

<table>
<tr><td></td><td>Stage 5
The carriage is pushed all the way down to its lower position, fully compressing the springs, and allowing the solenoids to extend once more, locking down the carriage.</td></tr>
<tr><td></td><td>Stage 1
The plunger moves back up to its raised position, and the device is now back to its standby state, ready for the next impact event.</td></tr>
</table>

To allow a user to hold the device, a handle was added to the bottom of the device. During construction of the device, it became apparent that the device's weight would make it unsuitable for use in certain batting sports with lightweight equipment, such as table tennis or badminton. For this reason, Cricket was the batting sport chosen to simulate, as a cricket bat can typically weigh upwards of 1.25kg [55]. To provide a similar passive haptic experience to the user, a real cricket bat handle from a size 5 cricket bat was used.

Once the HFD's final design was constructed, a device enclosure was built to protect users from pinch and burn hazards that the unshrouded device may present. The enclosure was

3D printed out of PLA, a featured ventilation slots to ensure the motors and solenoids had adequate airflow for cooling. The final state of the device with its enclosure and handle attached is shown in Figure 19. The full haptic device without its shroud is shown in Figure 20.

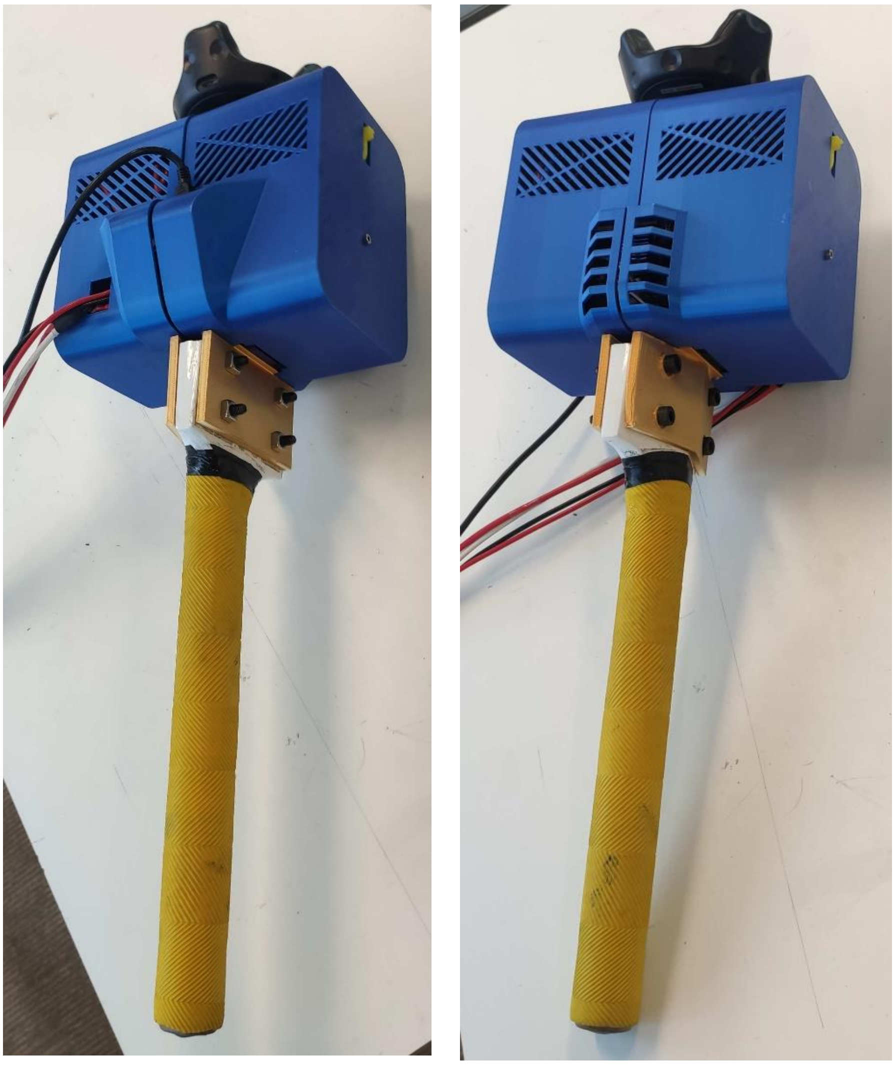


Figure 19: The final constructed design of the haptic device.

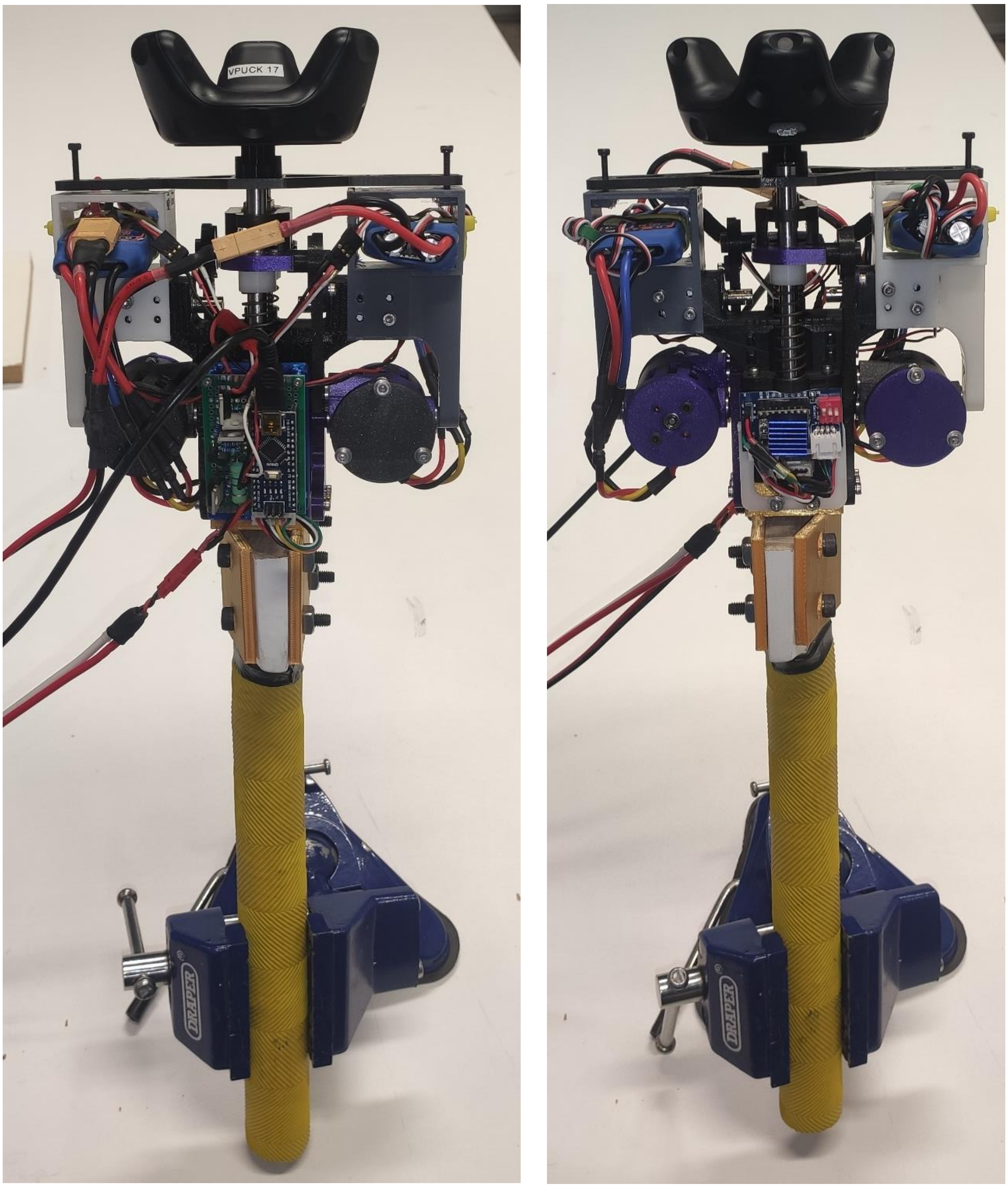


Figure 20: Front and back view of the final HFD with shroud removed

3.2.2 Electrical design

The stepper motor and solenoids were powered by a benchtop power supply operating at 31V with a 10A current limit. The solenoids were driven by a custom driving circuit and the stepper motor was driven by an LV8729 StepStick style stepper driver. The flywheels were powered by a three cell 11.1V lithium polymer battery and driven by two 60A HobbyKing electronic speed controllers. And Arduino Nano micro controller was programmed to communicate with a computer using serial over USB, and to control the electronic speed controllers, stepper motor, and solenoids.

The solenoids selected were latching SK07306V solenoids, meaning they required power only to retract or extend the plunger, but not to remain in each state. This latching behaviour was enabled by a built-in permanent magnet and spring. The magnetic field provided by the permanent magnet kept the plunger in latched in the retracted position. When a current is applied in one direction, the magnetic field generated by the solenoid's coils strengthen the produced by the magnet, but a reverse polarity current produces a field that opposes that of the magnet. In the reverse current state, if the coil's field opposes the magnet's field exactly, the net magnetic field strength approaches zero, allowing the plunger to be pulled into the extended position by the spring. If the coil's field is too weak, the magnet will hold the plunger in place, and if the coil's field is too strong, it will hold the plunger in place itself, as the plunger is pulled towards a magnetic field regardless of its polarity. This behaviour means there is only a small voltage range that will cause the solenoid plunger to move into the extended position. This voltage was experimentally found to be about 3-4V. To retract the solenoid, a much larger voltage of 31V was needed to be applied to the coils, as when the solenoids are holding the carriage against the compressed springs, there is a significant shear force causing a resistive friction force inside the solenoid that the plunger must overcome. To maximise the retraction force of the solenoid, the 31 Volts had to be applied in a forward polarity, so the coil's magnetic field was increased by that of the permanent magnet instead of reduced.

In summary, the operational requirements of the solenoids were for a voltage of +31V to be applied to retract the solenoids, and a voltage of -3.5V to be applied to extend the solenoids. For this behaviour, a custom driving circuit had to be designed. The circuit designed was a modified H bridge circuit design that used a 5W 47Ω resistor to reduce the delivered voltage to the solenoids to 3.5V in one polarity, and a fast-switching Schottky diode to bypass the voltage reducing resistor in the other polarity, and protect one of the H bridge MOSFETs affected by the modification from the inductive voltage spike the solenoids could produce when turned off. The full circuit schematic is shown in Appendix A.

The solenoid control circuitry was implemented on protoboard, to which the microcontroller was also connected. The protoboard component placement was planned and optimised for space using KiCad; a 3d model of the protoboard component layout is shown in Figure 21 The protoboard was then attached directly to the haptic device via a 3d printed mounting bracket. The layout of the electrical components is shown in Figure 22 and Figure 23.

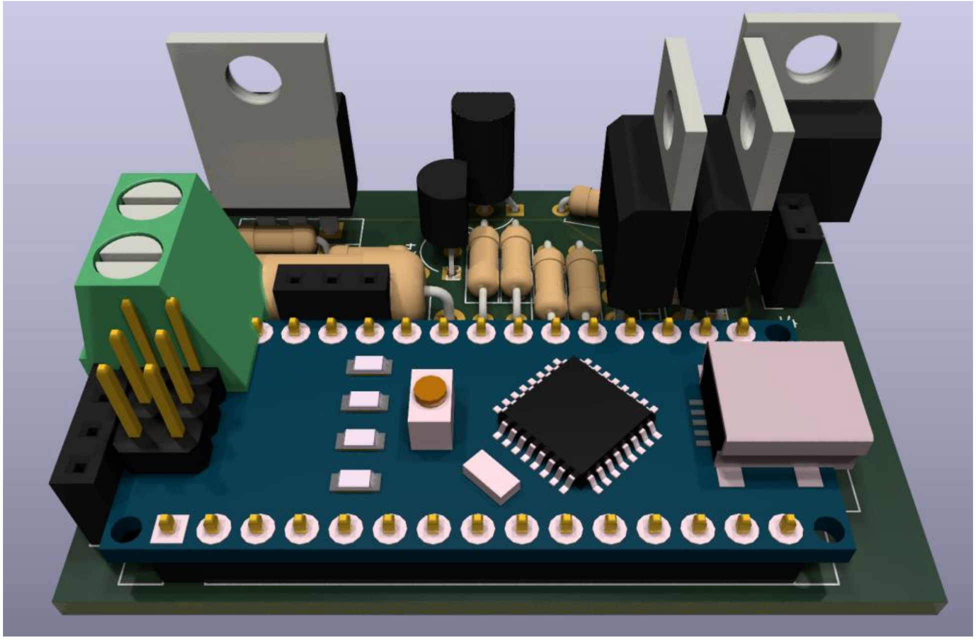


Figure 21: A 3d model of the protoboard that was made to help layout components.

