VR-Shuttlecock: Toward Enhancing Older Adults' Balance Through Kicking Shuttlecock in VR with Multi-Sensory Feedback

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The decline in balance among older adults is a pressing public health issue that significantly impacts their well-being and independence. While traditional balance training methods are effective, they often face challenges with adherence, particularly among those living alone. Virtual reality (VR) presents a promising solution through immersive and gamified experiences. Although some VR exergames have shown potential for improving balance, their long-term effectiveness remains uncertain due to a lack of fundamental exercise principles and complexities that may hinder sustained engagement. To address these challenges, we developed VR-Shuttlecock, a customized VR exergame that incorporates shuttlecock kicking. This game features effective leg exercises, diverse gamification designs, progressive difficulty levels, and protection measures to promote long-term participation while minimizing fall risks. The VR environment enables home-based exercise free from weather constraints and offers social interaction with virtual characters to reduce loneliness. In a four-week controlled study, 14 older adults trained with VR-Shuttlecock, while 13 in the control group received no intervention. The experimental group demonstrated significant improvements in four balance assessments (SLST, TUG, FRT, and YBT) and expressed positive attitudes toward continued training. These findings highlight the potential of VR-Shuttlecock as an effective, engaging, and safe balance training tool for older adults.

CCS Concepts: • **Human-centered computing → Empirical studies in HCI**; **Virtual reality**.

Additional Key Words and Phrases: Older Adults, Virtual Reality, VR exergames, Balance Training

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1 INTRODUCTION

As older adults age, their balance abilities gradually decline. This phenomenon is influenced by various factors, including decreased muscle strength, diminished sensory capabilities (e.g., proprioception and tactile sensation), and the decline of vestibular function [44, 57, 87]. Even those who are currently healthy and without significant mobility impairments face progressive declines due to the normal aging process [21, 30, 56]. Although these changes may not initially lead to observable mobility difficulties, they pose potential risk factors for future falls [56, 68]. Research has also found a strong correlation between poor balance and impaired cognitive function, suggesting that cognitive decline may exacerbate balance issues [20, 87, 88]. Balance impairments stemming from multiple causes significantly increase the risk of falls, leading to serious injuries (such as fractures and head trauma), which can elevate morbidity and mortality rates [20, 87, 88]. Data indicate that among older adults aged 65 and over, one in three experiences at least one fall each year, which not only may lead to a loss of independence but also increases healthcare costs [87]. Therefore, the decline in balance ability among older adults is not only a critical indicator of individual health but also a major public health concern [20, 43, 46, 58, 87, 88]. Early, preventive balance training interventions for all older adults are crucial and effective. These interventions can enhance balance [50, 55] and boost confidence in balance and reduce the fear of falling, significantly reducing the incidence of falls and the related severe consequences [11, 26, 60, 79, 97]. Therefore, effectively improving older adults' balance has become an urgent public health issue.

Various studies have demonstrated that balance training is an effective method to enhance older adults' balance, thereby reducing the risk of falls [51]. Traditional methods for balance training include functional balance interventions (e.g., the Otago Exercise Program [80], perturbation-based balance training [25], and reactive balance training [42]) and physical exercises (e.g., Tai Chi, Qi Gong, dance, yoga, and kicking shuttlecock [31, 64]). However, long-term adherence to traditional exercises among older adults often declines with age, making it challenging for those living alone to maintain consistent exercise routines [100, 101]. These limitations may reduce the feasibility of long-term balance training using traditional methods, thereby affecting the effectiveness of balance interventions.

In recent years, virtual reality (VR) has emerged as a promising technology for enhancing older adults' physical health [1, 16, 34]. VR can bring the outside world into a controlled indoor environment, eliminating concerns about weather and spatial limitations [90]. VR exercises often include gamification designs, which can help older adults engage in meaningful activities through enjoyment [63]. Studies indicate that VR can provide practical alternatives to traditional exercise programs [10, 17, 28, 72, 93]. For example, SilverCycling provides VR-based cycling technology designed to enhance older adults' spatial orientation, delivering a safe and immersive user experience [10]. Similarly, Canoe VR is designed as a fitness tool for older players, with varying levels of game difficulty and rich visual feedback [36]. However, both SilverCycling and Canoe VR lack effective feedback on the long-term adherence of older adults to VR systems for enhancing physical health.

On the other hand, some commercial VR exergames have become tools for balance training in older adults [9, 12, 13, 17, 36, 83]. However, commercial VR exergames primarily designed for entertainment may not be efficient for long-term balance training, as they lack fundamental exercise principles and can be too complex for sustained adherence [14, 45, 83]. Therefore, developing customized VR exergames focusing on lower limb exercises is crucial to enhance the effectiveness of balance training [13, 17, 36, 83].

Overall, long-term balance training is necessary for older adults, including those who are healthy, and VR exergames have shown potentials in improving older adults' balance, but there are some challenges that need to be addressed with existing methods, including: 1) how to design customized VR exergames for effective balance enhancement; 2) how to motivate older adults to adhere to long-term training; 3) how to ensure older adults' safety during training.

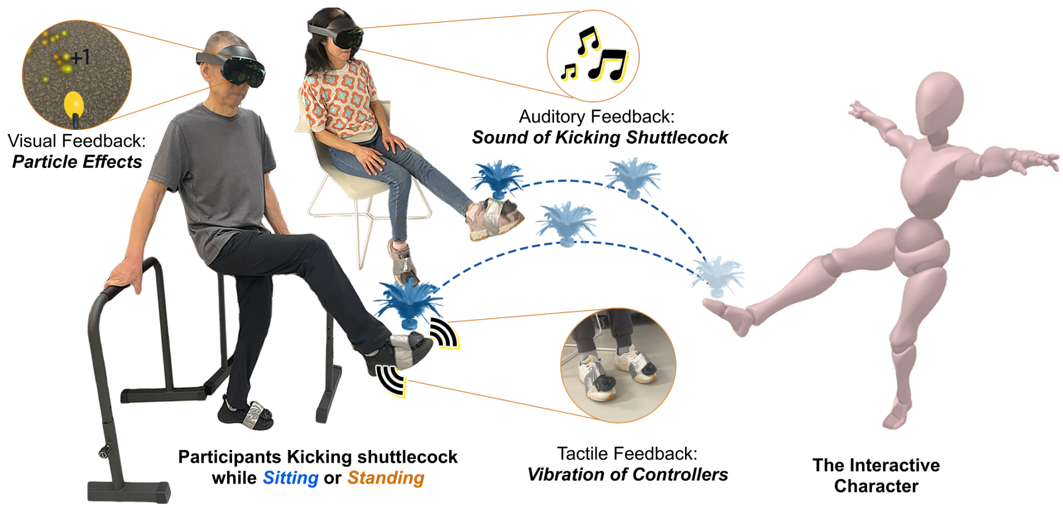

Fig. 1. The figure shows that two of the participants were performing balance training through kicking shuttlecock in VR with the interactive character while sitting or standing. When the participants cought the shuttlecock, they would experience multi-sensory feedback, including the visual feedback (particle effects in VR), the auditory feedback (the sound of kicking shuttlecock), and the tactile feedback (the vibration of controllers).

In this paper, we proposed a VR exergame, VR-Shuttlecock (shown in Figure 1), to assist older adults in targeted long-term balance training. We chose kicking shuttlecock as the exercise form because it is not only a fun and historically significant traditional recreational activity but also enhances balance through leg lifting and full-body coordination [7, 54, 74]. To design this VR exergame for balance training, we posed our first research question:

- RQ1: What design considerations should be taken to build a VR exergame that effectively supports balance training in older adults?

To answer RQ1, we conducted a formative study, recruiting 14 healthy older adults without mobility impairments (i.e., gender: 8 females, 6 males; age: M=64.93 years, SD=4.03 years) and explored their concerns regarding gamification, requirements for the VR environment, and expectations for VR interactivity through semi-structured interviews. Based on the findings from the formative study, we derived several design considerations: 1) effective leg exercise content; 2) motivation in encouraging long-term active engagement; 3) progressive difficulty; 4) safety in long-term physical exercise in VR. Based on these design considerations, the implementations of VR-Shuttlecock contain: 1) simplified exercises to enhance training efficiency, including simple and effective leg movements, as well as streamlined interaction with VR devices; 2) diverse gamification designs to enhance motivation, incorporating an open natural environment, interactive characters, and multi-sensory feedback; 3) customized progressive difficulty to ensure adherence; 4) corresponding protection measures for safety.

