Wings of Imagination: Strengthening Avian Embodiment and Flight Immersion in Virtual Reality Through Multisensory Haptic Feedback

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Abstract. This research develops an integrated system using multimodal haptic feedback to enhance users' sense of body ownership when embodying avian avatars in virtual reality. The hardware components include retractable bands to guide limb movements and inflatable cushions to simulate environmental conditions during flight. The system aims to replicate key aspects of avian embodiment through synchronized virtual and physical stimuli. A user study evaluates the potential of this approach to strengthen feelings of ownership over non-human avatars. Results demonstrate moderately positive overall usability, with variable individual responses. Spatial haptics augmented realistic wing simulations for over half of the participants. However, limitations exist regarding personalized interactions and simulating comprehensive tactile sensations. This pioneering work contributes an innovative methodology for prototyping and assessing bodily transformations in virtual environments. It advances avatar embodiment knowledge and underscores the nuanced interplay of multisensory feedback. Further refinements may build empathy and connections with the natural world.

Keywords: Wearable Haptic Devices · Virtual reality · Body Ownership.

1 Introduction

Throughout history, humanity has yearned for the ability to soar through the skies and has dedicated significant efforts toward advancing aerial technology.

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However, birds can achieve flight without needing mechanical energy; instead, they utilize their bodies to overcome the force of gravity and ascend into the sky. Humans have never experienced the physical sensation of birds defying the forces of gravity and air resistance. The inquiry into the disparities between avian and human anatomical encounters poses a challenge in enhancing the human embodiment of bird avatars, warranting further investigation. This study aims to improve the users' sense of immersion and ownership over virtual bodies by employing multimodal haptic feedback interactions. Specifically, we focus on enhancing body and space simulation, developing a design framework to expand the study of avatar diversity in virtual reality, and examining the individual and combined impacts of these two simulations on haptic feedback through quantitative and qualitative research.

The theoretical framework in the field helps this study. First, this study provides users with the body senses of a bird in flight, which belongs to beyond-real haptic feedback simulations, showing that humans and birds have different movement mechanisms and living environments. For instance, the avian's musculature and respiratory system have all evolved to accommodate flight and high altitude. Abtahi has proposed the concept of Beyond-Real transformations in virtual reality [11]. He explored how visual information input in the virtual world affects the sensory-motor loop, centring on the central nervous system when the Beyond-real transformation occurs. His proposed model links the user's physical body with the user's vision in the virtual world, which helped this study establish interaction design between wearable devices and VR headsets. Secondly, this study introduces the formula for haptic feedback fidelity proposed by Muender to conduct a quantitative analysis of haptic feedback data [5]. This formula quantifies the haptic feedback fidelity into specific values for comparison and exploration. The above theoretical framework provides a reference and basis for using haptic feedback in conjunction with VR to transcend the human body's limitations in daily life.

In this study, we researched the above body mechanisms and spatial transformation and designed wearable hardware for haptic feedback and software in a VR headset for vision. The body simulation hardware comprises a retractable strap system, and space simulation hardware consists of an inflatable airbag and a wind blower. Users wear wings and counterweights for controlled experiments to compare with the body simulation hardware. Furthermore, the space hardware will combine the other two sets separately for simulation. In all, we recruited a total of 15 participants for the experiment. To better evaluate the user experience, the System Usability Scale and haptic fidelity factors questionnaires were sent to the participants after the experiment. Based on the collected data, this study uses the formulas proposed by Muender to get the quantitative haptic feedback fidelity values and the formula of the System Usability Scale (SUS) to derive the participants' experience using this system. In addition to data collection, this study also conducted interviews with participants to collect personalized comments and suggestions. We also calculated the mean, median, mode, range, variance, standard deviation, and P-value in the Analysis of Variance of the haptic fidelity scores for each group of devices, and we discussed device evaluation and future development.

This study concludes with four main contributions. Firstly, it develops a design methodology to enhance body ownership by simulating the movement mechanisms of non-human avatars through haptic feedback. Based on this, an interaction design framework is established for how the software interface in a virtual environment cooperates with haptic feedback hardware devices in the physical world. Additionally, this study evaluates the effects and issues of combining spatial and bodily haptic feedback devices and analyzes opportunities for future development. Furthermore, it enhances the field's understanding of how space simulations interact with body simulation through haptic feedback in beyond-real virtual reality environments. Finally, from an evaluation perspective, this study establishes a framework for assessing haptic feedback based on factors influencing users' sense of body ownership.

2 Related Works

The allure of avian flight taps into a profound existential yearning inherent to the human condition - our restless impulse to evolve and transcend the limitations of earthly existence. Soaring freely through the skies is akin to transcending the flesh, momentarily casting off our terrestrial bodily forms to glimpse an elevated state of being unhindered by physical laws, symbolizing our deepest aspirations for liberation from the constraints of material reality. Pioneers like Leonardo da Vinci dedicated their brilliance to designing exotic ornithopters and aircraft [24]. The dawn of the modern industrial age brought forth machines capable of achieving lifelong dreams of mastery over the skies. Early planes took to the air, swiftly followed by developments in aeronautical engineering that swiftly progressed from frail wood and fabric contraptions to reliable metal giants spanning the globe [25].

On a metaphysical level, flying symbolizes humanity's quest to reconcile our heightened consciousness and intelligence with our ephemeral mortal nature [29]. It speaks to our dual nature - the conflicting desires to embrace our animal roots yet flee the inevitability of earthly decay through transcendence into higher spheres of thought and being. Birds traversing the boundary between heaven and earth with ease remind us of possibilities beyond the narrow confines of our average worldly experience. At the same time, the dream of flight touches on humanity's search for meaning and purpose beyond our fleeting individual lives. Taking to the skies on wings like birds allows us to view life from a loftier, more celestial vantage point and contemplate our place in the grand universal order.