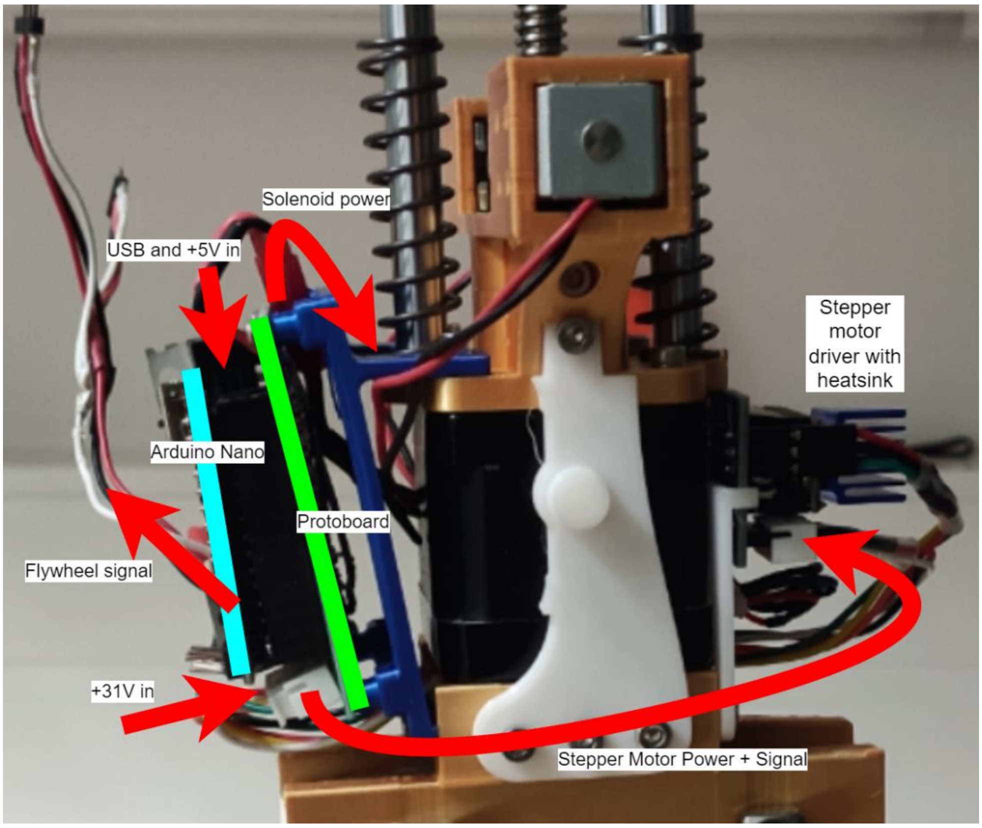


Figure 22: Side view of electrical component layout.

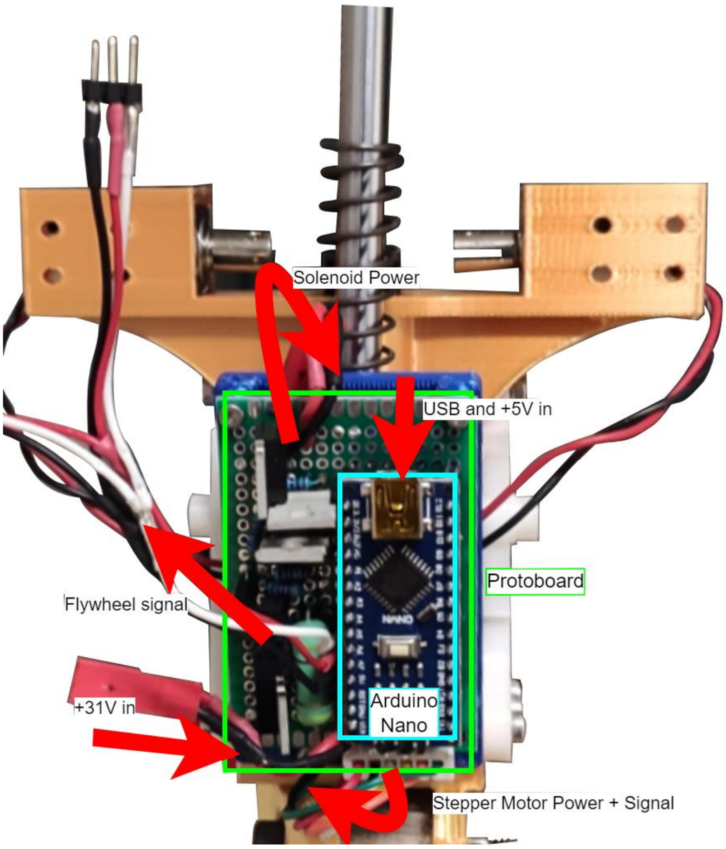


Figure 23: Front view of electrical component layout.

3.2.3 Computer interface design

The HFD was controlled by an Arduino Nano microcontroller programmed in C++. The Arduino ran a program that would listen for a certain set of valid instructions characters to arrive via serial communication with a PC over USB. Some instructions also required a subsequent number to be received over serial as a command parameter. Commands and their descriptions are listed in Table 2. The Arduino C++ source code written is available in Appendix C. A serial communication GUI was written in JavaScript to help test the device during development. The interface is shown in Figure 24.

Table 2: List of valid serial commands for the Arduino to interpret

Command	Command description
p	Ping. Return a "p" character as a serial response. Used for checking when the Arduino is ready to communicate.
e	Extend solenoids
r	Retract solenoids
a, #	Set the stepper motor acceleration to # RPM/s
P, #	Set solenoid voltage pulse period to # ms
B, #	Set BLDC throttle to # (30 is minimum, 180 is maximum)
W, #	Set BLDC wind up time to # ms
R, #	Set stepper motor speed operation speed to # RPM
M, #	Set stepper motor micro steps to #. (Match this to the micro stepping dipswitches on the stepper driver breakout board)
m, #	Move the stepper motor # degrees
d, #	Pause for # milliseconds

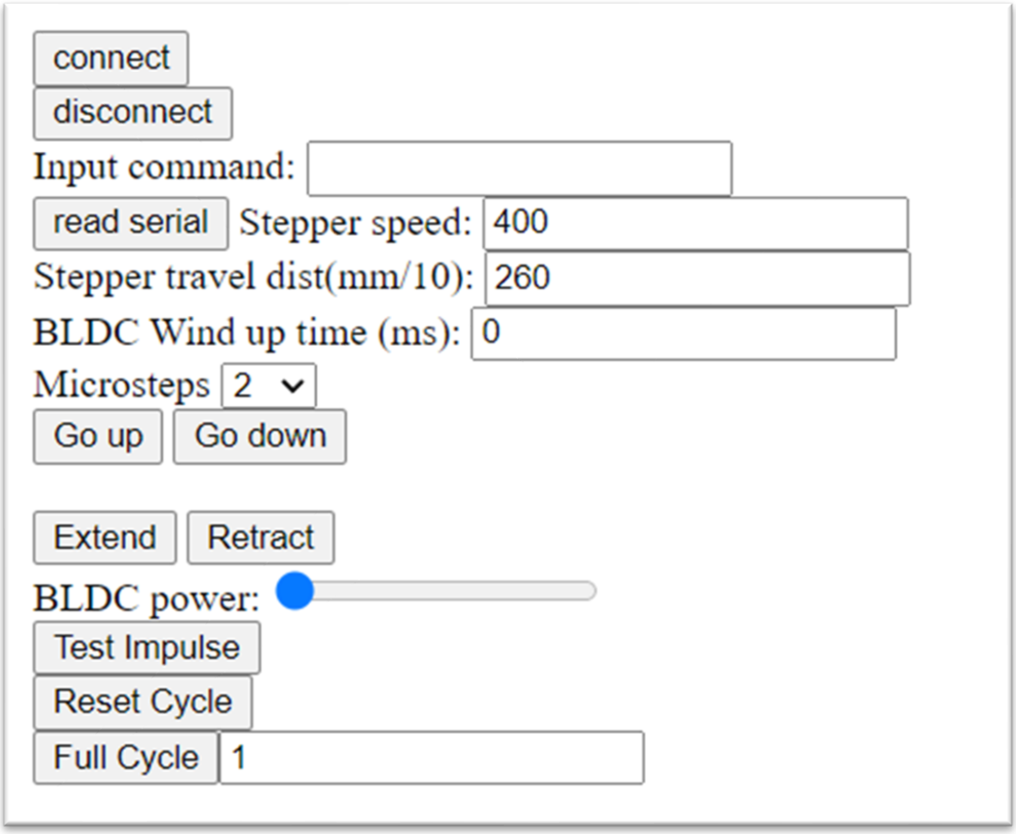


Figure 24: Graphical user interface for controlling the HFD during development

To enable use of the HFD in a VR exergame, a Vive tracking puck was affixed to the top of the device, allowing its position and orientation in to be registered and reported in real time with a SteamVR tracking system. A system diagram showing the interaction between hardware components is show in Figure 25.

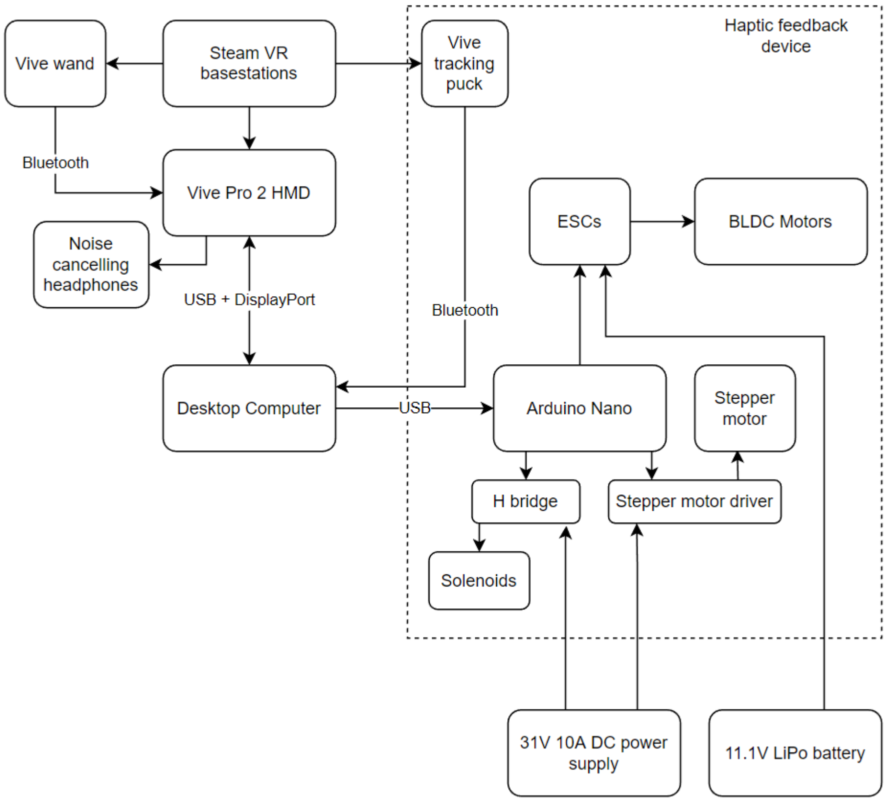


Figure 25: A system diagram of the hardware involved with the experiment

3.3 User study design

To answer research question Q1.2, a user study was designed evaluate the HFD and its effect on player presence.

To attract participants, the study was advertised digitally through both official and student supported university channels. The advertisement posted is attached as Appendix D. Participant requirements were that they had normal or corrected to normal vision, were older than 18 years of age, and had the physical capability of playing a batting sport for a short period. The user study plan was reviewed and approved by the Human Research Ethics Committee (Appendix H)

The advertisement contained a link to a booking website where participants could book a time slot to do the study. The booking website contained a link to an information sheet including more details about the study, which is included in Appendix E.

The user study was of a within-subjects design, where each participant was to play the exergame described in Section 3.4 three times, each time with the HFD in a different HFF mode. The order of modes was randomised per participant. The three HFF modes were:

- None: the device does not provide any haptic feedback during an in-game impact event beyond the passive haptics of the bat handle and weight. This is the lowest HFF mode.
- Clicking: the HFD mechanism fires during an in-game impact event, but the flywheels are not spinning so only vibratory haptic feedback is generated. This is an increased HFF mode.

- Flywheels: the HFD mechanism fires during an in-game impact event with the flywheels running, so both vibration and a torque impulse are generated. This is the highest HFF mode for this study.

After each condition, the participants were to fill out the Presence Questionnaire (PQ) [27] to record indicators of their level of presence during each condition. This questionnaire is included in Appendix I.

The procedure of the user study itself was as follows:

The study participant would come to the experiment lab and be presented with a hard copy of the information sheet in case they had not read the copy on the booking site. They were then given a brief verbal explanation of the exact tasks they would be asked to perform, and given a consent form to sign, included in Appendix F.

The user was then presented with a pre-experiment questionnaire to fill out on a computer, comprised of three demographics questions (age, gender, and previous cricket experience) and a copy of the Immersive Tendencies Questionnaire (ITQ) [27]. A copy of the pre-experiment questionnaire is included in Appendix G.

After completion of the questionnaire, the participant was equipped with a pair of noise cancelling headphones (Bose Quiet Comfort 45) to help dull the noise of the flywheels, a VR headset (HTC Vive Pro 2), and a small camera bag to hold the lithium polymer battery that powered the flywheels. They were then given the HFD to hold, and the power and signal cables connected to the device were strapped to their elbow to keep them out of the way of the user, as shown in Figure 26. When the participant was in VR, the exergame was started, and the game music was adjusted to a comfortable volume for the participant.