We conducted a four-week controlled experiment consisting of eight sessions, involving 14 older adults in the experimental group from the formative study and 13 older adults in the control group with similar physical conditions to assess the effectiveness of VR-Shuttlecock in enhancing balance ability. Participants in the experimental group engaged in a balance training program with sessions twice a week, each lasting twenty minutes, while the control group gained no interventions and maintained a regular daily routine. In the pre-test (before the training), the mid-test (after 2 weeks of training) and the post-test (after 4 weeks of training), we assessed participants using Single Leg Stance Test (SLST) [3, 8, 35, 61, 89, 96], Timed Up and Go Test (TUG) [29, 69, 81], Functional Reach Test (FRT) [15, 19, 76], and Y Balance Test (YBT) [24, 47, 70, 82] to quantitatively evaluate their balance abilities. Additionally, we gathered qualitative feedback through observations of participants' performances in VR-Shuttlecock and semi-structured interviews conducted at the conclusion of the training experiment. We employed both quantitative data and qualitative feedback to address the following research question:

- RQ2: Does VR-Shuttlecock enhance older adults' balance?
- RQ3: How do older adults perform in VR-Shuttlecock? What are their perceptions of using it for long-term balance training? What factors influence their performance and perceptions?

Our findings indicate that VR-Shuttlecock provides an engaging, effective, and safe long-term balance training program for older adults, employing strategies such as simplified exercises (kicking shuttlecock), diverse gamification designs (e.g., open natural environment, interactive characters, and multi-sensory feedback), customized progressive difficulty, and corresponding protection measures for safety. Through quantitative measures, participants in the experimental group showed significant improvements in SLST, TUG, FRT, and YBT after the four-week balance training. These findings prove the effectiveness of VR-Shuttlecock in enhancing older adults' balance. Through qualitative feedback, participants expressed a positive attitude toward using VR-Shuttlecock for long-term balance training. Their perceptions towards VR-Shuttlecock contain: subjective perception of balance improvement; motivation from gamification and multi-sensory feedback, including environment and immersion, interactivity of virtual characters, multi-sensory feedback, real-time feedback and goal setting; adaptability to progressive difficulty; psychological safety. Furthermore, we explored the guidelines for designing VR exergames for balance training. In summary, our contributions include:

- The design of a VR exergame, VR-Shuttlecock, which aims to motivate older adults to adhere to balance training. The game offers an enjoyable, leg-focused activity of kicking shuttlecock in a safe environment.
- We conducted a four-week controlled experiment to investigate the effectiveness of VR-Shuttlecock, as well as participants' performance in the game and their perceptions of using it for long-term balance training.
- We discussed the significance of VR-Shuttlecock and summarized the guidelines for designing VR exergames for balance training. These guidelines include aspects such as gamification design, multi-sensory feedback, progressive difficulty in training, and ensuring psychological safety.

2 RELATED WORK

To clarify our research motivation and identify existing research gaps, we reviewed related work on balance training for older adults, focusing on three key aspects: 1) We assessed the current state of balance decline in older adults and its severe consequences, and emphasized the importance of proactive measures to improve balance in older adults, including those who are healthy, for effective fall prevention; 2) We outlined the evolution of balance training methods (e.g., kicking shuttlecock) and noted challenges in accommodating older adults' physical condition and exercise adherence; 3) We examined VR technology's role in enhancing older adults' physical health and identified gaps in progressive difficulty and long-term adherence. This review aims to guide future research in advancing balance training for older adults.

2.1 Balance Decline in Older Adults

As older adults age, their balance declines relatively, influenced by factors such as decreased muscle strength, proprioception, cutaneous sensation, and vestibular function [44, 57, 87]. Previous research has demonstrated that balance decline in older adults is a significant public health concern [20, 43, 46, 58, 87, 88]. For example, Balance disorders significantly increase the risk of falls, leading to severe injuries like fractures and head injuries, which can result in increased morbidity and mortality [20, 87, 88]. The consequences of balance disorders are severe, with one in three people over 65 experiencing at least one fall annually, leading to potential loss of independence and increased healthcare costs [87]. Besides, poor balance is linked to an increased risk of cognitive impairment, indicating a bidirectional relationship in which cognitive decline can also exacerbate balance issues [20, 87, 88]. Additionally, there exists a reciprocal relationship between balance and depressive symptoms, where poor balance may contribute to increased depressive symptoms, while depression can also negatively impact balance [43].

Even healthy older adults, like those in this study, experience declines in muscle control, strength, and sensory function due to normal aging [21, 30, 56]. Although these changes may not result in immediate mobility issues or falls, they can increase the risk of falls in the future [56, 68]. Research shows that early preventive balance training is crucial and effective for this seemingly "healthy" population [50, 55]. Such interventions can delay or even reverse age-related functional decline, enhancing postural control, muscle strength, coordination, and overall balance abilities. They also boost confidence in balance control and reduce fear of falling [11], which significantly decreases the incidence of falls and their associated consequences [26, 60, 79, 97]. In conclusion, proactive measures to assess and improve balance in all older adults, including those who are healthy, are essential for effective fall prevention.

2.2 Traditional Methods of Balance Training for Older Adults

Various studies have demonstrated that balance training is an effective method to improve balance (e.g., static/dynamic balance, proactive/reactive balance and performance in balance test batteries) in older adults and reduce the risk of falls [51]. It's indicated that traditional methods for balance training, including functional balance intervention (e.g. Otago Exercise program [80], perturbation based balance training [25], reactive balance training [42], etc.) [80] and physical exercises (e.g., Tai Chi, Qi Gong, dance, yoga, kicking shuttlecock [7, 54, 74], etc.) [31, 64], could effectively improve older adults' balance.

For example, Tiffany E. Shubert et al. found that the Otago Exercise Program (OEP) is an effective intervention for improving balance and reducing the risk of falls among older adults [80]. Notably, this program does not require the involvement of a physical therapist [80]. Besides, Marissa H. G. Gerard et al. found that perturbation-based balance training PBT may be more effective and require fewer training sessions to reduce the risk of falls among older adults through experiments [25]. Furthermore, Youngwook Kim et al. emphasized that task-specific reactive balance training could be the best exercise to improve reactive balance in older adults [42]. Additionally, 3D physical exercises, including Tai Chi, Qi Gong, dance and yoga, can enhance balance performance in various assessments, such as the Berg Balance Scale, one-leg standing test, and Timed Up and Go test [31].

Particularly, kicking shuttlecock is a popular traditional leisure activity in China with a long history [48], which requires the utilization of the lower limbs to keep a feathered object, often made of feathers and either iron or cork, airborne for as long as possible [7, 32, 54, 74]. Kicking shuttlecock is not only a leisure activity for entertainment but also serves as a form of exercise that engages the legs and demands whole-body coordination, thereby enhancing balance and stability [7, 54, 74]. E. Spina et al. found that kicking shuttlecock could significantly improve balance performance, as measured by the Berg Balance Scale after a six-month intervention [85].

However, traditional methods exhibit certain limitations regarding the physical condition and exercise adherence of older adults. The commitment of older adults to traditional exercise often declines with age [100]. For older adults living alone, maintaining functional balance interventions or physical exercises can be particularly challenging [101]. These limitations may reduce the feasibility of long-term balance training using traditional methods, thereby negatively affecting the effectiveness of balance interventions.

