Enhancing Balance Rehabilitation in Adults: A Virtual Reality Approach to Engagement and Adherence

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**Abstract.** Balance deterioration in older adults increases fall risk, yet traditional rehabilitation exercises often suffer from low adherence due to disengagement. This study proposes a Virtual Reality (VR) balance-training game, PaperPlane VR designed to enhance engagement and physical activity through intuitive mechanics (standing, sitting, lateral stepping) in an immersive environment. A closed-beta trial with eight adults compared VR-based exercises to conventional methods using a within-subjects design. Subjective feedback revealed VR scored significantly higher in engagement, comfort, and perceived effectiveness. While preliminary due to the small sample size, results suggest VR’s promise as a rehabilitation tool for adults, warranting larger trials and older adults with objective biomechanical metrics. This work highlights VR’s capacity to address adherence barriers in balance rehabilitation, potentially reducing fall risks and improving quality of life.

# INTRODUCTION

The global population is going at fast rate by 2050, the number of individuals aged 60 years and older is increased to the double, placing many demands on healthcare systems and support services worldwide [1], [2]. Furthermore, within many challenges faced by this demographic, balance deterioration stands out as a critical factor, meaning that poor balancing increases the risk of falling which will cause serious injuries due to this problem the independence and the cost of healthcare will increase [3], [4].

Traditional training for balancing methods such as static standing exercises, weight‑shift drills, and Tai Chi offer proven advantages but often lake poor long‑term adherence. Furthermore, boredom, lack of feedback, and fear of injury contribute to low engagement, undermining the sustained participation required to do meaningful functional gains [5], [6]. There are some evidences suggests that immersive technologies can address these limitations by transforming repetitive movements into engaging, game‑like experiences [7], [8].

To overcome this gap, we propose a Balance‑Based Virtual Reality (VR), PaperPlane VR game specifically designed for adults. Leveraging intuitive mechanics (e.g., sit‑to‑stand, lateral stepping, forward/backward shifts) within an immersive, low‑poly environment, the game aims to enhance motivation, provide real‑time feedback, and facilitate safe progression through adaptive difficulty levels. This study focuses on two keys, firstly designing and development of an accessible VR balance‑training application tailored to the needs and limitations of older users. Secondly, evaluation of user engagement, comfort, and perceived effectiveness through a closed‑beta within subjects' trial.

By integrating VR’s immersive capabilities with evidence‑based balance exercises, this work looks to overcome adherence limitations in geriatric rehabilitation. Additionally preliminary in scope, the findings will inform future large‑scale trials incorporating objective biomechanical metrics (e.g., center‑of‑pressure sway, gait variability) [8], which will lead to contributing to more effective fall‑prevention strategies and an improved quality of life for older adults.

# RELATED WORKS

## VR/AR in Therapeutic Contexts

Immersive technologies like Virtual Reality (VR) and Augmented Reality (AR) have shown significant potential in therapeutic contexts, especially for older adults experiencing balance deterioration a key contributor to fall risk. In clinical settings, VR has matched traditional physiotherapy in restoring balance and mobility for individuals with neurological impairments while offering enriched feedback and programmable difficulty [9]. Similarly, AR/VR-based cognitive and motor training tools have facilitated skill acquisition and rehabilitation in stroke and dementia patients [10], [11], [12]. When used to balance training, especially for older adults, these technologies not only provide safe and engaging environments for practicing essential movements (such as sit-to-stand, stepping, and lateral shifts) but also address common limitation to adherence like boredom and fear of injury [4], [5], [6]. Studies show that older adults adjust more carefully to virtual obstacles, highlighting VR’s potential to safely simulate variable conditions that enhance gait adaptability [13]. The integration of VR into balance rehabilitation programs offers a scalable, motivating, and adaptive solution, as evidenced by user centered trials demonstrating improved engagement, comfort, and perceived effectiveness important factors for long-term adherence and fall prevention [7], [14].

# GAME CONCEPT

## Game Mechanics Design

The PaperPlane VR Game translates four fundamental physical movements into in‑game actions, guiding a paper plane through an immersive environment while promoting balance training. By mapping each exercise to a distinct plane control, the mechanics encourage leg strength, postural control, and coordination in an intuitive, low‑cognitive‑load format.