Figure 26: The equipment used by a user study participant during the exergame.

The participant then played one round of the exergame, where they had to hit ten balls. After the first round, the participant was presented with the PQ. The questionnaire was delivered in VR to prevent each participant from having to take off and put on the gear three times. For the questionnaire, they put the HFD down, were given a seat to sit in to reduce fatigue and were given a lightweight controller (a Vive wand) to press virtual buttons to answer the questions, as shown in Figure 27. After completion of the questionnaire, they stood back up, took hold of the HFD again, and begun the second round with a new HFF condition.

Figure 27: The equipment used by a user study participant during the PQ section

After three rounds of the exergame and PQ, the equipment was removed from the participant, and the participant was given a quick verbal interview where they answered four questions:

- Which haptic condition did you prefer the most?
- Which haptic condition did you prefer the least?
- What did you find distracting (if anything) during the exergame?
- What other comments or feedback do you have on the study?

This interview concluded the study.

3.4 Game design

As mentioned in section 3.2.1 the chosen batting sport to target was cricket, as the weight of the HFD made a two-handed batting sport more suitable. To this end, a cricket themed exergame for virtual reality was developed using the Godot game engine (v3.5rc6).

The primary purpose of the exergame in relation to this research was to provide an immersive virtual environment in which the effectiveness of the HFD on player presence could be evaluated.

The main design criteria for the exergame were:

- The game must present the player with balls to hit with a bat. The HFD is designed to simulate ball impacts, so the exergame used to evaluate it must contain ball impact events.
- The game must use the medium of virtual reality.
- The game must facilitate user feedback between gameplay rounds. Between gameplay rounds, the user must answer a questionnaire. The player will be

wearing equipment that would need to be removed and then put back on and readjusted between each round if the questionnaire were not in the virtual space.
- The game should be visually and auditorily pleasant, but also simple enough to not be too distracting or overstimulating

The designed exergame had the VE situate the user in an outdoor area on a cricket field, facing a cricket ball launcher and a target zone for them to focus on during gameplay, shown in Figure 28.

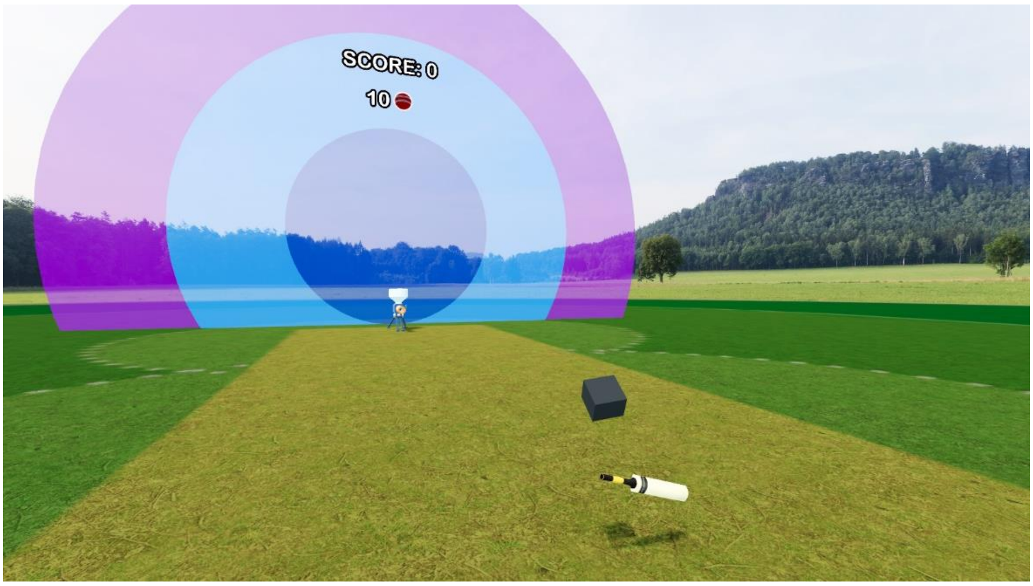


Figure 28: The cricket exergame virtual environment. The position of the player's head in the VE can be seen as the dark grey block

The spatial tracker affixed to the top of the HFD enabled player in the VE saw a virtual bat in a location consistent to the location of the haptic device they were holding in the real world, as illustrated in Figure 29.

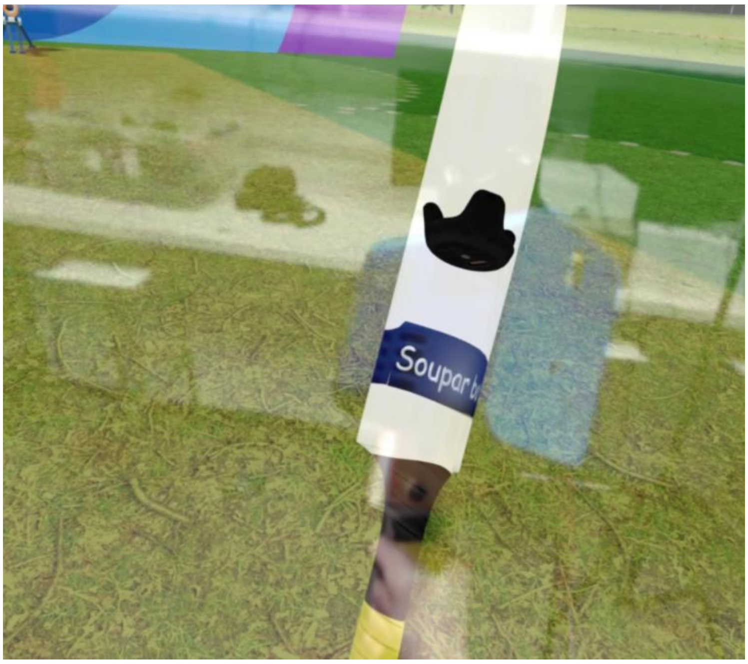


Figure 29: The VR headset's passthrough camera view overlayed onto the view of the virtual environment, showing the virtual bat and HFD occupy the same spatial position relative to the player

The player's main mode of interaction with the game was simply to swing the bat to hit balls launched from the ball launcher. During gameplay, the ball launcher launched balls towards the player every five seconds, with each launched pre-emptively telegraphed with a visual cue (shown in Figure 30) as to prepare the player for each incoming ball, and accompanied by a visual effect and audio cue at the moment of launch. The launched balls, modelled as cricket balls, had white outlines and maroon trails to aid visibility.

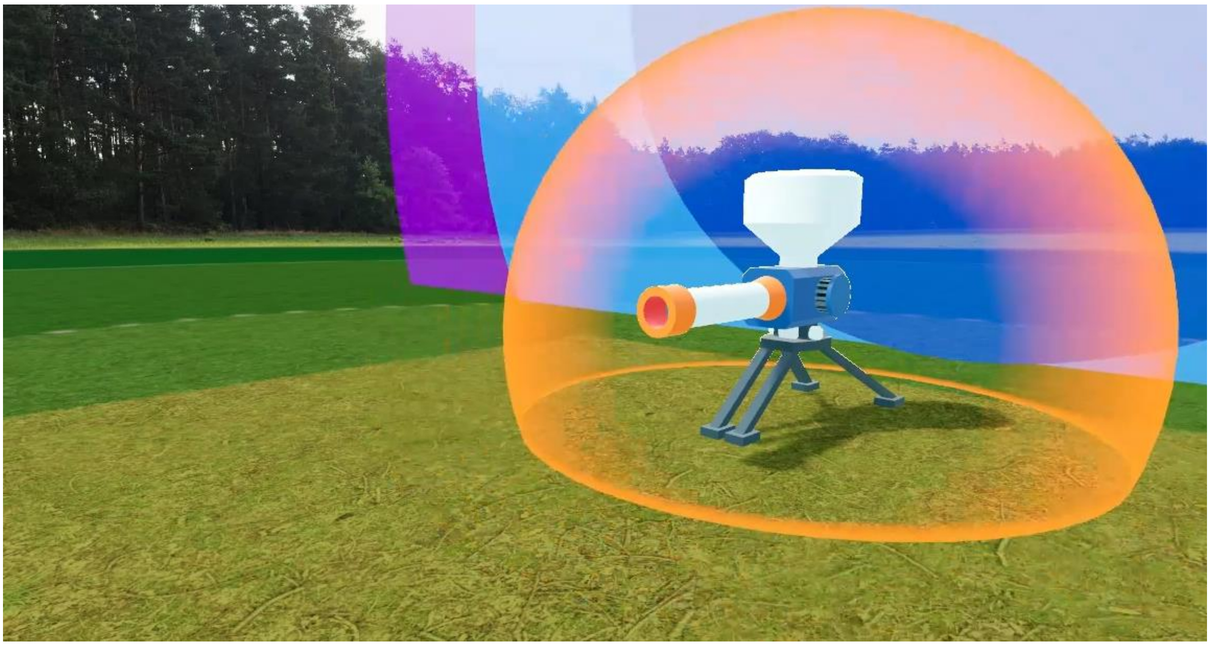


Figure 30: The ball launcher's visual launch warning

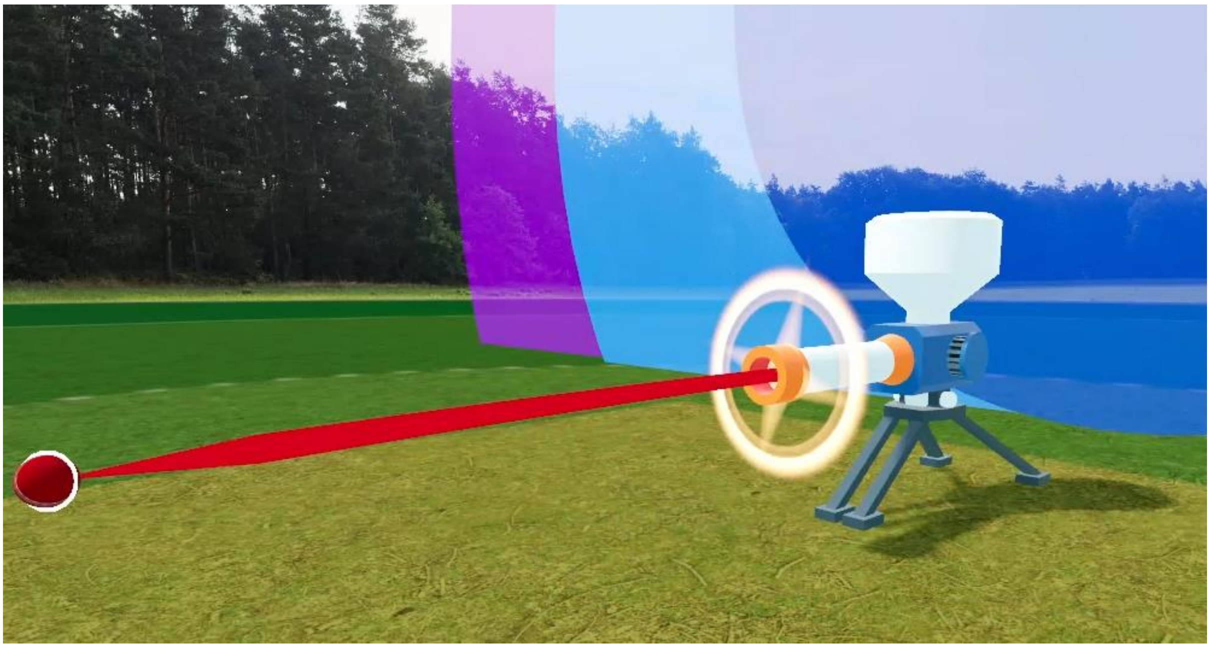


Figure 31: A ball is launched from the launcher, with an outline and trail following the ball for visibility, and a visual launch cue from the launcher

To give the player a goal to focus on during gameplay, a large target was positioned behind the ball launcher with three scoring zones to hit the ball into. A visible score counter was incremented when the player successfully hit the ball back into a score zone. Players were awarded 1-3 points, depending on how close they got the ball to the centre of the target.

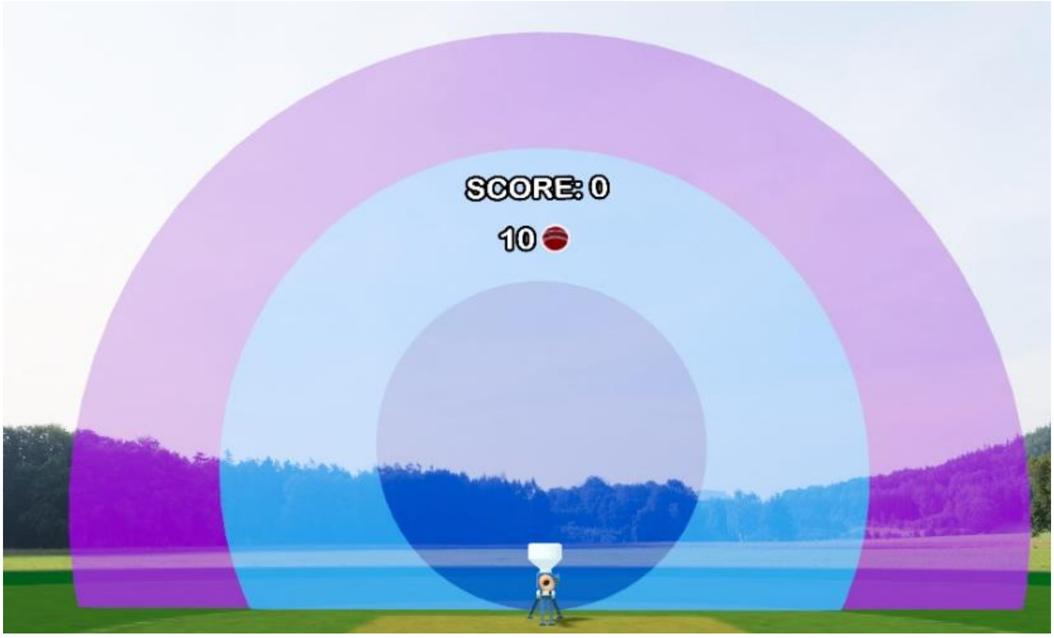


Figure 32: Scoring zones, the score indicator, and remaining ball count

When the player hit the ball, it produced a visual and audio cue, and produced an impact event to be handled by the HFD.