2.3 VR for Older Adults Physical Health

In recent years, virtual reality (VR) has emerged as a promising technology for enhancing the physical health of older adults [1, 16, 34]. VR can bring the external world into a closed indoor environment [90], eliminating concerns about weather changes and spatial limitations. Additionally, engaging in leisure activities within VR can provide older adults with positive social and emotional experiences [90]. Moreover, VR exercises often incorporate gamification designs, which help older adults overcome boredom and engage in meaningful activities through enjoyment [63]. Various studies indicate that VR can provide practical alternatives to traditional exercise programs [10, 17, 28, 72, 93]. For instance, SilverCycling offers VR cycling technology to improve spatial orientation for older adults, providing a safe and intuitive virtual experience with indoor bicycles [10]. Similarly, Canoe VR is a fitness tool designed for older players, featuring adjustable game difficulty and rich visual feedback [36]. However, SilverCycling does not adequately address progressive game difficulty, while Canoe VR lacks sufficient exploration of real-time sensory feedback. Most importantly, both systems fail to provide effective feedback on long-term adherence among older adults, which is crucial for enhancing physical health.

On the other hand, some commercial VR exergames have become tools for balance training in older adults, providing an engaging and effective way to improve physical function and reduce the risk of falls [9, 12, 13, 17, 36, 83]. However, the efficiency of these commercial VR exergames in providing long-term balance training for older adults is questionable, as they are primarily designed for entertainment rather than based on fundamental exercise principles [14, 83]. Additionally, the complexity of certain VR exergames may hinder users from adhering to their exercise plans [45], which can compromise older adults' commitment to long-term training. Although Sebastian Cmentowski et al. designed and developed a VR game prototype for training vertical jumps and adjusted the difficulty based on player abilities and improvements [13], this is not suitable for older adults to exercise their lower limbs due to the risk of collisions during jumping [13]. Therefore, customized VR exergames focusing on the lower limbs are particularly crucial for further enhancing the effectiveness of balance training [13, 17, 36, 83]. Overall, long-term balance training is crucial for older adults, including those who are healthy. While VR exergames show potential in enhancing balance among older adults, there are several challenges that need to be addressed with existing methods to maximize their effectiveness, including: 1) how to design customized VR exergames for effective balance enhancement; 2) how to motivate older adults to adhere to long-term balance training; 3) how to ensure the safety of older adults during training.

In comparison to traditional balance training and commercial VR exergames, VR-Shuttlecock in this study combines kicking shuttlecock with VR technology, offering the following unique advantages: 1) introducing kicking shuttlecock as an exercise targeting the lower limbs to effectively enhance balance; 2) utilizing VR to control virtual shuttlecocks, thereby designing progressive game difficulty to encourage older adults to adhere to long-term balance training; 3) employing virtual shuttlecocks triggered by interactive characters to eliminate the risks that older adults might face when kicking shuttlecock in the real world (e.g., the risk of falling); 4) creating a virtual social space by rendering a park environment, allowing for home-based exercises without the constraints of weather or physical location; and 5) providing older adults with opportunities for social interaction with interactive characters, thereby reducing the sense of loneliness and social isolation.

3 DESIGN OF VR-SHUTTLECOCK

Based on insights from prior literature, we decided to introduce kicking shuttlecock into VR exergames, allowing older adults to engage in leg exercises while enjoying this leisure activity, ultimately enhancing their balance. To address RQ1, we conducted a formative study to understand what aspects older adults focus on when kicking shuttlecock, which would inform the design of a VR exergame that incorporates this activity for balance training. From the findings of the formative study and related previous work, we identified four key design considerations. These considerations guided our development of the VR exergame that combines kicking shuttlecock with VR for both entertainment and balance training.

3.1 Formative Study

In order to design this VR exergame following the human-centered principle, we conducted semi-structured interviews with older adults to understand their concerns.

Table 1. Participants' Demographic Information, Physical Health Status, the Willingness for Balance Training, Familiarity with Kicking Shuttlecock and VR Experience.

ID	Age	Gender	Fall Experience	Mobility Impairments	Willingness for Balance Training	The Experience of Kicking Shuttlecock	The Last Time of Kicking Shuttlecock	Prior VR Experience
P1	62	Female	No	No	Yes	In Childhood	Over 50 Years Ago	No
P2	60	Male	No	No	Yes	In Childhood	Over 50 Years Ago	No
P3	66	Female	No	No	Yes	In Childhood	Over 50 Years Ago	No
P4	63	Female	No	No	Yes	In Youth	Over 40 Years Ago	No
P5	61	Female	No	No	Yes	No	Never	No
P6	60	Male	No	No	Yes	In Childhood	Over 50 Years Ago	No
P7	67	Male	No	No	Yes	In Childhood	Over 50 Years Ago	No
P8	64	Female	No	No	Yes	Recently	Last Week	No
P9	61	Female	No	No	Yes	In Childhood	Over 50 Years Ago	No
P10	65	Male	No	No	Yes	In Childhood	Over 50 Years Ago	No
P11	70	Female	No	No	Yes	In Youth	Over 50 Years Ago	No
P12	71	Male	No	No	Yes	In Childhood	Over 60 Years Ago	No
P13	73	Female	No	No	Yes	In Childhood	Over 60 Years Ago	No
P14	66	Male	No	No	Yes	In Youth	Over 40 Years Ago	No

3.1.1 Data Collection.

First, we distributed a questionnaire to recruit eligible older adults for semi-structured interviews. The questionnaire included demographic information (i.e., gender, age), physical health status (i.e., fall experience, mobility impairments), the need and willingness to participate in balance training, familiarity with kicking shuttlecock, and previous experiences and acceptance of VR. Ultimately, we recruited 14 healthy older adults without mobility impairments who were willing to improve their balance through kicking shuttlecock in VR (age: M=64.93 years, SD=4.03 years) and conducted semi-structured interviews with them. Participants' demographic information is detailed in Table 1. With informed consent, we recorded the interview content, which lasted approximately twenty minutes per person. The interviews covered three themes: concerns about game design; requirements for the VR environment; and expectations for the VR interaction.

3.1.2 Data Analysis.

After the interview, the recordings were transcribed into text scripts, and then three researchers independently encoded the scripts based on these three topics using an open coding method [86]. Finally, researchers compiled and shared their findings, summarizing and comparing the similarities and differences to ensure the completeness and objectivity of the data.

3.1.3 Findings.

Through semi-structured interviews, we explored the reasons why participants are currently reluctant to kick shuttlecock. By prompting them to imagine scenarios of kicking shuttlecock in VR, we also gathered insights into their preferences and concerns regarding a system combining VR with kicking shuttlecock. Our key findings from the analysis of interviews are as follows:

Reasons for not Kicking Shuttlecock Now. We learned that one participant had never kicked the shuttlecock, while another recently resumed the activity after discovering its benefits through short videos. Most participants (n=12) had experience with shuttlecock kicking in childhood or youth, but their last engagement with the activity occurred at least forty years ago, leading to decades of inactivity. Several reasons contributed to their reluctance to continue the activity. Firstly, 13 participants expressed a fear of falling, a common concern among older adults that causes hesitation when considering kicking shuttlecock. Secondly, many (n=12) regarded it primarily as a recreational activity from their youth and did not recognize its benefits for balance, which led to the gradual abandonment. Additionally, 6 participants reported a decline in physical coordination with age, making it more challenging to catch shuttlecocks. This difficulty negatively affected their confidence and contributed to their reluctance to participate, despite their awareness of the potential benefits.

Minimal Interaction with VR Devices. Due to the lack of VR experience, many older adults stated that they were reluctant to engage in complex interactions with VR devices, such as using controllers for command input. They preferred simple interaction with the virtual environment using their hands or legs.

Open Outdoor Spaces. The interviews revealed that older adults preferred kicking shuttlecock in open outdoor spaces, such as parks, gardens and squares. These venues offer enough space for unrestricted movement and provide opportunities for more people to join in.

Preference for Interactive Kicking Shuttlecock. Kicking shuttlecock is a relatively flexible activity that allows older adults to play alone or interact with others. However, our interviews revealed a preference for multiplayer interactive kicking. Many participants indicated that while solo kicking could be physically beneficial, it often lacked enjoyment. This diminished enjoyment led to a gradual loss of motivation, making it difficult for them to sustain the activity.

Concerns About Game Difficulty. Most older adults expressed concerns about the game's difficulty, which could hinder their participation. Therefore, when designing the VR exergame, it is essential to ensure a gradual progression of difficulty and simplify the game flow to help maintain their confidence.