However, all of the above flying dreams are covered by tangible objects instead of human bodies. This highlights the limitations of current technology in achieving accurate human flight without external aids. The critical difference between bird flying and human arm waves is the specialized wing musculature that the birds possess is not found in humans, while both human arm swinging and bird wing flapping involve coordinated movement of antagonistic muscle pairs across the body in a rhythmic pattern to flex and extend the limbs, utilizing muscles like deltoids and supraspinatus to abduct and horizontally extend the arms or wings [30]. As birds use powerful pectoralis and supracoracoideus muscles to power the downstroke, they require more significant overall muscular effort against gravity given their more enormous wings, and their movement is more synchronized in a backward elliptical stroking motion versus human arms [26]. Birds do not have rotational elbow joints but have additional wing bones and joints to fold feathers tightly. Their wing feather proportions allow more efficient conversion of muscle work to propulsion than arms.

Consequently, our work aims to allow people to experience relaxation and effectiveness through extreme movement simulation that transcends human limitations. Physically, extreme sports push the body to its limits and induce a "runner's high" effect where the release of endorphins counters feelings of stress. Psychologically [27], engaging in virtual high-risk activities in a safe environment satiates our innate thirst for adventure while providing feelings of control over dangerous situations. It also allows people in increasingly sedentary lifestyles to fulfil basic human needs for the challenge, stimulation, and complex movement. By simulating experiences we cannot access in reality, this study aims to create an interactive system that could deliver positive mental health benefits of relaxation through immersion in intense sensations.

After thoroughly researching the relevant works, we have identified several key studies that inform our research on the sense of immersive realism, the materiality of virtual embodiment, and genuine haptic feedback mechanisms.

The projects investigating animal avatars in virtual reality, such as "Haptic Around," employ a hybrid system that provides various haptic sensations in VR using wind blowers, heat blowers, misters, and heat lamps [22]. Oyanagi's, on the other hand, focuses on the illusion of ownership in non-human avatars, specifically a bird in VR, building upon previous research on embodiment [23]. Krekhov investigates the utilization of animal avatars in virtual reality, employing body-tracking techniques to maneuver various creatures such as spiders and bats [14]. Other studies have highlighted valuable methodological advancements, such as Grabbe's semiotic analysis of "TreeSense," which investigates the physical nature of virtual embodiment. This study demonstrates the correlation between the physical characteristics of signals and how users perceive them, expanding semiotic theory to include dynamic, embodied virtual reality interactions [20]. The remaining efforts focus on user immersion in virtual reality. Freude's work explores how virtual body ownership and agency can be enhanced through virtual reality, suggesting that additional control devices can improve the sense of ownership [21]. Wee et al.'s study examines haptic interfaces for virtual reality and highlights essential challenges and future research directions in this field [18]. The study emphasizes ongoing issues such as adaptability, size reduction, integration of multimodal feedback integration, and the replication of bi-manual interactions. It suggests that overcoming these hurdles is crucial for advancing the realism and functionality of VR haptic systems.

The absence of genuine haptic feedback integration also greatly inspired us. Michael's research examines the constraints of kinesthetic feedback in consumer-grade VR technology, which does not incorporate authentic haptic feedback mechanisms [19]. Visual-based feedback, also known as pseudo-haptics, may undermine the authenticity of the kinesthetic experience, highlighting a need to assess the genuine effectiveness of haptic feedback. Richard's research centres on examining the influence of haptic feedback on the feeling of being fully present in virtual environments, particularly in the context of VR drawing tasks [13]. These findings emphasize the intricate connection between the ownership of one's body and the ability to exert control, as well as the significance of receiving feedback through multiple sensory channels. Upon reviewing the related works, several recurring limitations were identified that inform the focus of our research, centred around the narrow representation of avatars, incomplete evaluation of fidelity factors, lack of genuine haptics, and focus on individual modalities rather than holistic multisensory experiences. We introduce diverse avatar representations while thoroughly evaluating fidelity across modalities. Specialized hardware provides authentic haptics within complex flight simulations, such as the connecting muscles added to mimic the bird's wing. A user-centred mixed interview methods approach assesses synergistic multisensory effects beyond singular components. Through these enhancements, we seek to advance the authenticity and generalizability of embodied virtual experiences.

3 Study Overview

To address the current issue, this study examined the pertinent material. It determined that a sophisticated amalgamation of hardware, software, and interaction design is necessary to integrate human and animal movement experiences seamlessly. The Double Diamond design model is the basis of our methodical approach, comprising four distinct stages: Discover, Define, Develop, and Deliver Phases [28]. This model guarantees our project a meticulous and all-encompassing development process, from the initial concept to the final execution.

In the **Discovery Phase**, we analyzed the limitations of current VR technology and user requirements for immersive avian experiences through a literature review. Its multi-faceted understanding of our project context was enhanced through the amalgamation [17]. The reviewed literature focused on recent sources from 2019, ensuring updated data and information and a clearer comprehension of the latest haptic feedback advances in virtual reality. The **Definition Phase** involved synthesizing our findings to pinpoint critical areas for development. By studying bird flight movement mechanisms to inform our hardware design approach, where we carefully selected key components - a microcontroller, sensors, and operators - and prototyped a blower and inflatable airbag to simulate bird flight transformations through haptic sensations in space. During the **Development Phase**, we translated defined requirements into a tangible haptic interface through iterative prototyping to perfect feedback factors, and the software integrated sensory data to create a cohesive VR experience. Thus, we developed a series of wearable devices incorporating retractable straps and inflatable airbags, building on our research to enhance the feeling of acting like a bird. These devices simulate a bird's movements during takeoff and flight sensations like air resistance and temperature through our digitally mapped interaction model [15]. After the development, we implemented the complete system and conducted user testing for validation to guarantee the further development of **Delivery Phase**. Experimental processes and data collection were designed based on the System Usability Scale (SUS), and adjustments were made based on feedback to ensure the interaction design facilitated convincing body ownership and met haptic immersion outcomes.