After one gameplay round of hitting ten balls, virtual walls would fade in around the player, and they would be presented with an array of virtual buttons to press. The player could use these to answer questions from the PQ, which would be displayed in front of them, as shown in Figure 33.

Figure 33: A player answering questions from the PQ with a Vive wand in the VE.

4 RESULTS

4.1 Questionnaire results

The user study was completed by 16 participants (5 male, 9 female, 2 other/non-binary), aged 20 to 40 years old. The age distribution is shown in **Figure 34**, and previous cricket experience of the tested population is shown in Figure 35.

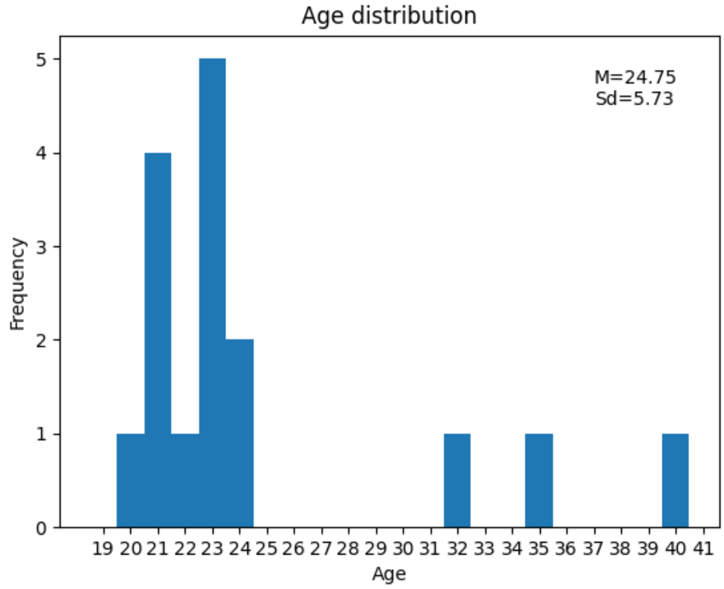


Figure 34: Age distribution of participants that completed the study.

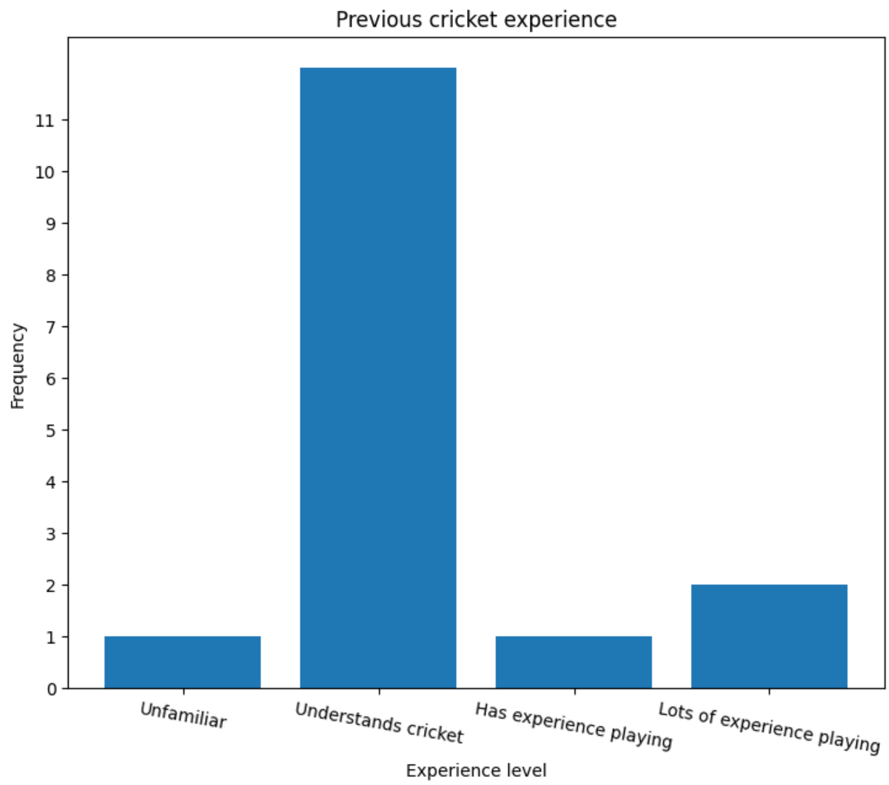


Figure 35: Previous cricket experience among participants.

The questions from the PQ were answered on a seven-point Likert scale, and the resulting score was gathered from the sum of points (with questions 19, 22, and 23 reversed scored). Results for the PQ by condition are shown in Figure 38, and results for the PQ by round number are shown in Figure 39.

A Shapiro-Wilk test was performed on the results of the PQ to check for data normality, the results for which are also in Table 3. The results of the test showed evidence for normal data distributions for the questionnaire as whole and for all subscales except interface quality.

For these normally distributed subscales, an Analysis Of Variance (ANOVA) test was conducted with $\alpha = 0.05$ to check for evidence of significant difference between the mean PQ scores of each condition.

The ANOVA test assessed the outcome of the null (H_0) and alternative (H) hypotheses:

$$H_0: \mu_N = \mu_C = \mu_F$$

H: mean PQ scores increase for higher HFF conditions

The results for the ANOVA test for each PQ subscale and for the complete PQ are shown in Table 4. All p-values are >0.05, meaning H_0 failed to be rejected for any tests, and so evidence for a statistically significant difference in presence scores between conditions was not found.

PQ subscale	Condition	Normalised mean	Standard deviation	Shapiro-Wilk test p-value
Involvement/Control	None	4.82	0.68	0.167
	Clicking	4.91	0.53	0.104
	Flywheel	5.19	0.62	0.146
Natural	None	4.75	1.46	0.249
	Clicking	5.33	1.00	0.597
	Flywheel	5.40	1.28	0.271
Auditory	None	5.35	0.83	0.443
	Clicking	5.81	0.79	0.466
	Flywheel	5.83	0.82	0.312
Haptic	None	4.44	0.96	0.195
	Clicking	4.81	0.79	0.266
	Flywheel	4.91	1.07	0.278
Resolution	None	4.97	1.55	0.211
	Clicking	4.94	1.25	0.468
	Flywheel	5.00	1.34	0.302
Interface quality	None	3.29	0.42	<0.001
	Clicking	3.40	0.46	0.002
	Flywheel	3.38	0.53	0.012
Complete PQ	None	4.67	0.54	0.133
	Clicking	4.88	0.44	0.508
	Flywheel	5.03	0.57	0.201

Table 3: PQ results across subscales and test conditions.

Subscale	ANOVA p-value
Involvement/Control	0.218
Natural	0.290
Auditory	0.180
Haptic	0.344
Resolution	0.992
Complete PQ	0.153

Table 4: ANOVA test results for each normally distributed subscale and the entire PQ.

Visually inspecting the PQ results in Figure 36 indicates that the higher HFF conditions had slightly higher scores for the Involvement/Control, Natural, Auditory, and haptic subscales, and equal scores for the Resolution and Interface Quality subscales.

Visually inspecting the PQ results in Figure 37 indicates later rounds had slightly higher scores for only the Auditory and Haptic subscales.

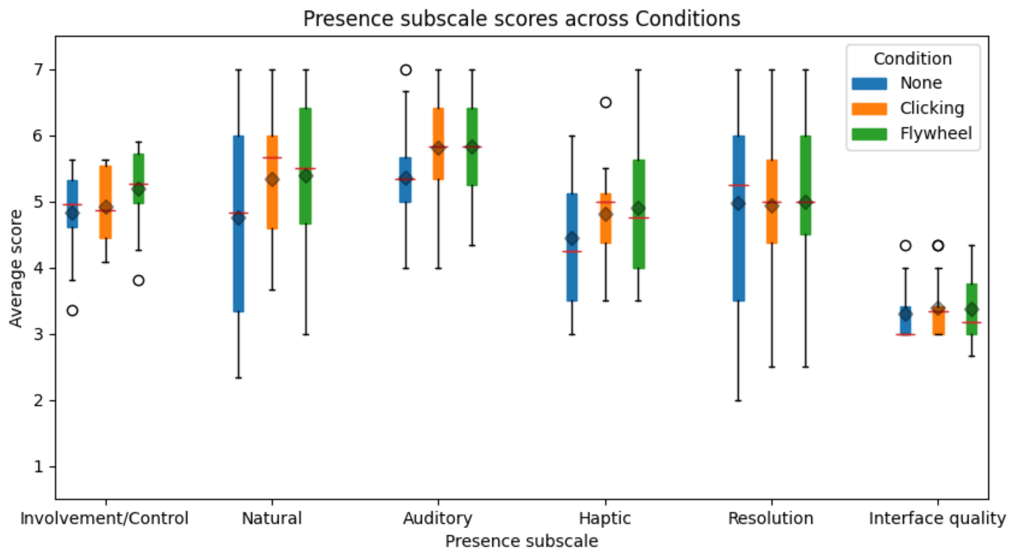


Figure 36: PQ subscale scores by HFD condition. The red line is the median subscale score, the black diamond is the mean, and the circles are statistical outliers.

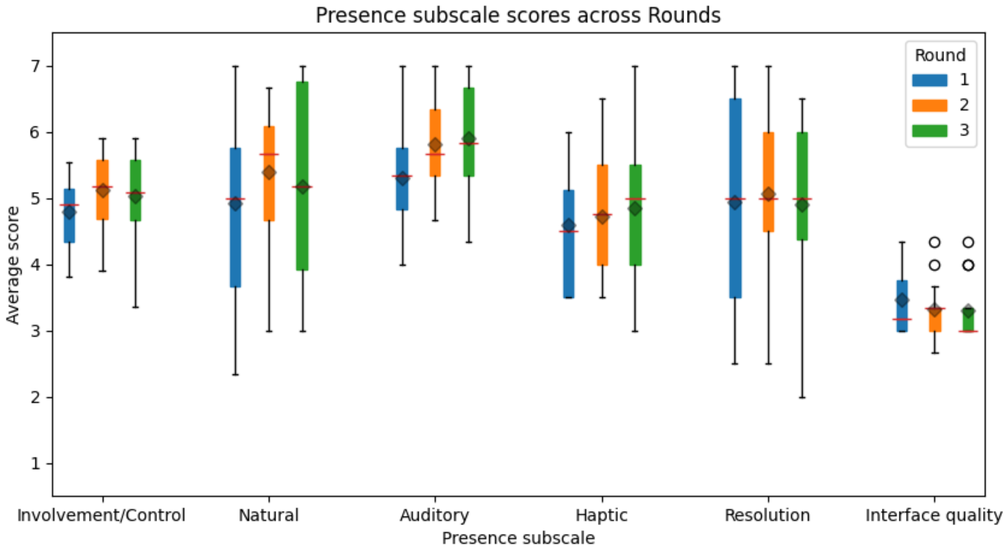


Figure 37: PQ subscale scores by round number. The red line is the median subscale score, the black diamond is the mean, and the circles are statistical outliers.

Visually inspecting the PQ results in Figure 38 indicates that the higher HFF conditions had slightly higher PQ scores overall, while Figure 39 indicates similar PQ scores for rounds 2 and 3, and a slightly lower score for round 1.