Concerns About Safety. Most older adults indicated that although they used to kick shuttlecock in their youth, they now fear falling, which has led to infrequent participation in the activity due to aging and the decline in lower limb strength and flexibility. When it comes to kicking shuttlecock in VR, they expressed a need for protective measures to enhance their psychological safety.

3.2 Design Considerations

Based on the findings of our formative study and previous literature on VR exergames, we identified the following four design considerations to guide the design and development of VR-Shuttlecock.

3.2.1 DC1: Effective Leg Exercise Content.

When designing the VR exergame as a balance intervention, our primary goal is to enhance the effectiveness of balance training. To achieve this, we considered simplified movements and scenarios related to kicking shuttlecock, emphasizing leg exercises. Additionally, the interviews revealed that older adults preferred minimal interaction with VR devices and direct engagement with the virtual environment using their body parts. Consequently, we simplified the game content and interaction methods, allowing older adults to focus their energy and physical effort on leg-raising activities.

3.2.2 DC2: Motivation in Encouraging Long-term Active Engagement.

The interviews highlighted older adults' preference for kicking shuttlecock in open outdoor spaces and their desire to recall familiar things through VR [90]. They also expressed a preference for multiplayer interactive kicking shuttlecock. To foster long-term training adherence, VR-Shuttlecock creates a familiar outdoor park environment that enhances the immersive experience through multi-sensory elements, such as environmental sounds. Additionally, interactive characters are integrated into VR-Shuttlecock to enhance players' performance, overall experience, and exertion levels [4, 27, 99].

Furthermore, previous research indicates that older adults often struggle to maintain exercise routines [101], which can reduce the effectiveness of balance training. Some studies emphasize the importance of promoting game adherence [83], as enhancing motivation is crucial for encouraging long-term active engagement. Prior research has shown that multi-sensory feedback can significantly enhance user immersion and interaction within virtual environments [49, 95, 102]. Therefore, we incorporated multi-sensory feedback into the design of VR-Shuttlecock to enrich the balance training experience and improve adherence among older adults.

3.2.3 DC3: Progressive Difficulty.

To help older adults adapt to the training process, the game difficulty in VR-Shuttlecock gradually increases. This progressive difficulty is essential for maintaining player engagement and motivation, as it allows the game to start with easier levels that help players understand the basic mechanics and gradually introduce more challenging obstacles as players progress [23, 71]. This gradual increase in difficulty is crucial for providing a satisfying experience and ensuring that older adults remain motivated to continue playing.

3.2.4 DC4: Safety in Long-term Physical Exercise in VR.

Some literature indicates that users may experience cybersickness or perceive a higher physical workload in VR exergames [45]. Our interviews also revealed older adults' concerns about falling while kicking shuttlecock. Therefore, it is crucial to minimize the risk of cybersickness, which can arise from a mismatch between visual and vestibular inputs. This mismatch often occurs due to delays in visual updates in VR environments, particularly during rapid head movements [41, 53, 62, 77, 84]. To mitigate the likelihood of cybersickness and reduce physical workload, VR-Shuttlecock incorporates stationary movement, eliminating the need for older adults to walk or redirect within the virtual environment [94]. This design consideration helps ensure a safer and more comfortable experience while still allowing for effective balance training.

4 SYSTEM IMPLEMENTATION

Based on the exploration of design considerations, we developed VR-Shuttlecock using Unity3D [91] to provide an effective and engaging balance training tool for older adults. During the implementation phase, we focused on creating customized game content for targeted leg exercises. Besides, also employed several strategies (e.g., an immersive VR environment, interactive characters, and multi-sensory feedback) to motivate older adults to engage in long-term exercise. Furthermore, we considered progressive difficulty and safety in the VR exergame to ensure a comfortable and effective balance intervention. In this section, we detail the scenario of VR-Shuttlecock and the technical implementations based on our design considerations.

Before launching the system, we invited five older adults who had participated in the formative study to test VR-Shuttlecock. Based on their experience feedback, we made adjustments to the details of VR-Shuttlecock, including the frequency of the interactive character's leg lifting, the flight time and distance of the shuttlecock, the intensity and duration of the vibration of the controllers on participants' feet when catching the shuttlecock, as well as the duration of each training session and the training frequency. These modifications were aimed at enhancing the participants' experience during balance training within VR-Shuttlecock.

4.1 The Scenarios of VR-Shuttlecock

In VR-Shuttlecock, participants are immersed in a natural park environment, where they face a simple virtual character while their bodies remain out of view. Only their feet are tracked using controllers, and when looking down, participants can see two small yellow spheres that represent the controllers attached to their feet. The game is initiated by researchers on a computer connected to the VR headset. At the beginning, a timer appears above the virtual character and counts down. After a 10-second acclimatization period, the character start to alternate raising its legs every 2 seconds. When the leg reaches a specific height, a virtual shuttlecock is generated, following a parabolic trajectory to a fixed location within 2 seconds. Participants must lift one foot to catch the shuttlecock using the yellow spheres. A successful catch occurs when a yellow sphere collides with the shuttlecock, which then visually disintegrates into particle effects, accompanied by a "+1" notification. At the same time, the corresponding controller vibrates, and participants hear the sound of a successful catch. If the catch

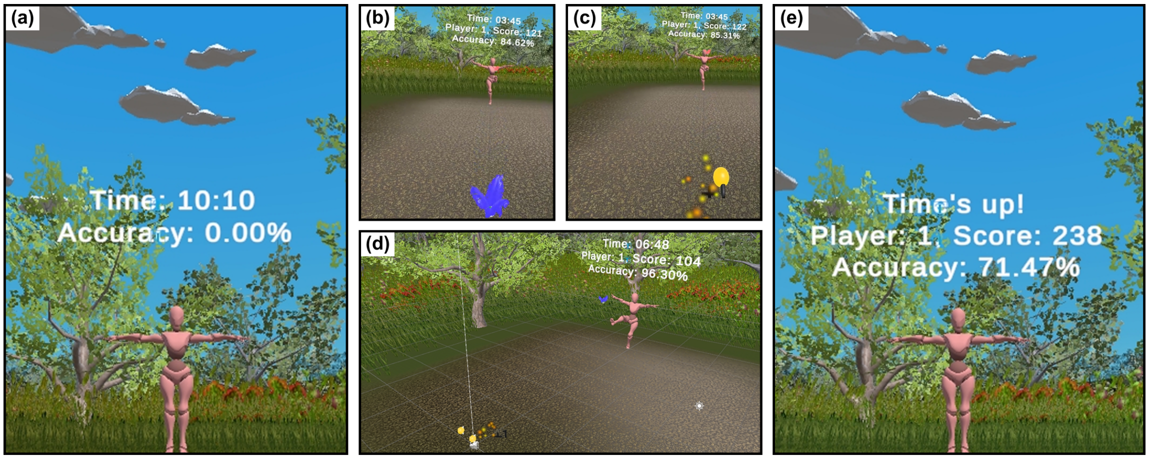

Fig. 2. The scenarios of VR-Shuttlecock include: (a) The participant's view at the beginning of the training session; (b) The participant's view as the virtual shuttlecock flies in front of them; (c) The participant's view when they successfully catch the virtual shuttlecock, featuring particle effects and a "+1" notification; (d) The spectator's view when the participant catches the virtual shuttlecock; (e) The participant's view at the end of the training session.

is unsuccessful, the shuttlecock disappears without any feedback. Throughout the game, the timer, score, and catch accuracy are updated in real time. When the countdown ends, the character stops moving, and participants can view their final score and accuracy.

4.2 Simplified Exercises to Enhance Training Efficiency (DC1)

4.2.1 Simple and Effective Leg Movements.

Kicking shuttlecock contains various movements (e.g., kicking straight forward, kicking forward with a bent leg, kicking backward, turnaround kick). However, many of these movements are too complex for older adults. Therefore, we designed the scene to feature shuttlecocks flying directly in front of the players, allowing them to perform a simple straight kick.