4 Hardware Design and Implementation

Our design strategy is to simulate the bird flight sensation from spatial and bodily perspectives with haptic feedback. The hardware design focuses on the bird's movement mechanism to give users haptic feedback on bird flight, and the software design in the VR headset provides a visual experience.

4.1 Birds Movement Mechanism Research

Birds overcome air resistance and gravity through evolved movement mechanisms, including their respiratory, structural, and force-exertion adaptations suited for flight. Birds have developed air sacs within their chest cavities to aid oxygen uptake under the low pressures experienced during lift-off in the perspective of respiratory physiology [9]. They possess well-developed pectoral muscles and feather-covered wings, allowing for continuous flapping to generate lift to counteract air resistance and support body weight in structural biomechanics [6]. Regarding force exertion dynamics, birds lower their centre of mass by bending their bodies downward during takeoff. We studied the avian flight mechanics through the lens of these above factors to inform the design of interactive hardware devices that mechanically transform these elements of the bird movement mechanism to enhance the sensory experience of embodied avian flight simulation.

4.2 Hardware Design Approach

The hardware design includes space simulations that imitate the environment transformations and body simulations that mimic the body movement. The space simulations mainly involve the air sacs in birds' respiratory systems and cold, strong wind in high altitudes. Birds' respiratory system bears more burden than humans in fighting against the lack of oxygen at high altitudes. Therefore, we placed an inflatable airbag on the user's chest, designed to simulate the air sacs of birds. The higher the user rises in VR, the more the airbag expands, bringing extra pressure to the user's chest, and a wind blower is equipped to simulate the strong wind in the air.

Bodily simulations targeted mimicking avian movement biomechanics. Primary avian flight muscles include the pectoral and scapular muscles evolved for power output [4]. Birds exploit drag and lift forces through the coordinated activity of back muscles and flapping wings to generate upward thrust and partially support weight [6]. Research indicates biceps and deltoid activity corresponds to locations of important avian flight musculature [7]. Accordingly, retractable elastic straps linked the user's upper body muscles, such that shortening one strap would drive surrounding straps to mobilize target areas. Besides, considering the flight movements of birds begin with a lowering gravity centre and a quick flap of the wings, the chest strap is shortened by the hardware when the user takes off, guiding them to bend over. Moreover, elastic bends tie the arm and the waist, making it difficult for users to flap fast, simulating the burden of real wings.

4.3 Retractable Straps System

Retractable Straps System is an integral component of the VR setup, including the straps and waist belt with arm cover.

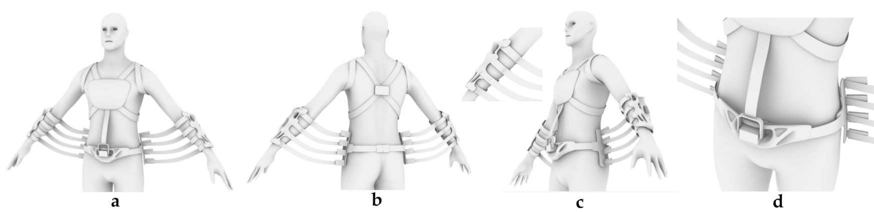


Fig. 1. The Hardware Design Model.

Straps The straps offer direct force feedback by reducing the distance between the chest and waist, decreasing the wearers' centre of gravity. The user's upper chest is restrained by four inelastic nylon straps, which are fastened in a criss-cross pattern in front of the chest (see Figure 1a), and the same nylon straps are wrapped around the armpits on either side. This guarantees that the chest remains stationary during physical activity. The stretch straps were placed into each arm and the matching side of the waist (see Figure 1b).

Waist Belt and Arm Cover From the view of holding the whole weight of the device, considering that the servo motor is limited to be placed in front of the waist to complete the telescoping of chest straps, the supporting position stays the waist and arm, we develop waist belt and forearms covering. The waist brace consisted of a laser-cut galvanized steel base plate covered with 3D printed components inspired by avian bone structure (see Figure 1c). The servo is secured in front of the waist for diverse body sizes, and the back side of the belt has adjustable elastic nylon straps that pass through the waist. Solid metal side strips fixed the elastic bands (see Figure 1d). The basement of the arm cover is made of metal plates covered with hollowed-out 3d printed parts designed to reduce weight and provide support. The arm cover is attached to the waist near the inside of the body by elastic straps, simulating the tension received by a bird's wings in flight, aiming to mimic wing tension dynamics during avian flight. This brace configuration distributed device weight across the waist, arms and chest while retaining the range of motion.

4.4 Controlling System Design

The core of the controlling system is an Arduino microcontroller with an RDS5180 servo (80kg-cm), an inflatable airbag with two air pumps, and an SW-520D vibration sensor. The Arduino is responsible for reading the data from the vibration sensor (0 or 1) and controlling the servo's motion accordingly.

Arduino with Vibration Sensor The Arduino microcontroller acts as the system's brain and is responsible for processing the input signals and controlling the output. The sensor (SW-520D) detects vibration or motion in the environment. This study uses its tipping detection function by placing the device at the wrist or the hand back and placing its copper post in the direction of the fingers. When the users raise their arms, the metal ball inside the copper post slides to the metal pin and forms a path. Then, a motion is detected, and the Arduino serial signal is inputted. When the users lower their arms, the metal ball slides in the opposite direction of the pin, and no path can be formed, so the signal is interrupted, and the Arduino serial signal is input 0. The sensor detects the signal once every 1 second to prevent accidental touching. This time is the same or longer than most users' flapping once. The coding logic is to detect two flappings within 3s as the official start. When the user's arm has been down for over 10 seconds, then Arduino serial signals are 0 at the official end.