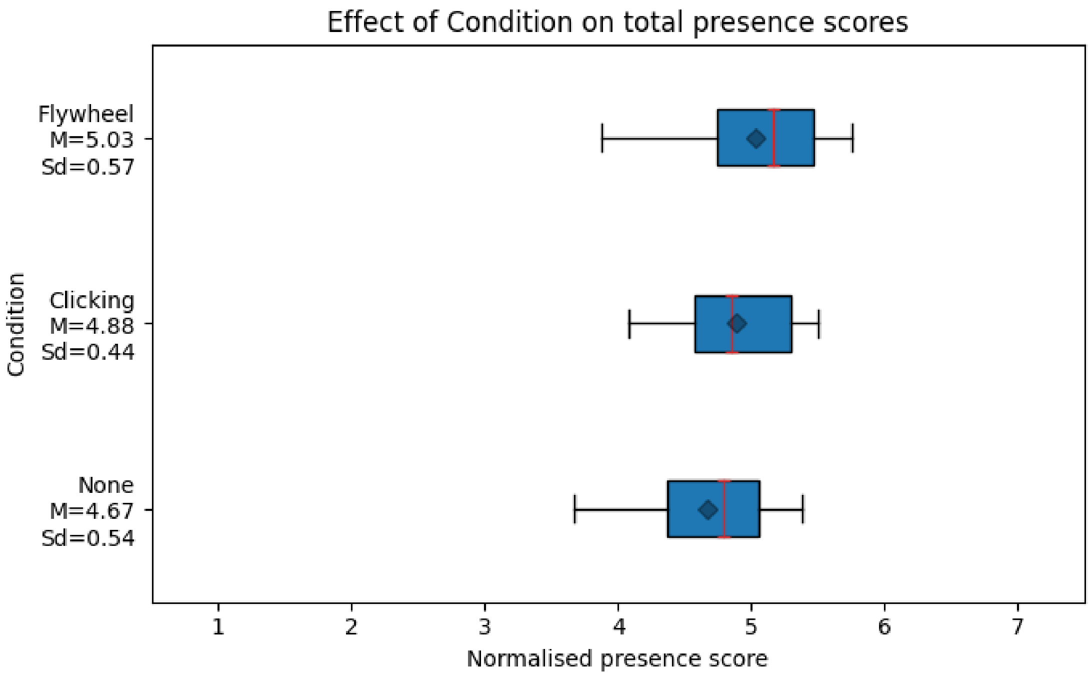


Figure 38: Presence scores by HFD condition. The red line is the median presence score, and the black diamond is the mean.

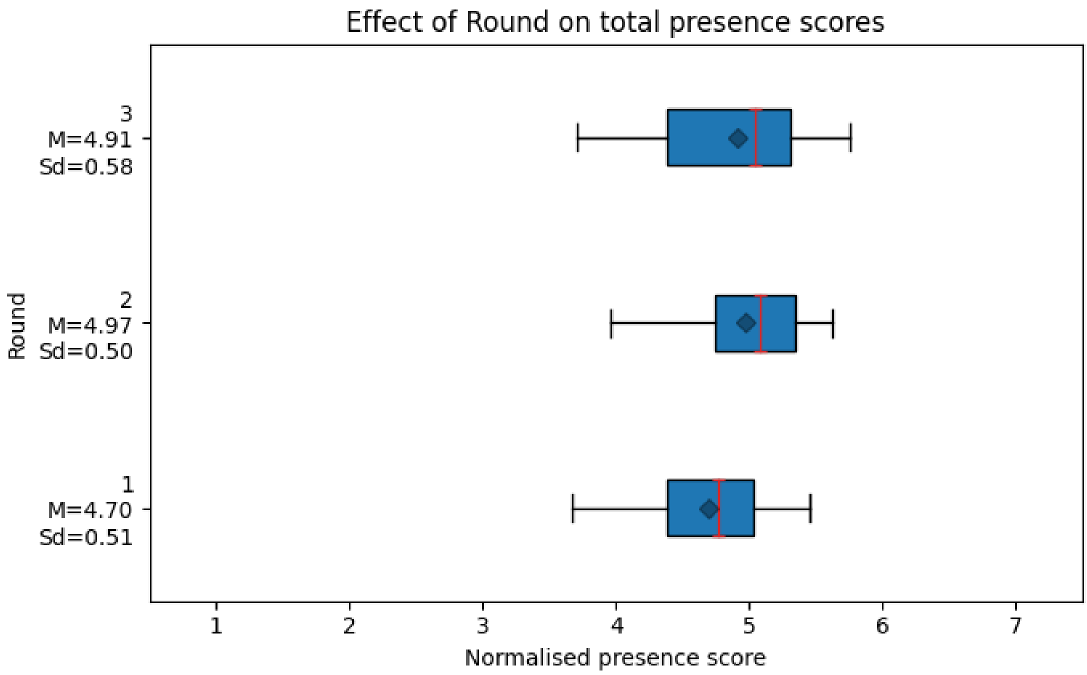


Figure 39: Presence scores by round number. The red line is the median presence score, and the black diamond is the mean.

The ITQ scores for each participant are plotted against their PQ scores in Figure 40, showing a negligible Pearson correlation coefficient of 0.125.

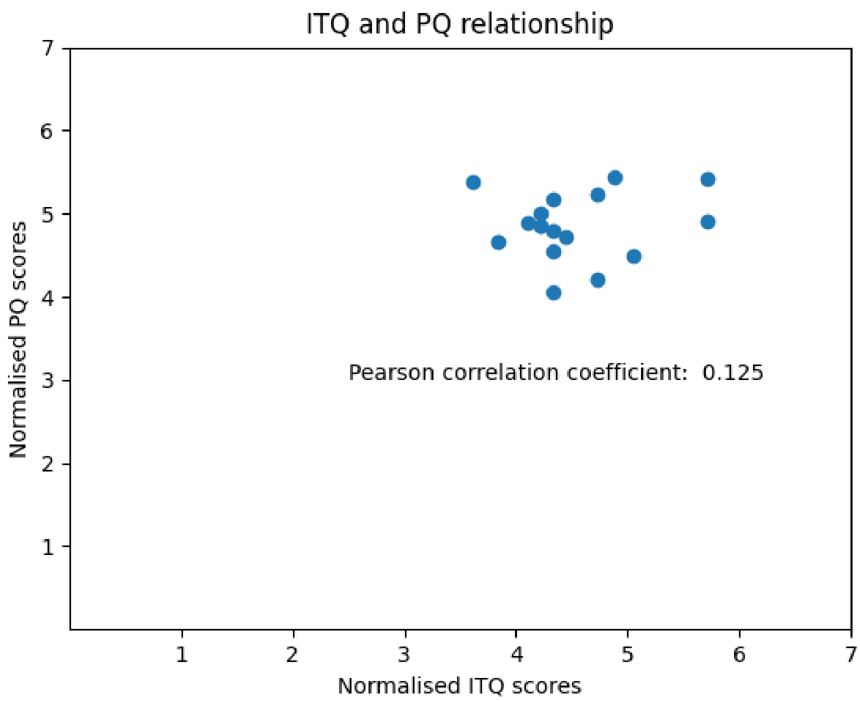


Figure 40: Normalised ITQ scores vs normalised PQ scores per participant

4.2 Exergame

In the short interview, participants were asked which condition was their favourite and which was their least favourite. The results for this question are shown in Figure 41. Results for the same question but indexed against round number are shown in Figure 42. Visually inspecting the results indicates that the condition had a much lower effect on enjoyment than how familiar the user was getting with the VE and game.

Figure 43 shows how many points the participants scored across conditions and round number (this data is only for the last 13 participants, as the scoring results for the first 3 were accidentally overwritten and lost). The results indicate that players scored significantly less points on their first round in the game, and that their scores were largely unaffected by which condition they were doing. This coincides with participant feedback, where they often cited their least favourite condition was whichever one was first, as they were still getting use to the game and control scheme. Some did not realise the function of the targeting zone until halfway through their first round.

Participants were also asked what they found distracting. The most common distraction was the weight of the bat, with four different participants citing it as a distraction, though three participants noted that the weight of the bat added to the realism. Other common distraction factors (reported by 2+ participants) included the vibration of the bat in the Flywheel condition (with one user noting that it affected the tracking quality of the bat in the VE), the power cables running to the HFD and VR headset getting in the way, the noise and persistent vibration of the HFD in the Flywheel condition, fogging up of the lenses in the VR headset, and the lack of haptic feedback in the None condition. Though some found the vibration and sound of the HFD in the Flywheel condition, many reported that they filtered it out. Some participants described preferences that they had for certain rounds because the way the virtual ball launcher was behaving, pitching the cricket balls higher, lower, or "crooked" during some rounds compared to others, despite the ball launcher behaviour not being adjusted during any of the studies. Occasionally, the HFD would occlude the tracking puck from line of sight of the tracking stations, causing the in-game bat to move erratically. This issue was corrected with posture corrections. Other reported causes for distraction included a lack of feedback when they missed the ball, light leaking into the headset, the inability to walk around the environment, and one participant cited the haptic feedback itself as a cause.

Many participants expressed that they thoroughly enjoyed the exergame, and that they would have liked to spend more time playing. During the flywheel condition, the vibration of the bat sometimes caused the game to register impacts with the ball at a much higher speed, causing the ball to launch off the bat with increased speed. On participant noted enjoying this effect. When the players hit the balls with a shallow bat angle, it would often bounce backwards off the bat, confusing the participants. This led to some suggestions of improving how the user is informed of trajectory of the ball, as the trails are only useful when the ball enters a user's line of sight.

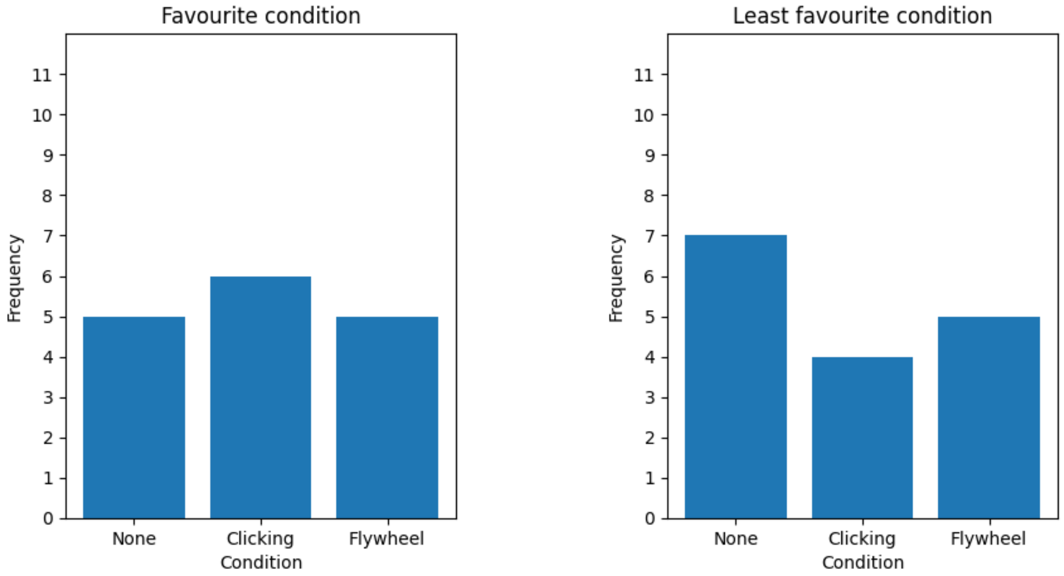


Figure 41: Frequency of each condition being described as most or least favourite.

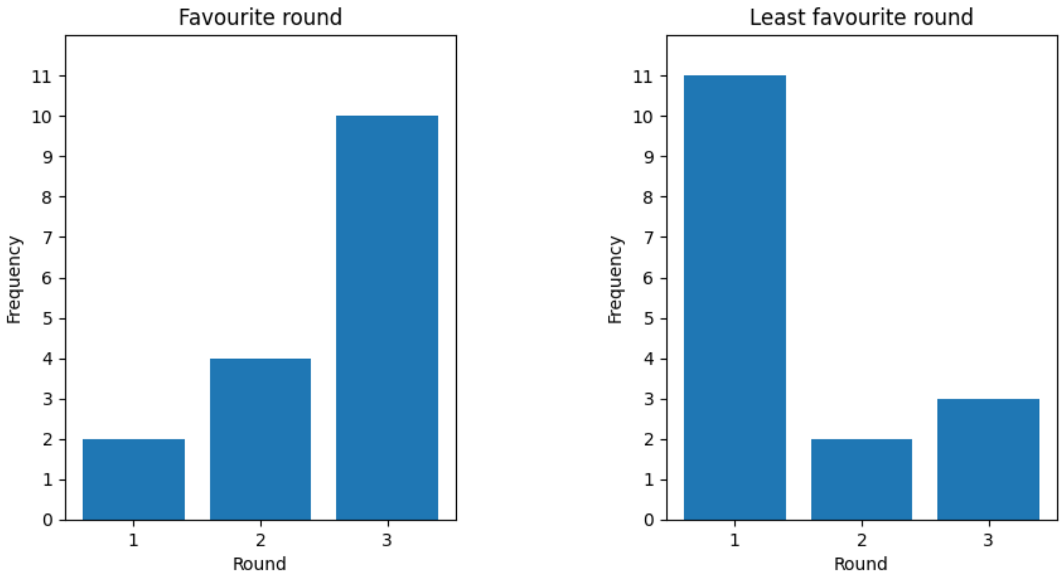


Figure 42: Frequency of each round being described as most or least favourite.