4.2.2 Streamlined Interaction with VR Devices.

In VR-Shuttlecock, the controllers paired with the VR headset are not used for hand interactions. Instead, they are attached to the player's feet to track foot position. In the VR interface, a small yellow ball represents the player's foot. During gameplay, older adults do not need to interact with the controllers. They simply lift their legs to catch virtual shuttlecocks generated by interactive characters. This design minimizes the burden of VR interactions, allowing participants to concentrate on balance training and enhancing its effectiveness.

4.3 Diverse Gamification Designs to Enhance Motivation (DC2)

As shown in Figure 3, the diverse gamification designs contain the design of VR environment, interactive characters and multi-sensory feedback.

4.3.1 The Design of VR Environment.

VR-Shuttlecock simulates an open natural park environment, which is familiar to older adults as a spacious outdoor venue for activities. In addition to natural elements like flora and fauna, the virtual environment features

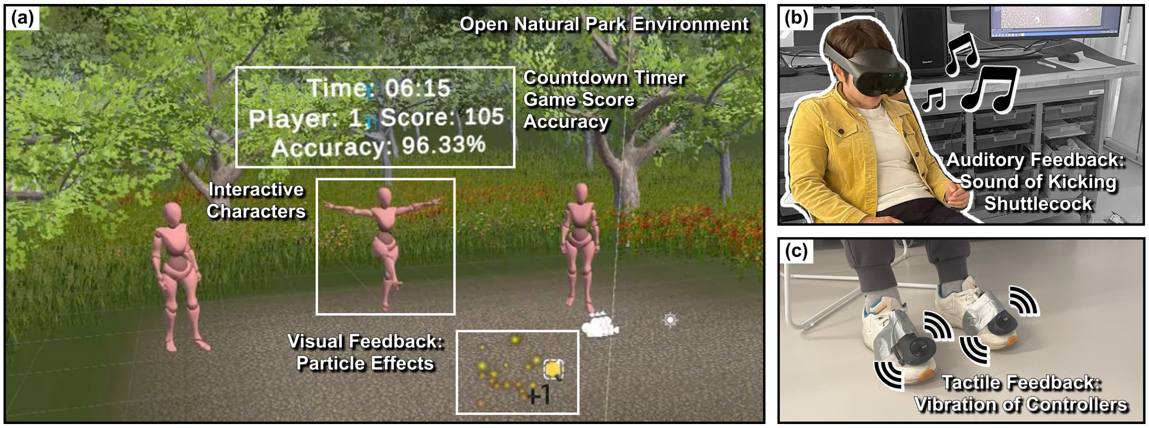

Fig. 3. The diverse gamification designs: (a) the design of VR environment (the open natural park environment), interactive characters, real-time temporal and score, visual feedback (particle effects); (b) the auditory feedback (the sound of kicking shuttlecock); (c) the tactile feedback (the vibration of controllers).

ambient sounds such as flowing water and bird calls, along with soothing music. This combination creates a comfortable and leisurely atmosphere that enhances immersion and a sense of presence [37, 38].

4.3.2 Interactive Characters for Social Interaction.
In VR-Shuttlecock, interactive characters with engaging attributes are introduced to compensate for the absence of real-life companions. At the start of the game, these characters simulate a leg-lifting motion to trigger the generation of shuttlecocks. The generated shuttlecock flies from the interactive character's foot to a fixed location on the ground before disappearing. Players positioned at this location must lift their legs to catch the shuttlecock before it lands. Successfully catching the shuttlecock earns them a corresponding score. The virtual characters stimulate participants' leg-lifting movements by alternately lifting their legs, thereby creating an interactive experience through their actions.

4.3.3 Multi-sensory Feedback.
Real-time Temporal and Score. In the VR interface, a countdown timer is displayed above the interactive character facing the player. An algorithm provides real-time feedback on scores and accuracy, allowing participants to see their scores immediately after catching the shuttlecock, which serves as positive reinforcement. This real-time feedback on timing and scoring can motivate players to engage more actively in the game [67, 73].

Real-time Multi-sensory Feedback. When players successfully kick the shuttlecock, they will receive multi-sensory feedback across tactile, visual, and auditory dimensions. As the controller's position briefly aligns with the shuttlecock's location, it vibrates to provide **tactile feedback**. At the same time, players experience **visual feedback** as the kicked shuttlecock transforms into particle effects, accompanied by a "+1" display. Additionally, the VR headset delivers **auditory feedback** that simulates the sound of kicking the shuttlecock, sourced from real-life recordings. This multi-sensory feedback not only creates an immersive experience similar to physically kicking a shuttlecock through auditory and tactile sensations but also enhances enjoyment with visual effects that differ from reality. This combination effectively motivates players to continue their training.

Based on participant feedback, we adjusted the vibration intensity and duration of the controllers worn on their feet. We incorporated a feature into the yellow sphere that enables real-time adjustments of vibration settings during gameplay. Initially, the vibration duration was set to 0.1 seconds, but participants felt this was too long,

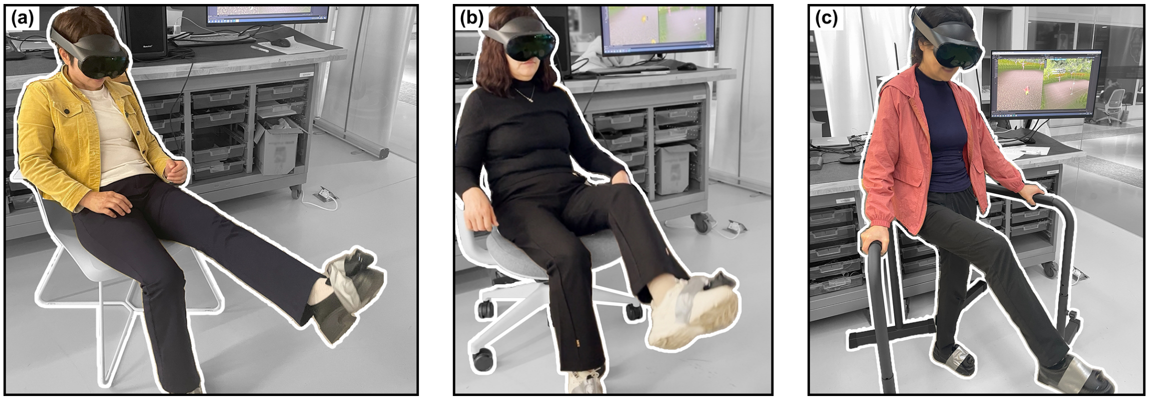

Fig. 4. The different protective measures: (a) The participant is kicking shuttlecock with one character while sitting in a fixed chair; (b) The participant is kicking shuttlecock with three characters while sitting in a rotatable chair; (c) The participant is kicking shuttlecock while standing in a fixed position while holding the fitness poles.

resulting in a sensory mismatch when catching the shuttlecock. Consequently, we reduced the duration to 0.05 seconds. The initial vibration intensity was set at 0.5, but some participants found it insufficient due to their shoe material. After increasing the intensity to 0.9, all participants expressed satisfaction with the feedback.

4.4 Customized Progressive Difficulty for Adherence (DC3)

Recognizing that many older adults lack VR experience and have concerns about game content that could increase their physical load, we developed a progressive difficulty system. The game features four difficulty levels: (1) Level 1 involves the player sitting in a fixed chair while kicking shuttlecock with one character; (2) Level 2 requires the player to sit in a rotating chair and interact with three characters, with fixed interaction duration and frequencies; (3) Level 3 involves standing and kicking shuttlecock with one character; (4) Level 4 requires the player to stand and interact with three characters, featuring random interaction duration and frequencies.

Based on participants' feedback gathered during testing, we made adjustments to the game duration and the frequency of the interactive character's leg movements, which influence the player's leg-lifting frequency. Each training session lasts 20 minutes, with the first phase (difficulty level 1) structured as follows: 4 minutes, 8 minutes, and another 8 minutes. The subsequent three phases each consist of 10 minutes followed by another 10 minutes. In the first three difficulty levels, the interval between interactions is set at 1.8 seconds to ensure players complete the leg-lifting motion. In difficulty level 4, where players stand and interact with three characters, the interval ranges from 2.06 to 2.08 seconds to facilitate successful leg-lifting.