### Vertical Movement

The Stand & Sit mechanic governs the plane’s altitude. When the player transitions from sitting to standing, the plane ascends; returning to sit causes it to descend. This simple yet effective cycle targets lower‑limb strength and static balance through repeated sit‑to‑stand motions. Figure 1 shows the pseudocode for the Stand & Sit vertical movement logic.

|  |
| --- |
| // Vertical Movement Mechanic  Enum State { Idle, Up, Down, ... }  currentState = State.Idle    Function HandleInput():  If playerStandsUp() AND currentState != State.Up:  moveUp()  Else If playerSitsDown() AND currentState != State.Down:  moveDown()    Function moveUp():  currentState = State.Up  // Animate plane ascending    Function moveDown():  currentState = State.Down  // Animate plane descending |

**FIGURE 1.** Stand and sit pseudocode

### Forward/Backward Movement

The Step Forward & Step Back mechanic modulates speed. A forward step doubles the plane’s velocity, simulating dynamic gait and reactive balance training; a backward return resets speed to baseline. This movement fosters-controlled weight‑shifts and enhances proprioceptive feedback. As in Figure 2, the following pseudocode implements forward and backward speed changes.

|  |
| --- |
| // Forward/Backward Movement Mechanic  Function HandleInput():  If playerStepsForward() AND currentState != State.Forward:  moveForward()  Else If playerStepsBackward() AND currentState != State.Backward:  moveBackward()    Function moveForward():  currentState = State.Forward  // Increase plane speed    Function moveBackward():  currentState = State.Backward  // Reset plane speed |

**FIGURE 2.** Move forword pseudocode

### Lateral Movement

The Step Left/Right & Return mechanic controls horizontal shifts. Stepping to the right (or left) moves the plane laterally; returning to center resets its course. These side‑to‑side weight‑shifts strengthen medio‑lateral stability, crucial for fall-avoidance. The lateral control flow is detailed (see Figure 3)

|  |
| --- |
| // Lateral Movement Mechanic  Function HandleInput():  If playerStepsRight() AND currentState != State.Right:  moveRight()  Else If playerStepsLeft() AND currentState != State.Left:  moveLeft()  Else If playerReturnsToCenter() AND currentState in {State.Left, State.Right}:  moveMiddle()    Function moveRight():  currentState = State.Right  // Animate plane shifting right    Function moveLeft():  currentState = State.Left  // Animate plane shifting left    Function moveMiddle():  currentState = State.Middle  // Animate plane centering |

**FIGURE 3.** Lateral movement pseudocode

Together, these three mechanics form the core of the game’s interaction model, seamlessly integrating real‑world exercise with engaging gameplay that adapts to the user’s ability and promotes adherence to balance training routines.

## Game Level Design

The PaperPlane VR Game employs a three‑level progression to scaffold skill acquisition, gradually introducing new mechanics, obstacles, and rewards to maintain engagement and appropriately challenge the user.

### Level 1: Introduction to Basics Objectives:

Familiarize players with the Sit‑to‑Stand mechanic, reinforcing leg strength and static balance through repeated vertical movements. Figure 4(a) shows the Level 1 environment and path layout.

* Environment: A tranquil, low poly landscape with minimal visual distractions and calming background music to aid focus.
* Mechanics Introduced: Basic vertical control standing to ascend the paper plane, sitting to descend.
* Obstacles: Slow paced birds flying across the screen, requiring timely vertical shifts to avoid collision.
* Rewards: Coins aligned along simple paths encourage exploration and provide instant positive feedback.

### Level 2: Intermediate Challenge Objectives:

Build on Level 1 by adding dynamic gait control, promoting faster and more precise movements. As illustrated in Figure 4(b)

* Environment: A slightly more detailed scene with additional ambient elements to enrich immersion while retaining a relaxing atmosphere.
* Mechanics Introduced: Forward/Backward stepping stepping forward doubles the plane’s speed, stepping back resets it.
* Obstacles: Increased number of birds with varied speeds and trajectories, demanding accurate timing and rapid responses.
* Rewards: Coins placed in more challenging positions, incentivizing use of the new forward‑stepping mechanic.

### Level 3: Advanced Challenge Objectives:

Encourage mastery of all movement types through complex, multi‑directional sequences. shown in Figure 4(c)

* Environment: A richly detailed, low‑poly world featuring layered depth cues to heighten immersion.
* Mechanics Introduced: Lateral weight shifts stepping right or left shifts the plane; accordingly, returning to center resets its course.
* Obstacles: Combination of birds and static rocks arranged in intricate patterns, requiring simultaneous vertical, forward/backward, and lateral control.
* Rewards: Strategically scattered coins that necessitate advanced maneuvering, rewarding skillful navigation of composite obstacles.

This structured ensures the users are neither overwhelmed nor under-stimulated, adapting continual improvement in balance and coordination while sustaining motivation via escalating challenges and achievements.

# IMPLEMENTATION

## Software & Hardware Requirements

### Software Tools

* Unity 3D: Chosen for its rapid prototyping capabilities, extensive asset store, and robust VR support.
* Unity’s C# scripting and built‑in version control streamline development and collaboration.
* OpenXR SDK: Provides a standardized API layer for headset and controller input, ensuring compatibility across a range of VR devices.
* Visual Studio 2019: The primary IDE for writing and debugging C# scripts, offering advanced code navigation and profiling tools.
* Unity Version Control: Manages the project repository directly within Unity, enabling atomic commits, branching, and rollback of scene and asset changes.
* Blender: Used to import, modify, and optimize 3D assets sourced from the Unity Asset Store and Sketchfab, maintaining a cohesive low‑poly aesthetic while minimizing draw‑calls.