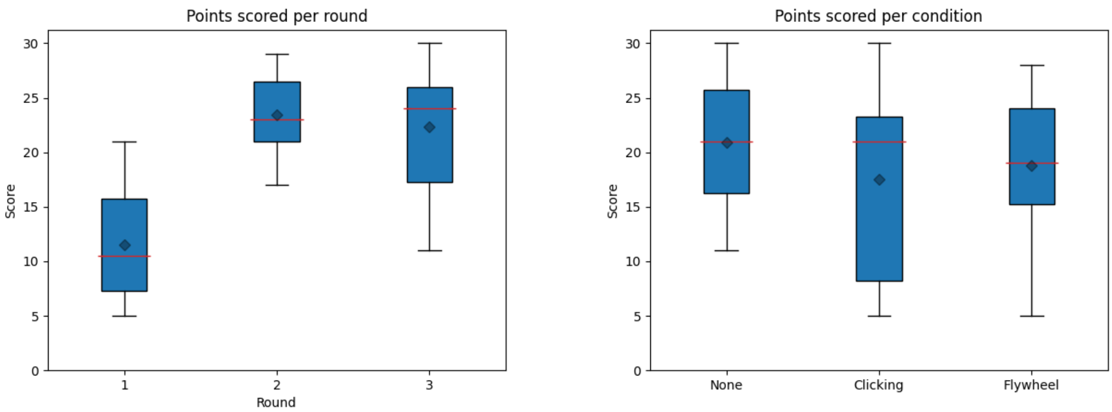


Figure 43: The points scored by the last thirteen participants by round and condition.

4.3 Device performance

Using speed measurements from the device, its torque output could be measured.

The reaction instantaneous torque for two flywheels in this configuration can be given by Equation (4)[32]

$$\tau = 2\Omega I\omega\cos(\theta) \tag{4}$$

given the tilt speed of the flywheels Ω, the rotational inertia of one of the identical flywheels I, the current tilt of the flywheels θ, and the rotational velocity of the flywheels ω. To get the average torque, Equation (4) can be integrated across the full $\frac{\pi}{2}$rad tilt:

$$\tau_{ave} = \frac{2\Omega I\omega}{\pi/2}\int_0^{\frac{\pi}{2}}\cos(\theta)\,d\theta \tag{5}$$

Which simplifies to:

$$\tau_{ave} = \frac{\Omega I\omega}{\pi} \tag{6}$$

The flywheels were measured to spin at 12,072 RPM, so $\omega = 1264\ \text{rad s}^{-1}$. The flywheels have a rotational inertia of $8.2 \times 10^{-6}\ \text{kg m}^2$ each, and the rotation action takes 25ms to rotate $\pi/2$ rad, giving a twist speed of $\Omega = 62.83\ \text{rad s}^{-1}$. Plugging these values into Equation (6) gives an average torque of

τ_{ave} =101 N mm

The total weight of the bat including shrouding and cables was 2.0kg.

The HFD was able to reload for another impulse every 2 seconds.

The device's reliability was lower than anticipated. A total of 28 participants begun the study, but only 16 of them completed the study due to technical problems with the HFD. The most common issue that interrupted the study was that one or both solenoids would stop functioning during the Flywheel and/or Clicking condition, preventing the haptic feedback mechanism from firing. When this happened, the study was ended prematurely, and the results discarded. The solenoids had two major failure modes: failure to retract when the carriage applied a shear loading force, and failure to extend. A reliable cause of failure could not be ascertained or reproduced, though was possibly due to the solenoids operating close to their operational limits failing with small environmental changes such as temperature. Some repair methods were identified and are listed in Table 5.

Fault	**Correction**
Solenoid retraction failure	Apply lubricate solenoid by applying grease to internal barrel
	Reduce spring force by swapping spring compressors for a smaller size. This method was only used during troubleshooting, and spring force remained constant between studies.
	3D-print new carriage to replace existing worn carriage
Solenoid extension failure	Manually pull solenoid plunger out and electrically retract. Repeat until solenoid operates as expected

Table 5: Identified troubleshooting and repairs guide.

Another mode of failure was that occasionally during testing, 3D-printed parts would break. They were then reprinted and replaced, sometimes with different printing parameters to increase their strength.

5 DISCUSSION

5.1 Total presence score

The results from the ANOVA test of the presence questionnaire fail to show evidence of significant differences between conditions on player presence or any single subscale of the PQ. Failure to reject the null hypothesis, is not equivalent to proving the null hypothesis, but informs us that this specific study did not provide a statistically significant difference between conditions. The ANOVA test gave a p-value of 0.153, meaning there is a 15.3% chance that there is not significant difference between presence levels. The small sample size of 16 participants was possibly the most limiting factor of the study and meant that a greater effect would be required for significance. Visual inspection of the data, however, can still provide some insights about trends that occurred.

In Figure 38, the means of presence scores increase with HFF level of the conditions they were tested on, implying the positive correlation between player presence and HFF, supporting our hypothesis.

In Figure 39, the mean player presence score is lower in round 1, and similarly greater in rounds 2 and 3. Ideally, the round number should be independent of the presence level, but here it is implied that round 1 evoked lesser feelings of presence in the VE. This coincides with round 1 being commonly rated as the least enjoyed round (Figure 42) by participants, and the feedback that some provided about spending the first round getting used to the game. It is likely that the perceived reduction in presence was due to the participants acclimating to the environment and equipment. This variation in presence over round numbers could have possibly been reduced by having participants play a training section before the first round, to allow them to get used to the game and bat. The lower game scores (Figure 43) in the first round reinforces this idea that the participants would have benefited from a practice round.

Figure 40 shows that there was no significant correlation between the ITQ scores and PQ scores, a result which is not unheard of when comparing the ITQ with a single experiment [27]. Otherwise, there are no trends of note in the distributions of scores in this plot.

5.2 Subscales

Trends from visual analysis of Figure 38 and Figure 39:

5.2.1 Involvement/Control

The involvement and control subscale mean score was similar for the None and Clicking conditions, but slightly higher for the Flywheel condition. This is possibly due to the extra impact effect noted in section 4.2, where the ball would launch off the bat with extra speed, making the participant feel like they got a good hit.

When comparing the subscale mean scores to round number, the score is lower for round one, and then higher for both rounds 2 and 3 by a similar amount. This is likely due to round 1 being the participants' first experience in the game, and so they would take some time figuring out the right feel and technique for controlling the response of the ball how they wanted.

5.2.2 Natural

The natural subscale mean scores were higher for the Clicking and Flywheel conditions compared to the None condition, implying that participants found the haptic feedback condition more realistic than no haptic feedback, but they did not find the Flywheel condition more natural than just the clicking condition. This is possibly due to the passive vibrations and noise the HFD made in the Flywheel condition.

The Natural subscale mean score was slightly lower for round 1, and higher for round 2. Round 3 had a mean score between the other two, but also had a larger variance, as shown by the larger interquartile range.

5.2.3 Auditory

The auditory subscale mean scores were higher for the Clicking and Flywheel conditions than the None condition. The HFD produced an impact noise when triggered, audible even through the noise cancelling headphones, and this could explain the increased score for the two conditions that did produce this sound. Interestingly, the mean scores for Clicking and Flywheel conditions were similar, indicating that the loud flywheel noise did not impact the auditory experience. This coincides with reports of filtering out the flywheel noise, with aid from the noise cancelling headphones and in game music.

Following the trend general trend, the scores were lower for round 1 compared to rounds 2 and 3.

5.2.4 Haptic

The haptic subscale mean scores were lower for the None condition, higher for the Clicking condition, and slightly higher still for the Flywheel condition. This general trend is expected, as this is the order of HFF. The smaller difference between the Clicking and Flywheel conditions implies that the vibrations caused by the spring-loaded mechanism has a greater impact on the haptic experience than the torque produced by the flywheels though the combination of both stimuli was still more effective than just the vibration. The torque produced was only 100 N mm, so it was possible that the vibrations also helped conceal the effects of the torque

Following the trend general trend, the scores were lower for round 1 compared to rounds 2 and 3, though round 3 had a higher

5.2.5 Resolution

The resolution subscale mean scores were nearly identical across conditions. This is the expected outcome given that this subscale relates to visual phenomena, which were entirely unchanged by different conditions. The scores are also very similar across round number.

5.3 Device discussion

The HFD had a limited reliability, mostly in solenoid operation. The reliability limitation directly affected the quality of the study by significantly reducing the usable data set sample size. Though not all causes of failure were identified, it might be possible to address the excessive shear loading on the solenoids with a lever design, as illustrated in Figure 44. Alternatively, a different release mechanism could be used that relied on a different actuator such as a servo motor.

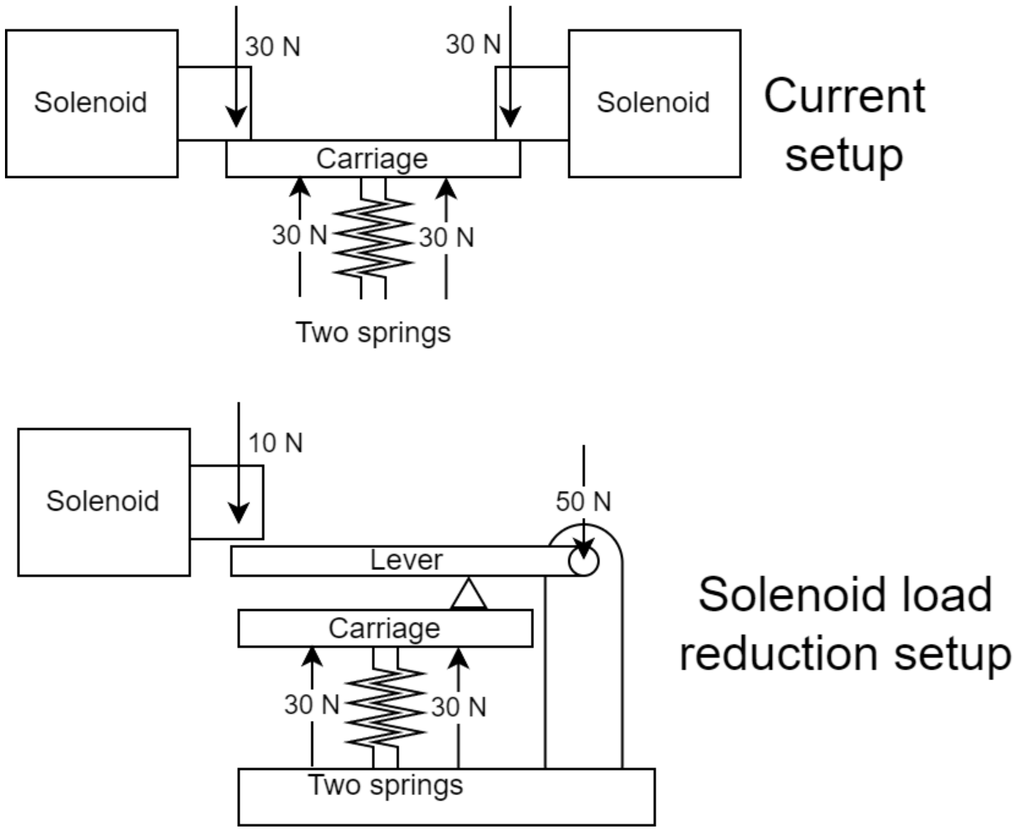


Figure 44: An alternative quick release mechanism to reduce solenoid load.

Some study participants noted the HFD would vibrate during the Flywheel condition, which were likely caused by small eccentricities in the flywheel assembly, whether it be in the flywheel disks themselves, the motors driving them, or join between the two. This vibration was not included by design, though some study participants felt it had a positive effect on their enjoyment. One participant noted that the vibration made the impulses less startling, as the vibration was already providing them with some base-level haptic stimulus, while they found the clicking condition more startling.

The device's total output torque was 101 N mm, just five times greater than the minimum perceivable torque in the human hand of 20 N mm [32]. For comparison, a tennis ball travelling at 180kmph (a standard serving speed in professional tennis games) impacting a tennis racket can produce a torque on the hand of 5,000 to 20,000 N mm. [54]. The torque impulse could be increased by increasing flywheel inertia (by making it heavier or increasing its radius) or using a higher speed motor.

Though the HFD's cables were tied up to prevent a tripping hazard, some participants noted that they could still feel the cables when they swung the HFD, and that caused them to restrain their actions in fear of accidentally pulling a cable out by tugging on it too hard. There were 3 sets of cables running to the HFD: one pair of 12.6V DC cables connected to the battery in the camera bag the participant wore, one pair of 31V DC cables running to a benchtop power supply, and one USB cable running to the PC running the exergame. The USB cable could be removed by replacing the wired serial communication method relying on it with a wireless communication method. The Vive tracking puck on top of the HFD has wireless communication capability via the output pin on its underside intended to provide a vibration signal to custom built VR peripherals. Additionally, the 31V DC cable and benchtop power supply could be replaced with a voltage boost circuit connected to the battery pack, thereby converting the HFD to a device completely untethered to any external connections.

6 CONCLUSION

A haptic feedback device for simulating batting sport haptics was designed using the resultant gyroscopic effect from rapidly reorienting spinning flywheels and integrated into a cricket themed virtual reality exergame. The device was capable of producing impact vibrations and a 0.1 N m torque on demand. A within-subjects user study conducted on 16 participants, and player presence was evaluated using the Presence Questionnaire. The results of the user study were statistically insignificant due to a small sample size (p=0.153), and we were unable to reject the null hypothesis, but visual data analysis was used to identify trends that supported our hypothesis that increase HFF increases presence in VR batting sports exergames. Due to the statistical insignificance of these results, further research should be conducted to confirm these findings.

The following research questions were answered:

Q1 – How can a device capable of simulating different levels of haptic feedback be designed for virtual reality batting sports?

A device was designed by considering haptic feedback devices from previous research and compiling the strengths and weaknesses of each mechanism. A design criterion was formulated for batting sports haptic simulation, with the following requirements:

- Fast impulse generation.
- Kinaesthetic haptic feedback
- Unidirectional impulse generation.
- Passive haptic realism.
- Mobility.