Arduino with Servo Motor and Inflatable Airbag The servo is set on the metal waist belt connecting with a non-elastic strap to the chest metal plate. The motor receives control signals from the Arduino and performs precise angle adjustments based on these signals. In our experiment, the servo motor range is 0 to 160 degrees. When the servo is at 0 degrees, the user can stand straight naturally, and when the servo is at 160 degrees, the user needs to bend down.

The inflation system consists of two 40L/min air pumps, two relays, a set of tubes, a tee device, and an airbag. The two air pumps are connected to a tee device through tubes; the pump inflates one tube, and the other is deflated. For safety reasons, the deflated air pump is used as a pressure relief valve for the inflated air pump to prevent the airbag from exploding due to overfilling. The third port of the teeing device is connected via a tube to the airbag, which is placed between the body and the metal plate on the chest. When the airbag is inflated, the non-stretchable nylon straps hold the metal plate and squeeze the airbag. Instead resulting in a feeling of compression by users.

5 Software Design and Implementation

For our user research and application development, we implemented VR games using the Meta Quest 2 virtual reality headset and the Unity game engine (version 2021.3.19f1c1). We utilised the XR Interaction Toolkit to develop user interactions within the VR games. We programmed two triggers for character control - one positioned above and one below the user's head position in VR space. When the Meta controller touched either the upper or lower trigger, it would prompt the character to move forward or upwards. By varying the relative distance between the triggers and the head position, we were able to test different avian flight postures. We also obtained terrain assets from the Unity Asset Store to construct virtual environments for testing. This setup allowed us to prototype our avian avatar simulations for evaluation with participants.

6 Interaction Design Approach

The interaction design approach relies on a harmonized interaction between software and hardware, crucial for creating immersive user experiences with minimal delay.

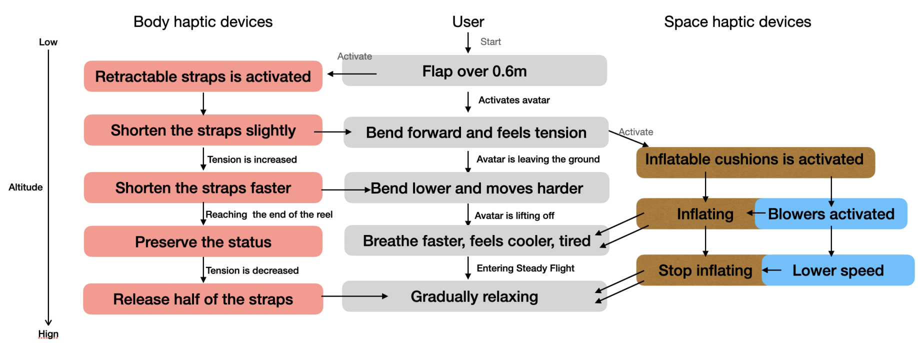


Fig. 2. The Flowchart of the Interaction between Haptic Feedback Devices and the User During the Taking-off Process.

6.1 Start and End Triggers

The delay and misunderstanding will decrease with the same command reacted to by visual and haptic feedback. Maintaining the synchronicity of software and hardware's start and end triggers is the key to immersive experiences. The hardware and software components ensured prompt triggering by accurately detecting the number of hand waves.

Hardware The hardware setup utilizes key components to simulate flight motions in a logical sequence (see Figure 2). This logical sequencing of hardware components and interaction settings aims to seamlessly translate natural avian motions into an immersive VR flight experience through realistic haptic feedback. At startup, the system initializes with the servo motor in the 0-degree position and the air pump switched off. In this system, we established two conditions to trigger the start and end of flights. The vibration sensor continually monitors for tilt cues from the user. When two flap motions are detected within a 3-second window, this is recognized as the official start signal.

Upon receiving the start signal, the servo motor transitions the apparatus from 0 to 160 degrees. Simultaneously, the inflatable air pump activates the inflation of the wearable airbag. Throughout flight simulations, the sensor evaluates motion cues every 1 second. So long as the movement continues to register within each 10-second interval, the current operational state is maintained. However, if no motion signal arises for ten whole seconds, the system interprets this as the end of the flight. In response, the servo motor reverses course to return from 160 to 0 degrees. Concurrently, the air pump switches modes to initiate the deflation of the inflated airbag.

Software To enhance the immersion experience for users, the start and end triggers are synchronous with the hardware. The start signal was set consistently as two detected flaps within a 3-second window, aiming to translate natural motions smoothly into VR takeoffs. Meanwhile, we established a natural end signal that helped seamlessly guide landings. Rather than abrupt stops, our project indicated falling sensations enhanced realism. Therefore, when flapping ceases, and the user's body stops elevating to fall gradually, this cues flight termination. Besides accounting for the duration of descents, relief is then provided by the system in tandem with ground contact in VR. Users experience relief from exertions as their flight seamlessly concludes on the digital landscape beneath.

6.2 Multisensory Interaction

Within the context of user-device interaction, we also considered the transformation of visual and physical interaction on software and hardware during this project.

Hardware For the hardware to translate avian motions, our project designed it to fit diverse body types. All joints and strap lengths are designed to be adjustable to accommodate varying human anatomies. When flight commences, haptic cues guide the user's posture and movements. Initially, tension is applied as the servo shortens straps connected at the waist, shoulders, and forearms. This gently pulls the user's posture downward, mobilizing back and arm muscles to simulate an avian stance against gravity. From this balanced position, further interactions cue realistic motions. Increased tension on the forearm straps with each flap simulates the muscular exertion of wings, coordinating with the user's physical actions. As the user responds instinctively through emulated flapping motions, corresponding haptic feedback loops recreate the experience of lift, thrust, and changing air pressures felt during avian flight. From initial posture cues through motion-guided feedback, our system aims to elicit natural movements that seamlessly translate the user's physical actions into an immersive virtual flight simulation. The user will receive commands not through words or verbal means but through haptic cues and react with motion.