### Hardware Specifications

* VR Headset: Oculus Quest 2, selected for its wireless 6 DoF tracking, high‑resolution display, and adjustable fit, ensuring comfort during extended sessions.
* Play Area: A minimum 2 × 2 m unobstructed floor space, with optional support rails or nearby chair placement to accommodate users with significant balance impairments.

|  |  |  |
| --- | --- | --- |
| Picture 19, Picture (a) | Picture 20, Picture (b) | Picture 21, Picture (c) |

**FIGURE 4.** (a)Level 1, (b) Level 2, (c) Level 3

# PRELIMINARY TESTING AND RESULTS

## Participants and Procedure

Close‑beta testing was done at Multimedia University (MMU), Cyberjaya, on June 29th from 10 am to 4 pm. Eight participants took part: current game‑development students, alumni, and parents visiting during MMU’s open day. Testing followed a within‑subjects design in two phases:

* Phase 1 (Non‑VR Exercises): Participants performed a series of traditional balance exercises (sit‑to‑stand, lateral weight‑shifts, stepping). Upon completion, they completed Survey 1 assessing comfort, engagement, and perceived effectiveness.
* Phase 2 (VR Game): The same participants then played the PaperPlane VR Game incorporating identical movements.

After gameplay, they completed Survey 2, which added feature‑implementation ratings for movement controls, camera control, object interaction, input handling, and state management. All survey feedback were collected via Google Forms and anonymized before analysis. Figure 5 shows the closed-beta testing setup

|  |  |
| --- | --- |
| A person wearing a headset and a computer  Description automatically generated, Picture | Picture 11, Picture |

**FIGURE 5.** Testing session

## Metrics

Four key metrics were evaluated:

* Comfort Level: Participant self‑report of physical comfort during exercise.
* Engagement Level: Degree of psychological immersion and enjoyment.
* Perceived Effectiveness: Participant belief in the exercise’s benefit for balance.
* Feature Implementation Ratings (VR only): Responsiveness and intuitiveness of core game features.

All metrics used 5‑point Likert scales (1 = “Very Low” to 5 = “Very High”).

## Analysis Methods

Descriptive statistics (mean scores) were calculated for each metric under both exercise modes. Comparative analysis highlighted differences between Non‑VR and VR conditions. Although sample size (N = 8) precludes strong inferential claims, paired comparisons were used to explain effect magnitudes.

## Key Findings

Table 1 shows the comparative results between traditional (non-VR) exercises and the PaperPlane VR game (see Table 1), Demonstrating clear advantages of the PaperPlane VR game over traditional exercises:

**TABLE 1.** Test key findings

|  |  |  |
| --- | --- | --- |
| **Metric** | **Non‑VR Mean** | **VR Mean** |
| Comfort Level | 4.0 | 4.5 |
| Engagement Level | 3.5 | 4.8 |
| Perceived Effectiveness | 4.2 | 4.6 |

Participants reported that the immersive environment and real‑time feedback of the PaperPlane VR game increased both comfort and enjoyment, leading to higher perceived effectiveness of the exercises. Feature implementation ratings were equally positive: movement controls were noted for their responsiveness and intuitiveness; camera control was smooth; object interactions (coins, obstacles) were enjoyable; input handling proved accurate; and state‑management transitions were seamless. Overall, the close‑beta testing indicates that the PaperPlane VR Game significantly enhances user experience in key dimensions critical to adherence and possibly rehabilitation efficacy.

# CONCLUSION

This study introduced a PaperPlane VR Game designed to transform conventional balance exercises into an engaging, game‑like experience for adults. Through intuitive sit‑to‑stand, stepping, and lateral‑shift mechanics embedded in a low‑poly environment, and powered by a modular Unity 3D/OpenXR framework, we demonstrated significant improvements in user‑centered metrics, engagement rose from 3.5 to 4.8, comfort increased from 4.0 to 4.5, and perceived effectiveness climbed from 4.2 to 4.6 on 5‑point Likert scales in a closed‑beta trial with eight participants. While this preliminary results underscore VR’s potential to boost adherence and motivation in balance rehabilitation, the reliance on subjective measures and a small, single‑session sample tempers broad generalization. Future research will validate these findings in larger, randomized cohorts, incorporate objective biomechanical assessments, and explore adaptive difficulty and home‑based deployment to establish VR‑augmented balance training as a scalable, effective intervention for fall prevention and quality of life enhancement in older adults.

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