4.5 Corresponding Protection Measures for Safety (DC4)

At the first two difficulty levels, players engage in leg exercises by sitting in a chair and interacting with interactive characters, as shown in Figure 4(a) and Figure 4(b). This process helps participants acclimate to the VR experience. By focusing on stationary leg movements rather than walking-based locomotion, we reduce physical exertion and lower the likelihood of cybersickness [94]. At the last two difficulty levels, players stand in a fixed position to interact with interactive characters, as shown in Figure 4(c). During this process, fitness poles are provided on either side of the player for support, eliminating the risk of falling due to unbalanced standing.

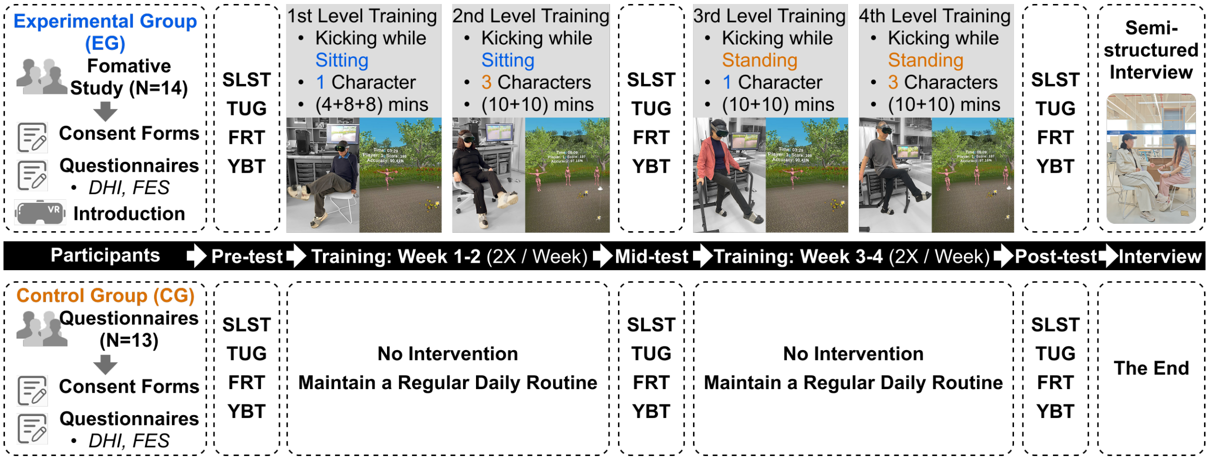

Fig. 5. The evaluation process consists of seven components: Preparation of participants in both the experimental group (EG) and the control group (CG) before training; Pre-tests for both groups, which include the Single Leg Stance Test (SLST), Timed Up and Go (TUG), Functional Reach Test (FRT), and Y Balance Test (YBT); EG participates in four balance training sessions over two weeks, while CG has no intervention and maintains a regular daily routine; Mid-tests for both groups, including SLST, TUG, FRT, and YBT; EG again conducts four balance training sessions over two weeks, while CG continues with no intervention. Post-tests for both groups, which include SLST, TUG, FRT, and YBT. Semi-structured interviews with EG following the balance training.

5 EVALUATION

To understand whether and how VR-Shuttlecock enhance older adults' balance, we conducted a controlled user study to evaluate the effectiveness of VR-Shuttlecock and assess older adults' experience. We focused on two aspects: 1) the effectiveness of VR-Shuttlecock in enhancing balance (RQ2); 2) older adults' performance in VR-Shuttlecock, their perceptions of using it for long-term balance training and the factors affecting their perceptions (RQ3). Considering these motivations for our user study, we employed quantitative measures to answer RQ2 and qualitative feedback to answer RQ3. The evaluation process is illustrated in Figure 5.

5.1 Participants

This study utilized repeated measures analysis of variance, involving two groups (EG and CG), each undergoing three repeated measures. At a significance level of α = 0.05, with a large effect size (f = 0.4) and a correlation parameter of ρ = 0.5 in the repeated measures design, we determined that a minimum sample size of 12 participants per group would provide 80% statistical power. To ensure the relevance and effectiveness of the user experiment in relation to our design considerations, we invited the same group of 14 older adults who participated in the formative study to evaluate the VR-Shuttlecock, which was developed in response to their concerns. EG consisted of 14 participants, meeting the sample size requirement. Additionally, to validate our findings and enhance the credibility of the study, we recruited another 14 healthy older adults for CG through a questionnaire. However, one participant withdrew from the experiment due to a scheduling conflict after the pre-test, leading to the exclusion of her data.

The information of participants in EG is detailed in Table 2 and the information of participants in CG is detailed in Table 3. To ensure the experiment proceeded smoothly and safely, all participants met the following health criteria: 1) no severe vision problems; 2) no mobility impairments; 3) no severe balance disorders or dizziness. All

Table 2. Demographic Information, Familiarity with Kicking Shuttlecock and Physical Health Status of Participants in EG.

ID	Age	Gender	Height (cm)	Weight (kg)	The Experience of Kicking Shuttlecock	The Last Time of Kicking Shuttlecock	Vision Problems	Mobility Impairments	Dizziness Handicap Inventory (DHI)	Falls Efficacy Scale (FES)
EP1	62	Female	164	72	In Childhood	Over 50 Years Ago	No	No	20 (Mild Handicap)	40 (High concern)
EP2	60	Male	160	55.5	In Childhood	Over 50 Years Ago	No	No	10	17 (Low concern)
EP3	66	Female	164	55	In Childhood	Over 50 Years Ago	No	No	10	32 (High concern)
EP4	63	Female	155	57	In Youth	Over 40 Years Ago	No	No	12	37 (High concern)
EP5	61	Female	157	56	No	Never	No	No	22 (Mild Handicap)	33 (High concern)
EP6	60	Male	172	61	In Childhood	Over 50 Years Ago	No	No	4	23 (Moderate concern)
EP7	67	Male	182	72.5	In Childhood	Over 50 Years Ago	No	No	24 (Mild Handicap)	22 (Moderate concern)
EP8	64	Female	158	53	Recently	Last Week	No	No	4	16 (Low concern)
EP9	61	Female	162	52	In Childhood	Over 50 Years Ago	No	No	14	37 (High concern)
EP10	65	Male	158	47	In Childhood	Over 50 Years Ago	No	No	2	19 (Low concern)
EP11	70	Female	163	51	In Youth	Over 50 Years Ago	No	No	12	32 (High concern)
EP12	71	Male	163	56	In Childhood	Over 60 Years Ago	No	No	4	29 (High concern)
EP13	73	Female	160	54	In Childhood	Over 60 Years Ago	No	No	0	23 (Moderate concern)
EP14	66	Male	157	50	In Youth	Over 40 Years Ago	No	No	12	23 (Moderate concern)

Table 3. Demographic Information, Familiarity with Kicking Shuttlecock and Physical Health Status of Participants in CG.