Software Users who interact with the software in a VR headset need clear visual feedback. In this project, we render a 3D forest environment scaled to a bird's perspective in flight (see Figure 3). Plants appear comparatively larger than from a human viewpoint, filling more of the visual frame. Additionally, two square elements placed before the user represent their avian wings for easy position tracking. The user's altitude and location are readily discernible using these wings and the scaled forest scenery. Lower flights see tower plants encompassing most of the view. The software transitions the perspective upward as the user mobilizes their wings through physical flapping mirrored in VR. Trees gradually diminish in size as the view elevates through the forest canopy. Eventually, at high altitudes, the tops of tree silhouettes come into view, signalling the user has broken through to the open sky. This vertical visualization cues a natural sense of increasing elevation through bodily movement more intuitively than isolated readouts.

Fig. 3. The 3D Wild Forest in the VR.

7 Experiment and User Study

The study concluded with a user evaluation of this installation, which incorporated the experiential design, methodology, participant composition, and questionnaire.

7.1 Experiment Design

This experiment aims to help users experience the haptic feedback and score the hardware. The users will be experimenting with both space and body simulations, and this experiment design aims to explore the interaction between space and body simulation.

Experimental Setup As the equipment applied in this experiment consisted of software and hardware, we programmed and developed our scenario in

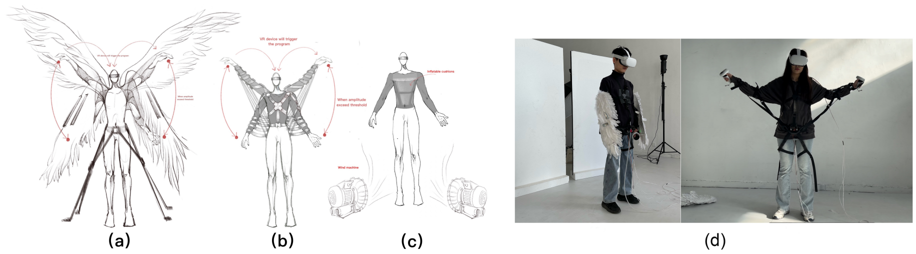


Fig. 4. The Single Simulation Groups and Records of Experiment.

Unity and imported it into the Meta Quest2 headset. The hardware includes three sections: realistic simulation, movement simulation, and space simulation. These first two sections are body simulations. The first, including the feather wings and the counterweight (see Figure 4a). While having lower versatility than other designs due to storage and transport difficulties, this direct representation of wings allows more intuitively natural flapping motions. It compares with the second simulation to analyze the fidelity of haptic feedback. The second section is thecriticaly hardware device developed in this research to study the flight mechanism of birds and change human movement and muscle force. The device uses the strap and servo motor to provide force feedback to guide the user's movements (see Figure 4b). Lastly, the third section is the space simulation, which includes a wind blower and an airbag to simulate the drop in atmospheric pressure and high winds at high altitudes (see Figure 4c) . The airbag was fixed beneath chest straps and inflated to generate pressure sensations in the experiments. Meanwhile, the external blower provided surrounding wind cues.

Group Classification We separated the experiment participants into five groups. The first three groups are single simulation groups, testing the hardware of each section independently. Meanwhile, the latter two groups are combination groups, combining realistic and movement simulations with space simulations. Each participant has attempted five flights as a result.

Experiment Site Due to the huge wings and considering the requirements of this experiment, the test should take place in an empty room, free of obstructions, able to provide adequate power connections, and able to accommodate other waiting participants.

7.2 Participants Information

For the experiment, fifteen volunteers between the ages of 19 and 40 were selected from the social community. The average age of the participants was roughly 25.7 years. The gender distribution was quite even, consisting of seven males and eight females, contributing to maintaining gender balance in the outcomes analysis. The participants in this study consisted mostly of university students and professionals from various sectors, such as interface design, finance, business management, computer science majors, programmers, professional photographers, and freelancers. The wide array of professional backgrounds brought forth a plethora of viewpoints and experiences for the study.

Significantly, 60% of the participants (nine persons) had previous familiarity with virtual reality haptic devices, whereas the remaining 40% (six individuals) did not. This broad composition is essential for examining the variances in responses and preferences across users with varying degrees of experience. Experienced participants can offer feedback that is grounded in their real-world usage. Conversely, viewpoints from novice people may provide more instinctive and sensory observations, which are crucial for understanding the usefulness and acceptance of a gadget.

7.3 Experiment Process

Upon arrival at the experimental site, participants are given the initial project overview with the organizer's help. The participants must read the project description, which contains the experimental purpose of this study, the experimental procedure, and the privacy protection and rights statement. The privacy statement includes the purpose and scope of the data collection, how the data is processed and stored, the rules for data use, the rights of the participants, and the privacy protection measures. All participants sign the document after indicating their approval of its content.

Following that, participants wear hardware equipment and VR headsets with our assistance. They individually wear the three pieces of hardware, corresponding to the contents of single simulation groups, as described in the group classification (see Figure 4d). Subsequently, we initiate the activation of the combined sets of equipment to carry out the fourth and fifth flights successfully. Once all flights have concluded, participants proceed to dismantle the equipment and proceed to submit the questionnaire on the Qualtric platform, marking the completion of the experiment.

7.4 Questionnaire and Interview

We conducted two questionnaires and interviews with participants after they experienced the single and combined simulation groups.

The SUS Questionnaire and Calculating Methodology

This study used the SUS (System Usability Scale) questionnaire to investigate software and hardware user experience [8]. It evaluates a system's usability, complexity, and technical support. The SUS is generated with a ten-item questionnaire, which has standardized entries and is used to assess a system's or product's usability.