This criterion was used to assess the compiled haptic feedback mechanisms and devise which one(s) to implement.

Q1.1 – What are different levels of haptic feedback for virtual reality batting sports?

Different levels of HFF identified were: No feedback, tactile vibratory feedback, and kinaesthetic torque feedback combined with vibratory feedback.

Q1.2 – How do different do different levels of haptic feedback affect player presence in virtual reality batting sports?

Higher HFF levels may have a positive effect on player presence, but the limitations of this study render the results inconclusive.

6.1 Future work

The haptic device developed weighed 2.0kg and was found to be cumbersome for some users and effectiveness of the device was also rather small, with a torque output of just 0.1Nm. Further research might focus on improvement of the haptic device design presented in this research, and develop a smaller, lighter, more effective, or more reliable version. The device could be modified to be untethered, as described in section 5.3. If so, it would be interesting to see its use in a more mobile exergame such as tennis.

In this research, several haptic feedback mechanisms from different applications were investigated, but only one mechanism (control moment gyroscope) was used. A potential avenue for future research would be to compare these different mechanisms (or combinations of them) directly for a single exergame.

The limitations of insufficient sample size, low device reliability, and insufficient opportunity for users to acclimate to the virtual environment could also be addressed in future research.

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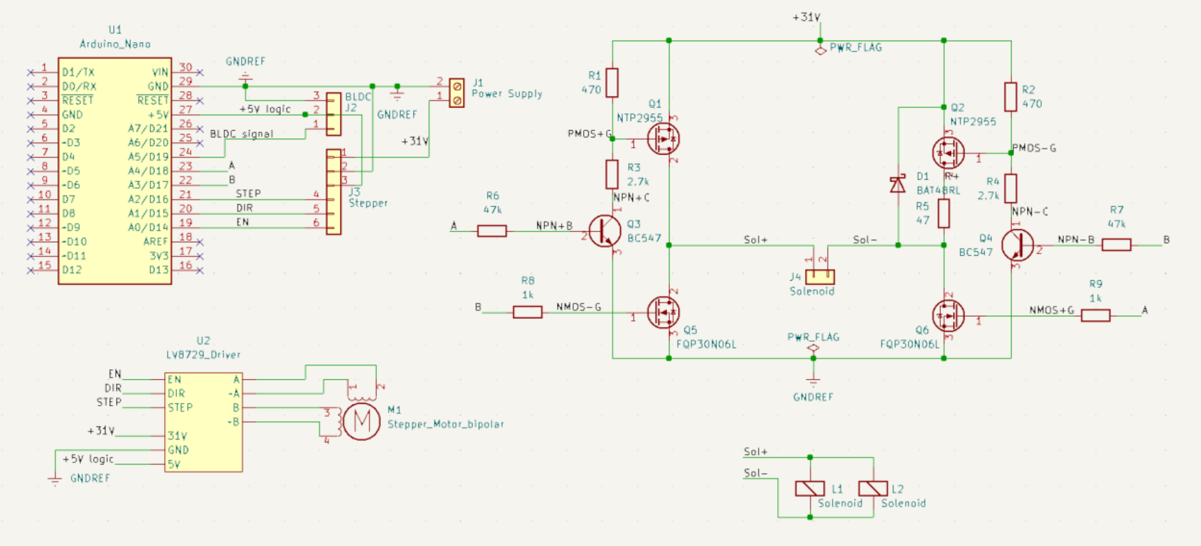
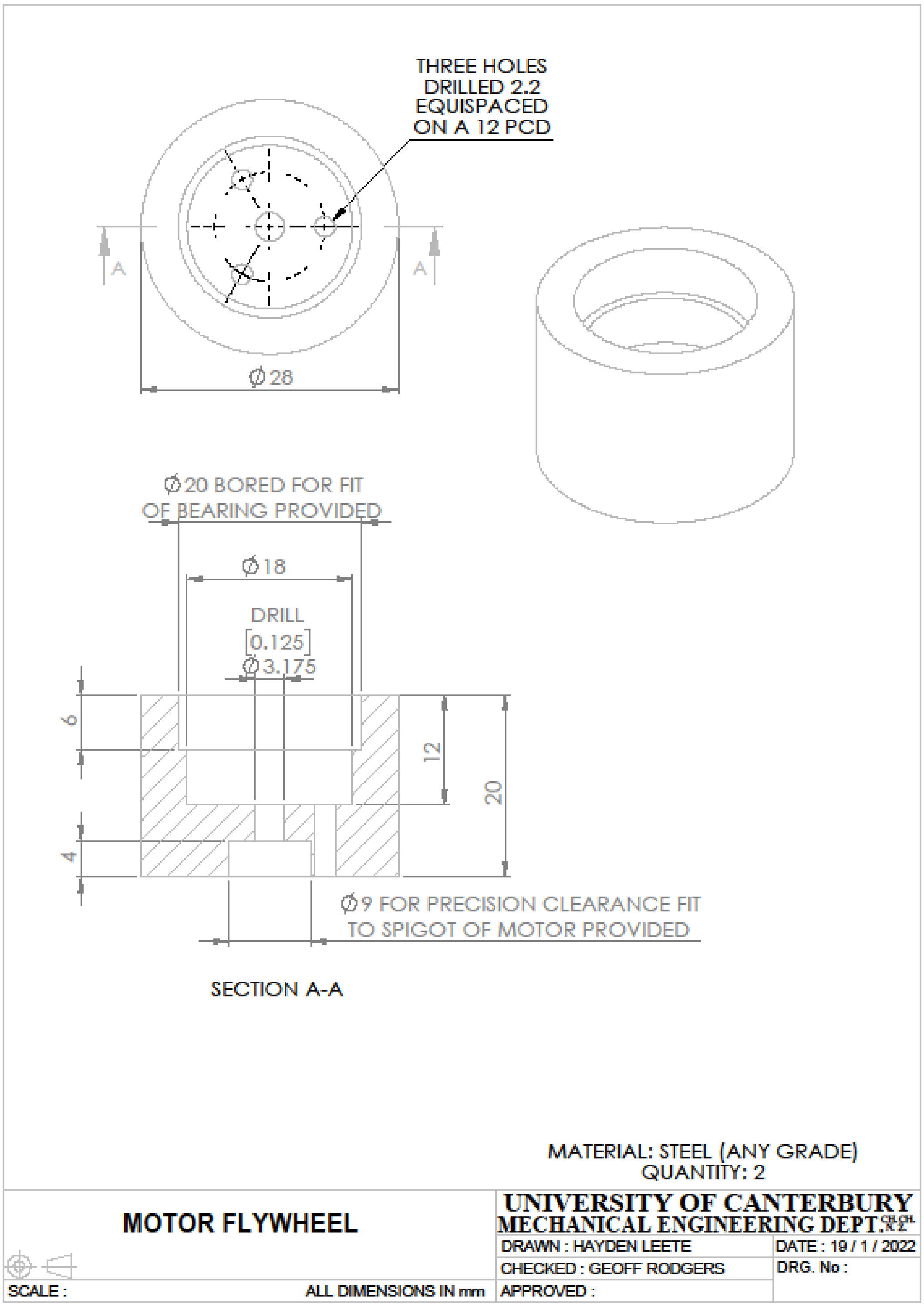
APPENDICES

Appendix A



Electronic schematic for control circuit

Appendix B



Flywheel Dimensions

Appendix C

Communication code running on the Arduino Nano

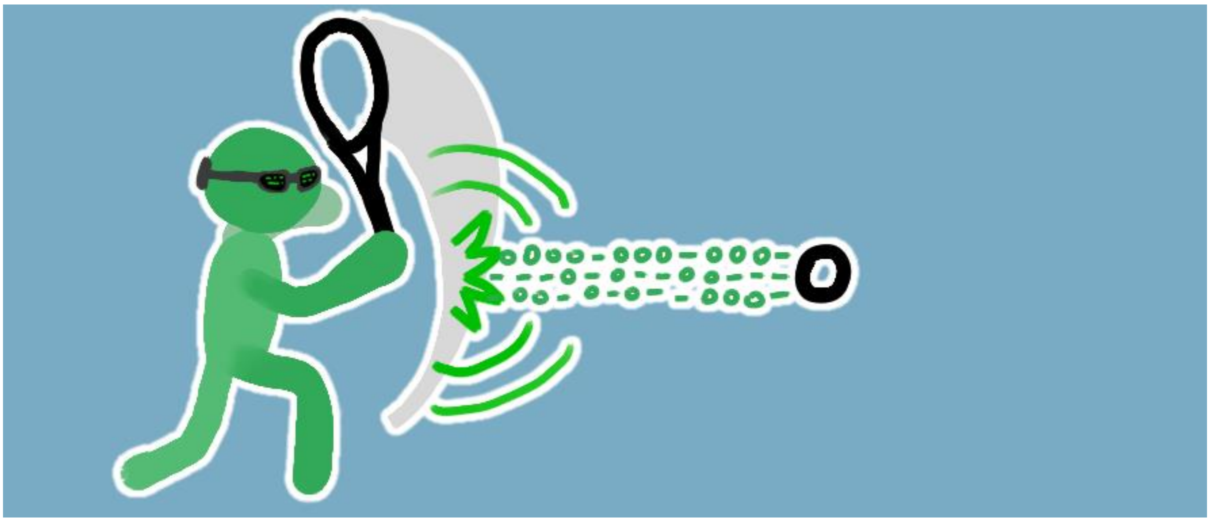
```
#include <Servo.h>
#include "BasicStepperDriver.h"

long delay_end = 0;

//////// Stepper Motor params ////////
int microsteps = 1;
int rpm = 300;
int spr = 200; // steps per revolution
int dst = 250; // stepper travel dist
int acceleration = 0;
const int step_pin = 16;
const int dir_pin = 15;
const int en_pin = 14;
BasicStepperDriver stepper(spr, dir_pin, step_pin, en_pin);

//////// Solenoid params ////////
const int retract_pin = 18;
const int extend_pin = 17;
int pulse_time = 150;

//////// ESC params ////////
const int esc_pin = 19;
int esc_wind_up_time = 2000;
long esc_wind_up_start = 0;
long esc_wind_up_end = 0;
int esc_target_val;
int esc_prev_val;
long esc_last_poll = 0;
long esc_poll_period = 50;

Servo esc;

void setup() {
  Serial.begin(9600);
  pinMode(LED_BUILTIN, OUTPUT);

  stepper.begin(rpm, microsteps);
  stepper.setEnableActiveState(LOW);
  stepper.disable();

  pinMode(retract_pin, OUTPUT);
  pinMode(extend_pin, OUTPUT);

  esc.attach(19);
  esc.write(0);
  delay(2000);
  esc.write(30);
}

void loop() {
  unsigned wait_time_micros = stepper.nextAction();
  if (wait_time_micros <= 0) {
      stepper.disable();
  }
```

```
  if (esc_wind_up_start){
    if ((millis() - esc_last_poll) >= esc_poll_period){
      esc_last_poll = millis();
      long t = ((millis() - esc_wind_up_start)*1000)/esc_wind_up_time;
      t = min(t, 1000);
      esc.write(esc_prev_val + t*(esc_target_val - esc_prev_val)/1000);
      if (t == 1000){
        esc_wind_up_start = 0;
      }
    }
  }
}

void pulsePin(int pin, int duration){
  digitalWrite(LED_BUILTIN, HIGH);
  digitalWrite(pin, HIGH);
  delay(duration);
  digitalWrite(LED_BUILTIN, LOW);
  digitalWrite(pin, LOW);
}

void serialEvent() {
  switch (Serial.read()) {
    case 'P': //ping
      Serial.println("P");//pong

    case 'a': //set acceleration
      acceleration = Serial.parseInt();
      if (acceleration == 0){
        stepper.setSpeedProfile(stepper.CONSTANT_SPEED);
      } else {
        stepper.setSpeedProfile(stepper.LINEAR_SPEED,         acceleration,
acceleration);
      }
      break;
    case 'e': // extend
      pulsePin(extend_pin, pulse_time);
      break;
    case 'r': // retract
      pulsePin(retract_pin, pulse_time);
      break;
    case 'p': // pulse time adjust
      pulse_time = Serial.parseInt();
      break;
    case 'b': // bldc motor run
      esc_target_val = Serial.parseInt();
      esc_prev_val = esc.read();
      esc_wind_up_start = millis();
      esc_wind_up_end = esc_wind_up_start + esc_wind_up_time;
      break;
    case 'w':
      esc_wind_up_time = Serial.parseInt();
      break;
    case 'R': // stepper RPM adjust
      stepper.setRPM(Serial.parseInt());
      break;
    case 'M': // Microstep adjust
      stepper.setMicrostep(Serial.parseInt());
```

```
      break;
    case 'm': // move stepper (in degrees)
      stepper.enable();
      stepper.startRotate(Serial.parseInt());
      break;
    case 'd':
      delay_end = millis() + Serial.parseInt();
      break;
  }
}
```

Appendix D
User study advertisement

Participants needed
for user study on haptic (force feedback) game controller in Virtual Reality (VR) racket sport simulation



We are looking for volunteers to participate in a study on realistically simulating ball-on-racket impacts in virtual reality.