ID	Age	Gender	Height (cm)	Weight (kg)	The Experience of Kicking Shuttlecock	The Last Time of Kicking Shuttlecock	Vision Problems	Mobility Impairments	Dizziness Handicap Inventory (DHI)	Falls Efficacy Scale (FES)
CP1	60	Male	160	62	In Youth	Over 40 Years Ago	No	No	4	21 (Moderate concern)
CP2	61	Female	158	44	In Youth	Over 40 Years Ago	No	No	2	17 (Low concern)
CP3	60	Female	157	55	In Youth	Over 40 Years Ago	No	No	10	24 (Moderate concern)
CP4	63	Female	165	55	In Childhood	Over 50 Years Ago	No	No	16 (Mild Handicap)	26 (Moderate concern)
CP5	64	Female	155	57	In Youth	Over 40 Years Ago	No	No	2	23 (Moderate concern)
CP6	67	Male	170	62	No	Never	No	No	0	26 (Moderate concern)
CP7	61	Female	160	60	In Childhood	Over 40 Years Ago	No	No	4	28 (High concern)
CP8	60	Female	152	66	In Childhood	Over 40 Years Ago	No	No	12	35 (High concern)
CP9	68	Female	168	68	In Childhood	Over 50 Years Ago	No	No	2	23 (Moderate concern)
CP10	62	Female	156	70	In Childhood	Over 50 Years Ago	No	No	24 (Mild Handicap)	41 (High concern)
CP11	63	Female	160	55	In Youth	Over 40 Years Ago	No	No	2	40 (High concern)
CP12	70	Male	164	60	No	Never	No	No	6	16 (Low concern)
CP13	62	Male	165	51	In Childhood	Over 50 Years Ago	No	No	2	16 (Low concern)

participants were required to complete two questionnaires: 1) The Dizziness Handicap Inventory (DHI) [65], to assess dizziness or unsteadiness in daily life; 2) Falls Efficacy Scale (FES) [66], to evaluate concerns about falling in various situations. Regarding the Dizziness Handicap Inventory (DHI), scores between 16 and 34 indicate a mild handicap. For the Falls Efficacy Scale (FES), scores of 16 to 19 signify low concern, 20 to 27 indicate moderate concern, and 28 to 64 reflect high concern. Results showed that three participants in EG reported a mild level of dizziness-related disability, while two in CG did as well. In EG, three participants exhibited low concern about falling, four had moderate concern, and seven had high concern. In CG, three showed low concern, six had moderate concern, and four had high concern. Overall, neither group had severe balance impairments or dizziness that would hinder participation in the study. Most participants expressed significant concern about potential falls, highlighting a strong demand for balance training.

Additionally, as shown in Table 4, we compared age, height, and weight between the control and experimental groups. The Shapiro-Wilk test indicated that age data for both groups followed a normal distribution (experimental group: p=0.0931; control group: p=0.211). However, while EG's height (p=0.7444) and weight (p=0.9654) also met normality criteria, CG did not (height: p=0.0119; weight: p=0.0193). An independent samples t-test on age indicated no significant differences (p=0.3252) between the groups. Mann-Whitney U tests for height (p=0.4946) and weight (p=0.5595) further suggested no significant differences respectively. Therefore, we conclude that the participants in both groups did not differ significantly in age, height, or weight.

Table 4. The Comparison of Characteristics (i.e., Age, Height, Weight) of CG and EG.

Characteristic	Control Group (N=13)	Experimental Group (N=14)	p-value	Significance
Age (years)	64.8 (±4.34)	63.4 (±3.23)	0.3252 (t-test)	No significant difference
Height (cm)	162.9 (± 7.15)	160.5 (±5.21)	0.4946 (Mann-Whitney U Test)	No significant difference
Weight (kg)	57.1 (±7.50)	58.2 (±7.26)	0.5595 (Mann-Whitney U Test)	No significant difference

Before the experiment began, we obtained written informed consent from all participants, detailing the purpose of the study and the tasks involved. Participants were informed of their right to withdraw at any time. One participant in CG withdrew from the experiment due to time constraints. Compensation was provided upon completion of the study. The research was conducted within the university and received approval from the university's ethics committee.

5.2 Apparatuses

Our training system was built on a computer and we used one Meta Quest Pro for the experiment. The VR headset was connected to a computer via a VR streaming cable. During the balance training, the game was launched on the Unity3D interface on the computer, while participants wore the VR headset and used controllers taped to their feet to catch the virtual shuttlecocks in VR.

5.3 Experimental Procedure

According to DiStefano et al., balance training programs that consist of at least 10 minutes per day, 3 days per week, for a duration of 4 weeks can significantly enhance balance ability [18]. Besides, Ren et al. found that the plan with 20–45 min, 5–8 week, and over 3 times per weel had significantly effects [75]. Based on participants' feedback regarding the reduction of training intensity, we customized the duration and frequency of balance training for this study. EG participated in a 4-week program, attending 2 sessions per week, each lasting at least 20 minutes. This resulted in a total of 8 sessions and 160 minutes of training. In contrast, CG received no intervention and continued with their regular routines. Following Khumpaneid et al., we evaluated participants' balance three times [39]. Both EG and CG completed a pre-test before the training, a mid-test at the end of the second week, and a post-test at the end of the fourth week. The pre-tests, mid-tests, and post-tests consisted of four same assessments. Additionally, after completing all 8 sessions, each participant from EG engaged in a 20-minute semi-structured interview. Researchers were present throughout to provide necessary assistance.

5.4 Data Collection and Analysis

5.4.1 Quantitative Data for RQ2.

We employed quantitative measures to demonstrate the effectiveness of VR-Shuttlecock in improving balance. As shown in Figure 6, their balance was measured using the following assessments: Single Leg Stance Test (SLST), Timed Up and Go Test (TUG), Functional Reach Test (FRT) and Y Balance Test (YBT). It is important to note that game scores in this experiment were not related to balance ability, serving only as a motivation for participation.

Single Leg Stance Test (SLST). SLST is commonly used to assess static balance, particularly single-limb stability in older adults [3, 8, 35, 61, 89, 96]. Participants stood unassisted on one leg with eyes open and arms at their sides. Timing began when they were ready and stopped when the other foot touched the ground or hands left their sides. The test was repeated with the other leg, with a duration of over 30 seconds indicating good balance.

Timed Up and Go Test (TUG). TUG is a widely used method for assessing lower limb function and mobility in older adults [29, 69, 81], though its predictive ability for fall risk is limited [5, 6]. Participants started seated with hands on armrests. Timing began as they stood, walked three meters to a mark, turned, and returned to sit, with timing stopping upon sitting. Use of assistive devices and any gait instability were recorded.

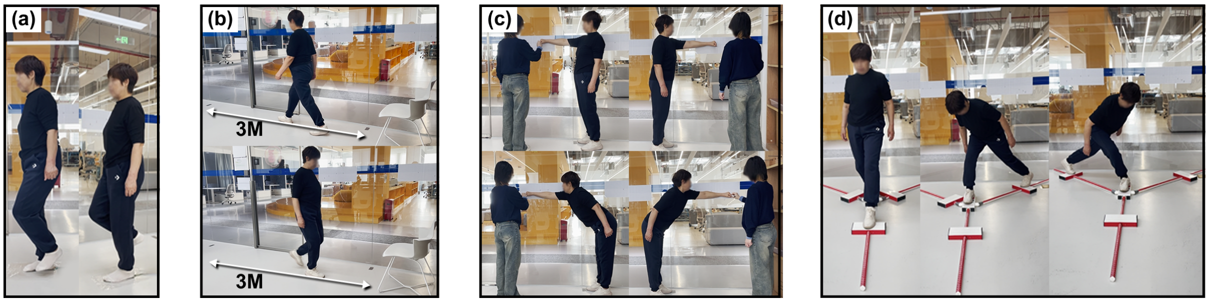

Fig. 6. Four assessments for older adults' balance: (a)Single Leg Stance Test (SLST); (b)Timed Up and Go Test (TUG); (c)Functional Reach Test (FRT); (d)Y Balance Test (YBT).

Functional Reach Test (FRT). FRT assesses dynamic balance during forward reach in older adults [15, 19, 76]. Participants stood beside a wall with their arm at 90 degrees of shoulder flexion. The starting position was recorded on graph paper, and upon cue, participants reached forward without moving their feet. The distance was measured, and the test was repeated three times, with the final score being the average of the last two measurements, also performed on the other side.

Y Balance Test (YBT). YBT assesses dynamic balance [24, 47, 70, 82]. In this assessment, participants stood on one foot at the center of the board and reached forward, sideways, and backward with the other leg. Researchers recorded the reach distances, and participants switched legs to repeat the test. Assistance was provided to help prevent falls in case of sudden imbalances.

5.4.2 Qualitative Data for RQ3.

During balance training with VR-Shuttlecock, researchers were present to observe and record each participant's performance, including physical movements and verbal feedback, analyzing differences across game scenarios.