Participants rated their level of agreement with each statement on a 5-point Likert scale ranging from "Strongly Disagree" (1 score) to "Strongly Agree" (5 scores), where odd-numbered questions are positives, and even-numbered questions are negatives. To calculate the score for this study, the researchers followed the standard SUS procedure: subtracting 1 from odd items, subtracting scores from 5 for even items, summing the adjusted scores, and multiplying by 2.5 to scale the final result from 0 to 100. Higher SUS scores indicate better usability of the system.

Haptic Fidelity Questionnaire and Interview

We also refer to Muender's research on the evaluation framework for the fidelity of haptic feedback [5], in which Muender proposed 14 factors, among which there are six limiting factors and eight foundational factors, and a formula for calculating the haptic fidelity score based on these factors. This formula uses a 5-point Likert scale (0-4) to assess the factors, where the foundational factors are averaged, and the limiting factors are scored by inverting squaring and combining them with a specific exponential function to calculate a number between 0 and 1. Finally, this number is multiplied by the average of the foundational factors to arrive at a value between 0 and 4; 4 is perfect, and 0 is the lowest (see Figure 5). Muender has proposed that the framework's validity and reliability are supported by its development process, which involves an iterative approach, a literature review on human haptic sensing, and feedback from experts in VR and haptic feedback.

Due to limited participants, this study focuses on five foundational factors: body location, hardware precision, sensory integrity, magnitude, and degrees of freedom. We also consider three limiting factors: side effects, constraints, and hardware latency. Every questionnaire item is designed to fit each factor, with 5 equipment groups in the scoring section. This allows for horizontal comparison of the same factors score among the equipment groups. After the questionnaires, the participants' scores are calculated using the formula. As the calculation of haptic fidelity here is not based on all 14 factors but on 8 of them, the result could not represent the total fidelity scores. The remaining six factors, software precision, software latency, dependency, distinguishability, stimuli, and body area, will be measured in the future with a larger capacity of participants and refined software.

In addition to the scoring items, the study also included open-ended interview questions in the questionnaires, for instance, suggestions they wanted to give the organizers, other species avatars they would like to play in VR, and their imaginings of bird body senses. The participants communicate with the researchers and discuss their experiences after the experience, and these feedbacks allow us to consider its updated version.

$$\text{Haptic Fidelity Score} = \left(\frac{\sum_{i=0}^{N_F} X_{F_i}}{N_F}\right) \times e^{-0.0027 \times \left(\sum_{j=0}^{N_L} X_{L_j}^2\right)^2}$$

Fig. 5. The Haptic Fidelity Score Formula.

7.5 Data Analyzing Method

Finally, the SUS and haptic feedback fidelity scores were calculated using the mean, median, range, mode, variance, and standard deviation to summarize the data. The scores can also be calculated for the p-value of one-way ANOVA to analyze the significance between each group. Based on this study's design and common conventions in the field, we set the significance level at 0.05. If the p-value is less than or equal to 0.05, we consider the difference between at least two groups significant.

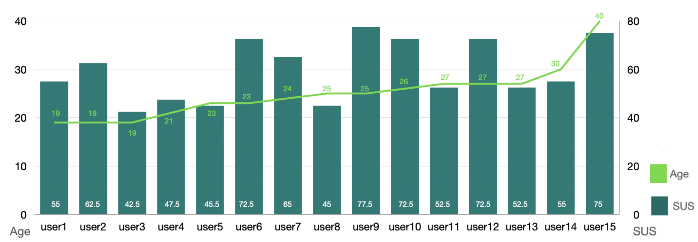
Those scores and figures are presented in tables or histograms, and the trend of specific groups of factor scores will be displayed in line graphs. In the graphs or tables, the users are listed according to age, from youngest to oldest. The higher the number, the older the age, so the relevance between age and data can be discerned.

8 Result Analysis

The quantitative and qualitative research results from the data collected through the SUS and haptic feedback questionnaire are shown below.

8.1 SUS Score Analysis

Based on the users' scores on the ten items shown in the SUS questionnaire, this study obtains a composite score for each user, and we compile a histogram after calculation (see Figure 6).



	Mean	Median	Range	Mode	Variance	Standard Deviation	P-Value
SUS Score	59.53	55	35	72.5 (3 users)	149.16	12.21	0.100

Fig. 6. The SUS Score with Age.

From the graph, the mode figure shows that 72.5 appeared three times in the ratings, which accounts for the mean being 4.53 higher than the median. At the same time, the variance in this data is 149.16, and the standard deviation is 12.21. These two values are relatively high, indicating high volatility in the data. Thus, in this case, the median, 55, is a more objective representative than the mean. It suggests that more than half of the users rated above average.

8.2 Haptic Feedback Fidelity Analyzation

According to the framework proposed by Muender, below are the scores based on the eight factors of haptic feedback fidelity for the single simulation groups

	Realistic Simulation							Movement Simulation							Space Simulation						
User	1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7
Score	3.6	1.8	3.0	2.4	2.9	4	1.9	2.8	2	3.6	2.4	3.4	0.9	2.7	4	1.8	3.99	1.0	4	0.4	1.8
User	8	9	10	11	12	13	14	8	9	10	11	12	13	14	8	9	10	11	12	13	14
Score	1.8	3.2	4	2.4	2.6	0	0	0	3	4	2.9	2.5	0	0	0.5	3.2	3.6	0.6	3.6	0	0
User	15							15							15						
Score	4							4							4						

(a) Single Simulation Groups

	Realistic Simulation+Space simulation							Movement Simulation + Space Simulation						
User	1	2	3	4	5	6	7	1	2	3	4	5	6	7
Score	3.8	3.2	3.8	0.4	3.8	3.4	3.4	2.873	4	3.6	0	3.8	0.19	4
User	8	9	10	11	12	13	14	8	9	10	11	12	13	14
Score	1.3	0.6	3.2	1	3.6	0	0	0.21	2.7	3.2	1.2	1.8	0	0
User	15							15						
Score	4							3.8						

(b) Combination Simulation Groups

Fig. 7. The Fidelity Scores of Three Single Groups and Two Combination Groups.