If you choose to participate, you will be asked to:

- Wear a virtual reality headset.
- Play some simulated racket sports using an experimental motion controller that physically reacts to events in the simulation.
- Complete an anonymous questionnaire and provide some verbal feedback on the simulated racket sports and your impression of the controller feedback.

The expected duration of the study is approximately 45-60 minutes, and take place in the HIT Lab, 2nd floor, John Britten building.

- A $20 voucher will be given at the end of the study.
- This study has been reviewed and approved by the UC Human Research Ethics Committee.

- Equipment shared across experiments will be sanitised and all procedures will conform to relevant covid restrictions.

For more details, or to participate in the study, please book from the QR code or the following link:
https://bookwhen.com/haydenleeteuc

If you require more information or have any questions, please contact the lead researcher Hayden, at Hayden.Leete@pg.canterbury.ac.nz

Appendix E

User study information sheet

Human Interface Technology Lab
Phone: *+64 3 369 0219*
Email: *hayden.leete@pg.canterbury.ac.nz*
12/05/2022
HREC Ref: *HEC 2021/99/LR*

Simulating racket sport haptics for exergames
Information Sheet for participants

Kia ora,

You are invited to participate in a research study on realistic haptic feedback in exergames. Haptic feedback is defined as the degree of realism with which a stimulus such as force feedback or vibration is generated by some mechanical means to simulate the sensation of touching something. This study is being conducted by Hayden Leete from the University of Canterbury l Te Whare Wānanga o Waitaha (UC). Other research team members include Stephan Lukosch and Geoff Rodgers. The study is being carried out as a requirement for the Masters of Human Interface Technology.

What is the purpose of this research?
This research aims to investigate the use of more realistic haptic simulation in exergames (games that incorporate exercise). I am interested in finding out about the effect of haptic simulation fidelity (the presence of vibrations or small impulses during a game) on player presence in the virtual environment. The information from this study will help to advise the design of future exergames and provide designers and researchers with tools to consider for better controlling player presence.

Why have you received this invitation?
You are invited to participate in this research because you have responded to a request for participants.
Your participation is voluntary (your choice). If you decide not to participate, there are no consequences. Your decision will not affect your relationship (if any) with me, the University of Canterbury, or any member of the research team.

What is involved in participating?
If you choose to take part in this research, you will be asked to wear a head mounted virtual reality headset and play a few rounds of a simulated racket sport in extended reality using a custom motion controller with force feedback for about 5 - 10 minutes. You will then be asked to fill out a survey about the experience. The motion controller force feedback will be modified, and you will be asked to play a few more rounds and fill out the survey again for the modified controller experience. Finally, you will be asked some questions about the game and controller in an informal interview. You may be audio recorded during the interview segment of the study for future review. I estimate

that your total participation in all these steps will take around 45 to 60 minutes.

Are there any potential benefits from taking part in this research?
At the conclusion of the study, I will provide you with a $20 Westfield voucher. You will get this inducement even if you withdraw from the study.

Are there any potential risks involved in this research?
The motion controller contains moving parts that have been shrouded to prevent pinch hazards or entanglement. The electrical components of the motion controller are isolated from the body and all external surfaces are made of an insulation/non-conductive material. Some users of virtual reality headsets can experience motion sickness, though the risk of motion sickness for this study is anticipated to be low, the study may be stopped at any time if you are feeling unwell.

What if you change your mind during or after the study?
You are free to withdraw at any time up until data analysis begins in August 2022. Beyond this time, it will become increasingly difficult to remove the influence of your data on the overall results and conclusions of the study.

What will happen to the information you provide?
All data will be confidential. To ensure your identity is not known to anyone outside the research team, we will keep your signed consent form in files separate from your observation results. Your identity will not be shared with anyone outside the research team. I will store all study data and recordings in password-protected files on the University of Canterbury computer network or in lockable cabinets in lockable offices.
All data will be destroyed five years after completion of the study. I will be responsible for making sure that only members of the research team use your data for the purposes mentioned in this information sheet.

Will the results of the study be published?
The results of this research will be published in a Master's thesis. This thesis will be available to the general public through the UC library. Results may be published in peer-reviewed, academic journals. Results will also be presented during conferences or seminars to wider professional and academic communities. You will not be identifiable in any publication. A summary of results will be sent to all participants who request a copy of these on the Consent Form.

Who can you contact if you have any questions or concerns?If you have any questions about the research, please contact the lead researcher Hayden at Hayden.Leete@pg.canterbury.ac.nz. If you have any concerns, you can contact the project supervisor Stephan at Stephan.Lukosch@canterbury.ac.nz

This study has been reviewed and approved by the University of Canterbury Human Research Ethics Committee (HREC). If you have concerns or complaints about this research, please contact the Chair of the HREC at human-ethics@canterbury.ac.nz).

What happens next?
Please review the consent form. If you would like to participate, please sign and return the consent form to the researcher.

Appendix F
User study consent form

Human Interface Technology Lab
Phone: *+64 3 369 0219*
Email: *hayden.leete@pg.canterbury.ac.nz*
14/10/2021
HREC Ref: *HEC 2021/99/LR*

Simulating racket sport haptics for exergames
Consent Form for Participants

- ☐ I have been given a full explanation of this project and have had the opportunity to ask questions.
- ☐ I understand what is required of me if I agree to take part in the research.
- ☐ I understand that participation is voluntary and I may withdraw at any time up until data analysis begins in August 2022, without consequences. Withdrawal of participation will also include the withdrawal of any information I have provided should this remain possible.
- ☐ I understand that any information or opinions I provide will be kept confidential to the researcher. I understand that any published or reported results will not identify me.
- ☐ I understand that a thesis is a public document and will be available through the UC Library.
- ☐ I understand that all data collected for the study will be kept in locked and secure facilities and/or in password protected electronic form. I understand the data will be destroyed after five years.
- ☐ I understand the risks associated with taking part and how they will be managed.
- ☐ I agree to being audio recorded. I understand how this recording will be stored and used.
- ☐ I understand that I can contact the researcher Hayden Leete at Hayden.leete@pg.canterbury.ac.nz or supervisor Stephan Lukosch at stephan.lukosch@canterbury.ac.nz for further information. If I have any complaints, I can contact the Chair of the University of Canterbury Human Research Ethics Committee, Private Bag 4800, Christchurch, (email: human-ethics@canterbury.ac.nz).
- ☐ I would like a summary of the results of the project (please provide an email address below).
- ☐ By signing below, I agree to participate in this research project.

Name:______________________________Signed:____________________________Date: ____________________________________

Email address *(for report of findings, if applicable)*:

____

Return this form to the researcher after signing

Appendix G

Pre study questionnaire

Start of Block: Block 1

Participant ID Participant ID (Ask the researcher to fill in this field)

____

End of Block: Block 1

Start of Block: Demographics

Q1 What is your age?

____

Q2 What is your gender?

Male Female Other / non-binary Prefer not to say

Q3 How familiar are you with cricket?

- Unfamiliar
- I understand cricket
- I have some experience playing cricket
- I have a lot of experience playing cricket

End of Block: Demographics

Start of Block: ITQ

Q4 Do you easily become deeply involved in movies or tv dramas?

Never (1) (2) (3) Occasionally (4) (5) (6) Often (7)

Q5 Do you ever become so involved in a television program or book that people have problems getting your attention?

Never (1) (2) (3) Occasionally (4) (5) (6) Often (7)

Q6 How mentally alert do you feel at the present time?

Not alert (1) (2) (3) Moderately (4) (5) (6) Fully Alert (7)

Q7 Do you ever become so involved in a movie that you are not aware of things happening around you?

Never (1) (2) (3) Occasionally (4) (5) (6) Often (7)

Q8 How frequently do you find yourself closely identifying with the characters in a story line?

Never (1) (2) (3) Occasionally (4) (5) (6) Often (7)

Q9 Do you ever become so involved in a video game that it is as if you are inside the game rather than moving a joystick and watching the screen?

Never (1) (2) (3) Occasionally (4) (5) (6) Often (7)

Q10 How physically fit do you feel today?

Not fit (1) (2) (3) Moderately Fit (4) (5) (6) Extremely fit (7)

Q11 How good are you at blocking out external distractions when you are involved in something?

Not very good (1) (2) (3) Somewhat good (4) (5) (6) Very good (7)

Q12 When watching sports, do you ever become so involved in the game that you react as if you were one of the players?

Never (1) (2) (3) Occasionally (4) (5) (6) Often (7)

Q13 Do you ever become so involved in a daydream that you are not aware of things happening around you?

Never (1) (2) (3) Occasionally (4) (5) (6) Often (7)

Q14 Do you ever have dreams that are so real that you feel disoriented when you awake?

Never (1) (2) (3) Occasionally (4) (5) (6) Often (7)

Q15 When playing sports, do you become so involved in the game that you lose track of time?

Never (1) (2) (3) Occasionally (4) (5) (6) Often (7)

Q16 How well do you concentrate on enjoyable activities?

Not at all (1) (8) (2) Moderately well (3) (4) (5) Very well (6)

Q17 How often do you play arcade or video games?

(OFTEN should be taken to mean every day or every two days, on average.) Never (1) (2) (3) Occasionally (4) (5) (6) Often (7)

Q18 Have you ever gotten excited during a chase or fight scene on TV or in the movies?

Never (1) (2) (3) Occasionally (4) (5) (6) Often (7)

Q19 Have you ever gotten scared by something happening on a TV show or in a movie?

Never (1) (2) (3) Occasionally (4) (5) (6) Often (7)

Q20 Have you ever remained apprehensive or fearful long after watching a scary movie?

Never (1) (2) (3) Occasionally (4) (5) (6) Often (7)

Q21 Do you ever become so involved in doing something that you lose all track of time?

Never (1) (2) (3) Occasionally (4) (5) (6) Often (7)

Appendix H
Human Research Ethics Committee approval

UC UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

HUMAN RESEARCH ETHICS COMMITTEE
Secretary, Rebecca Robinson
Telephone: +64 03 369 4588, Extn 94588
Email: human-ethics@canterbury.ac.nz

Ref: HEC 2021/99/LR Amendment 2

17 June 2022

Hayden Leete
HIT Lab NZ
UNIVERSITY OF CANTERBURY

Dear Hayden

Thank you for your request for an amendment to your research proposal "Simulating Racket Sport Haptics for Exergames" as outlined in your email dated 9th June 2022.

I am pleased to advise that this request has been considered and approved by the Human Research Ethics Committee.

Yours sincerely

Dr Dean Sutherland
Chair, Human Research Ethics Committee

Appendix I

Presence questionnaire

Answered on a 7-point Likert scale

1) How much were you able to control events?
1: Not at all, 4: Somewhat, 7: Completely

2) How responsive was the environment to actions that you initiated (or performed)?
1: Not responsive, 4: Moderately responsive, 7:Completely responsive

3) How natural did your interactions with the environment seem?
1: Extremely artificial, 4: Borderline, 7: Completely natural

4) How much did the visual aspects of the environment involve you?
1: Not at all, 4: Somewhat, 7: Completely

5) How much did the auditory aspects of the environment involve you?
1: Not at all, 4: Somewhat, 7: Completely

6) How natural was the mechanism which controlled movement through the environment?
1: Extremely artificial, 4: Borderline, 7: Completely natural

7) How compelling was your sense of objects moving through space?
1: Not at all, 4: Moderately compelling, 7: Very compelling

8) How much did your experiences in the virtual environment seem consistent with your real-world experiences?
1: Not consistent, 4: Moderately consistent, 7: Very consistent

9) Were you able to anticipate what would happen next in response to the actions that you performed?
1: Not at all, 4: Somewhat, 7: Completely

10) How completely were you able to actively survey or search the environment using vision?
1: Not at all, 4: Somewhat, 7: Completely

11) How well could you identify sounds?
1: Not at all, 4: Somewhat, 7: Completely

12) How well could you localize sounds?
1: Not at all, 4: Somewhat, 7: Completely

13) How well could you actively survey or search the virtual environment using touch?
1: Not at all, 4: Somewhat, 7: Completely

14) How compelling was your sense of moving around inside the virtual environment?
1: Not at all, 4: Moderately compelling, 7: Very compelling

15) How closely were you able to examine objects?
1: Not at all, 4: Pretty closely, 7: Very closely

16) How well could you examine objects from multiple viewpoints?
1: Not at all, 4: Somewhat, 7: Extensively

17) How well could you move or manipulate objects in the virtual environment?
1: Not at all, 4: Somewhat, 7: Extensively

18) How involved were you in the virtual environment experience?
1: Not involved, 4: Mildly involved, 7: Completely engrossed

19) How much delay did you experience between your actions and expected outcomes?
1: No delays, 4: Moderate delays, 7: Long delays

20) How quickly did you adjust to the virtual environment experience?
1: Not at all, 4: Slowly, 7: Less than one minute

21) How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?
1: Not proficient, 4: Reasonably proficient, 7: Very proficient

22) How much did the visual display quality interfere or distract you from performing assigned tasks or required activities?
1: Not at all, 4: Interfered somewhat, 7: Prevented task performance

23) How much did the control devices interfere with the performance of assigned tasks or with other activities?
1: Not at all, 4: Interfered somewhat, 7: Prevented task performance

24) How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?
1: Not at all, 4: Somewhat, 7: Completely