(see Figure 7a) and combination simulation groups (see Figure 7b). This study analyses data with these scores (see Figure 8).

.8

Haptic Feedback Fidelity Scores Analyzation of Five Groups

	Realistic Simulation	Movement Simulation	Space Simulation	Realistic+ Space	Movement+ Space
Mean	2.51	2.28	2.17	2.37	2.01
Median	2.60	2.70	1.80	3.20	2.70
Mode	4 (3 times)	0 (3 times)	4 (3 times)	3.8 (3 times)	0 (3 times)
Range	0-4	0-4	0-4	0-4	0-4
Variance	1.62	1.99	2.71	2.51	3.02
Standard Deviation	1.27	1.41	1.65	1.58	1.74
ANOVA P-Value	0.9382				

Fig. 8. The Data Analysis of Three Single Groups and Two Combination Groups.

Analysis of the data from 15 users shows that, in terms of the overall median, except for the Space Simulation group, the median of the other four groups exceeds the mean and stays above 2.60, indicating that more than half of the users gave high ratings. Regarding the mode, extremely high and low scores affect the mean. The high values show volatility in the overall variance and standard deviation data. Therefore, the median objectively represents the evaluation situation more objectively than the mean. Among all groups, the highest median of 3.20 belongs to the combination of the Realistic Group + Space Simulation group. The Movement Simulation group received the highest median of 2.70 among the three single-device groups. The P value of the one-way ANOVA analysis is 0.9382, higher than 0.05, so there is no significant difference in haptic fidelity scores between the five simulation groups, given the volatility in the data. The following result analysis and group comparison will be divided into **Realistic Simulations and Movement Simulations**, and the **Relationship between Space Simulations and Body Simulations**.

Realistic Simulations and Movement Simulations According to the data analysis table (see Figure 8), it could be found that the Realistic Simulation has the highest mean. However, its median is lower than that of Movement Simulation, and the mode is 4, occurring thrice, indicating that these high scores pull up the mean. On the other hand, the movement group's mode is 0 and occurs thrice as well, suggesting that the low scores pull down the mean. As a result, for Movement Simulation, more than half of the users' ratings are higher than or equal to 2.70, indicating that more than half of users evaluate it as high or medium, and a portion of users' ratings are low, even 0.

As for the formula of haptic feedback fidelity [5], the mean of the foundational factors scores and the sum of the limiting factors scores are the two variables (see Figure 5). The fidelity score is positively correlated with the mean of the foundational factor scores (see Figure 9a) and negatively correlated with the sum of the scores of the limiting factors (see Figure 9b) so that this study will be further analyzed in depth based on these two data sets.

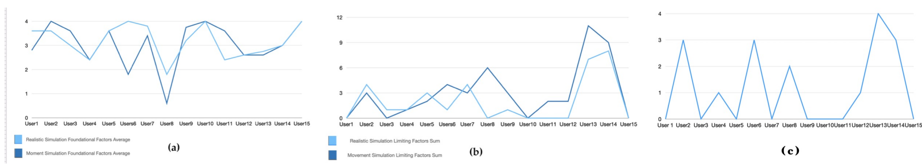


Fig. 9. The Foundational Factors Scores and Limiting Factors Scores of Realistic Simulation and Movement Simulation and Side Effect Factor Scores of Movement Simulation.

In the questionnaire results, the mean of the limiting factors sum in the Realistic Simulation group is 2. In contrast, the Movement Simulation group is 3.07, 1.5 times higher than the Realistic Simulation group. According to the line graph (see Figure 9b), several extremely high limiting factors are in the Movement Simulation group, which lead to the corresponding haptic fidelity score of 0. On the other hand, the fidelity score positively correlates with the foundational factors scores, with a mean of 3.18 in the Realistic Simulation group and 3.05 in the Movement Simulation group. This indicates that the difference in foundational scores between these two groups is much smaller than in limiting scores. A user interview was conducted to explore this issue further.

Some users considered the physical exertion of the device to be a side effect, one of the limiting factors. Therefore, I scored high on that item in the interview. On the other hand, some users were amused by the physical exertion of flapping their arms and felt their immersion was enhanced. The polarized scores of the side effect factor can be seen in the figure (see Figure 9c). For instance, user No.13 scored highly on foundational factors, indicating that she was optimistic about foundational factors. However, she noted that the soreness in her arms was very difficult, so she scored extremely high on the side effects factor. After calculating her perceived haptic fidelity, her score in all five groups was 0. This type of exception due to personality differences is additionally informative for this study.

Relationship between Space Simulations and Body Simulations

Based on the data in the table (see Figure 8) and the line chart (see Figure 10), it can be seen that the median of the combination groups is equal to or higher than that of the corresponding single group. The variance and standard deviation of the combination groups are higher than that of the related single

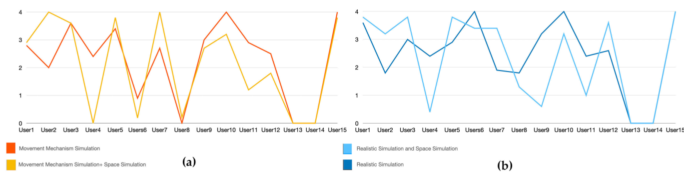


Fig. 10. The Haptic Feedback Fidelity Score of Single Group with Corresponding Combination Group.

group, suggesting that the haptic fidelity scores of the combination groups are more volatile and affected by very low scores.

Subsequently, the analysis is divided into two parts. Firstly, there is the Movement group and the Movement+Space group (see Figure 10a). The line chart shows the Movement + Space group's haptic fidelity score is slightly lower than the Movement group's. The mean decreased from 2.28 to 2.01; however, the median value remained at 2.70, which indicates that the decrease in the mean is related to some shallow scores. Considering the interview in the previous section, the low scores are associated with the extra discomfort of the added airbag. However, the three high scores for the combination group in the graph and the median of 2.70 imply that the simulation of atmospheric pressure by the airbags did not make this physical sensation a negative experience for all portions of users.

The second part compares the Realistic Simulation and the Realistic + Space groups. Compared to the Realistic group median of 2.60, the Realistic + Space group median rises to 3.2, which indicates that more than half of the users rated high with the space device combined with feather wings (see Figure 10b). At the same time, users with low scores remained, so the variance of this group increased further.

The haptic fidelity scores of the five groups have a median in the medium-high range, together with volatility, which is caused by participants' differences in ratings of the limiting factors.

9 Discussion, Limitation, and Future Work

The study provides a haptic feedback design framework centred on movement mechanisms by investigating space and body transformations in VR. It proposes a hardware design concept using an Arduino microcontroller, vibration sensors, and servo motor as the controlling system, which provides a reference for more haptic feedback hardware design in the future. In this project, immersive sharing of the physical sensations of birds can help humans better understand the stresses of the natural environment that birds may undergo in flight and the hardships of long-distance flight and build up empathy for birds that migrate long distances. It allows for body transformations and enhances the naturalness and intuitiveness of users' movements in VR. This research establishes the synchronization of sensations and perceptions between the physical and virtual bodies as the avatar of a bird. It is not limited to reducing the intensity of each part of the haptic feedback, coordinating the sequence in which the different haptic feedbacks occur, and adjusting the haptic magnitude to account for other users' acceptance levels.

From quantitative and qualitative research perspectives, the medium-high median of the haptic feedback fidelity scores shows that more than half of the participants validated the realism of the haptic feedback. In contrast, the high scores of variance and standard deviation and the polarized scores of side effect factors are related to personal preferences and body condition, consistent with the interviews. Some participants found the tiredness of arm flapping and the oppressive force in front of the chest unacceptable, while others found it amusing. This fact is also related to the limited number of participants, fifteen people—the small sample size limited diversity in identities, personalities, preferences, and body sizes. Therefore, the study will recruit more participants from different backgrounds, preferences, and body sizes in the future. This will enable the questionnaire to assess all fourteen factors more comprehensively while decreasing the impact of outlier data.

However, the current adjustment methods, especially the connecting muscles, are limited to calibrating variables like air pressure levels and motor ranges according to individual body sizes and weights. This diminishes the potential for optimal comfort across different user profiles. The software's bird takeoff functionality will be enhanced in the subsequent release due to the reduced accuracy with which the joystick and headset are recognized at low power levels. Meanwhile, the system is also confined by only promoting embodiment sensations from the waist up; the future versions must aim higher by pursuing whole-body ownership translations to exploit its immersive capabilities, such as placing the experiment in the vertical space of the loose ribbon to experience parallel flight. Even in the depth of the interview aspects, we consider our participants' feedback that when facing a sky view, they would like to scream out for relaxation, so the next version will incorporate speech controls to dynamize surroundings based on voice volume, cultivating a stronger sense of forward momentum, to achieve the flying speed control management.

We aim to widen content coverage to include additional globally significant heritage sites, artifacts, and architectural works that have the potential to broaden societal impacts. For example, extensions into virtual preservation initiatives and intangible cultural promotion could spurn valuable real-world applications. Still, they require the involvement of many participants, and the users can view them from a whole perspective. Moreover, the six factors not yet thoroughly examined within our evaluation framework, the Software Precision, Software Latency, Dependency, Distinguishability, Stimuli, and Body Area, will be assessed in forthcoming studies. These studies will feature an expanded participant pool and enhanced software capabilities to facilitate a more comprehensive evaluation to facilitate their classification and analysis in conjunction with scoring.

10 Conclusion

This research aimed to enhance users' sense of body ownership when embodying avian avatars in virtual reality. Our approach focused on developing an integrated system leveraging multimodal haptic feedback to mimic critical aspects of avian flight. The hardware components, including retractable bands and inflatable cushions, were designed to simulate avian movement mechanisms and environmental conditions during flight. The visualizations and interactions in VR software provided complementary virtual feedback synchronized with the haptics.

The user study results demonstrate the potential of this multisensory approach to strengthen feelings of body ownership for non-human avatars. The overall system usability ratings were moderately positive, with some variability based on individual preferences. The analysis of haptic fidelity factors indicates that refinements to limit side effects and constraints could further improve user experience. Interestingly, while the realistic wings simulation received higher fidelity scores, adding spatial haptics like air cushions and wind improved the ratings for over half the participants. This points to the value of coordinated multimodal feedback.

It contributes an innovative methodology for prototyping and evaluating bodily transformations in VR. The focus on replicating the motor experiences of avian flight advances avatar embodiment knowledge. The findings also underscore the nuanced interplay between multiple sensory stimuli in immersive environments. Potential social impacts include building empathy and connections with the natural world.

However, limitations remain regarding user sample diversity and the ability to simulate comprehensive tactile flight sensations within current technological constraints. Future work should explore more personalized and adaptive multisensory interactions based on user profiles. Investigating other non-human embodiments would also be valuable. This research pioneers new territory in reimagining and experiencing our embodiment potential.

11 ACKNOWLEDGMENTS

The authors would like to express their sincere gratitude to IEEE VR for the opportunity to present our work in a poster session. This platform allowed us to showcase our research and provided us with invaluable feedback and insights from our peers in the field. We sincerely appreciate the support and the engaging discussions that have contributed to the refinement and improvement of our research.

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