Following the four-week intervention, each participant of EG engaged in a 20-minute semi-structured interview to discuss their perceptions of long-term balance training using VR-Shuttlecock and corresponding factors (RQ3). Five themes were emphasized: effectiveness, motivation, difficulty, safety, as well as preferences regarding gamification design and training scenarios. The following questions were used to explore older adults' perspectives:

- Do you believe VR-Shuttlecock effectively helps improve your balance? If so, in what aspects?
- Which design features motivate you to persist in long-term training? Why?
- Is VR-Shuttlecock difficult for you, and how does it compare to real-life shuttlecock kicking?
- Would you like to adjust the difficulty level of VR-Shuttlecock? If so, which aspects (session duration, leg-lifting frequency, movement complexity) would you adjust?
- Did you experience any discomfort while kicking the shuttlecock in VR, or have any concerns about falling? What measures do you think could effectively alleviate your safety concerns?
- How do you evaluate the gamification designs in VR-Shuttlecock, such as the VR environment, interactive characters and multi-sensory feedback? Would you like to keep or change any of these designs, and why?

6 RESULTS AND FINDINGS

In the following section, we present the results and findings of our user study. We aimed to determine whether VR-Shuttlecock effectively enhanced older adults' balance. Additionally, we gained insights into the participants' performance throughout the training process, as well as their perceptions of using VR-Shuttlecock for long-term balance training and the associated factors influencing their perceptions.

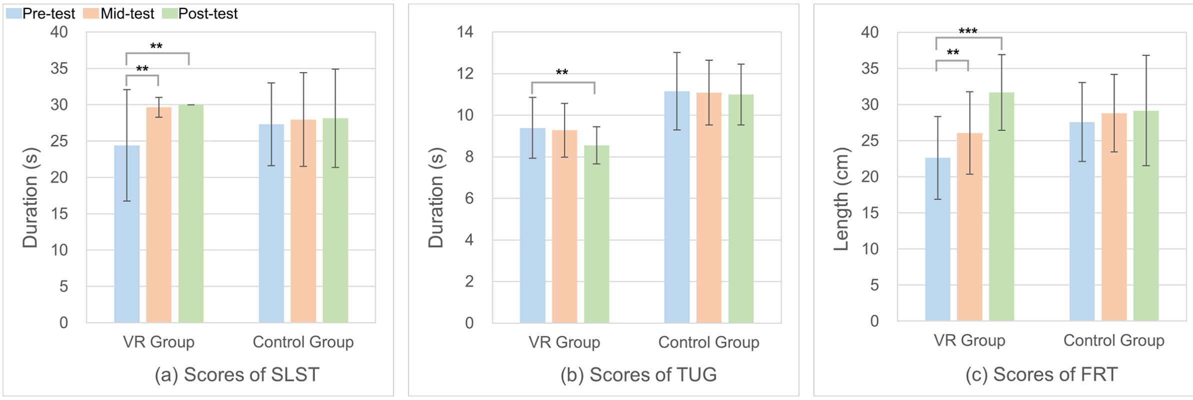

Fig. 7. (a) The pre-test, mid-test and post-test results of SLST in EG (VR group) and CG (control group); (b) The pre-test, mid-test and post-test results of TUG in EG and CG; (c) The pre-test, mid-test and post-test results of FRT in in EG and CG. "**" indicates p < 0.05. "***" indicates p < 0.005.

6.1 Enhancement of Balance Ability (RQ2)

We employed quantitative methods to validate the effectiveness of VR-Shuttlecock in improving balance among older adults, addressing RQ2 by analyzing the data obtained from SLST, TUG, FRT and YBT.

We conducted Shapiro-Wilk tests [78] to assess the normality of data distribution for various metrics (SLST, FRT, TUG, YBT (Forward, Sideways, Backward)) measured at different time points (Pre, Mid, and Post) for both EG and CG. The results indicated that for SLST, none of the three tests in either EG or CG followed a normal distribution. Similarly, for TUG, the pre-test and mid-test scores in EG did not conform to a normal distribution. In CG, the pre-test results for YBT (Forward) and the mid-test results for YBT (Sideways) also deviated from normality, as did the post-test results for the YBT (Backward) in EG. Consequently, we employed non-parametric tests (Friedman tests) to analyze the repeated test results and to determine whether there were significant changes over time within both EG and CG.

6.1.1 *The Effectiveness of VR-Shuttlecock in Enhancing the Performance of SLST, TUG and FRT.*

As illustrated in Figure 7, EG that underwent VR-Shuttlecock intervention showed significant improvements in SLST and FRT during the mid-test after two weeks of balance training (four sessions), compared to the pre-test results before training. After four weeks of balance training (eight sessions), the post-test results for SLST, TUG, and FRT demonstrated significant improvements over the pre-test results. Specifically, in the SLST test, the duration of single-leg standing in the mid-test (p=0.0082) and post-test (p=0.0082) was significantly longer than in the pre-test. As for TUG, the walking time in the post-test (p=0.0075) was notably shorter than in the pre-test. Regarding the FRT test, participants reached significantly farther in both the mid-test (p=0.0013) and post-test (p=0.0002) compared to the pre-test. Conversely, CG showed no significant changes between mid-test and post-test results compared to pre-test in SLST, TUG, and FRT.

6.1.2 *The Effectiveness of VR-Shuttlecock in Enhancing the Performance of YBT.*

EG exhibited significant improvements in all three directions of the YBT performance after the intervention of VR-Shuttlecock, whereas CG showed improvements in only some directions, with less pronounced growth compared to EG. As shown in Figure 8(a), in the Forward direction of the YBT test, only EG's post-test (p=0.0075) surpassed the pre-test performance. According to Figure 8(b), in the Sideways direction, EG's mid-test (p=0.0002) and post-test (p=0.0002) both exceeded the pre-test results. CG also showed improvements in the mid-test (p=0.0023)

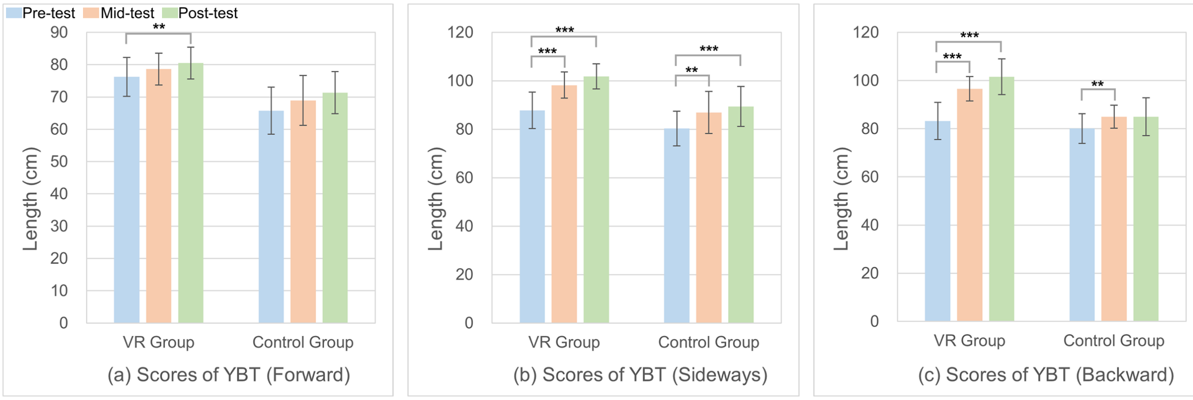

Fig. 8. (a) The pre-test, mid-test and post-test results of YBT (Forward) in EG (VR group) and CG (control group); (b) The pre-test, mid-test and post-test results of YBT (Sideways) in in EG and CG; (c) The pre-test, mid-test and post-test results of YBT (Backward) in in EG and CG. "**" indicates p < 0.05. "***" indicates p < 0.005.

and post-test (p=0.0003) compared to pre-test, while EG's improvement was more pronounced. According to Figure 8(c), in the Backward direction, EG's mid-test (p=0.0002) and post-test (p=0.0002) both outperformed the pre-test, while CG showed improvement only in the mid-test (p=0.0067) compared to the pre-test.

In summary, participants in EG showed significant improvements in SLST, TUG, FRT, and YBT after the intervention of VR-Shuttlecock, while the test performance of CG only increased in some directions of YBT, and was not as significant as that of EG. These results validate the significant impact of VR-Shuttlecock as a tool for enhancing balance among older adults.

6.2 Older Adults' Performance and Perceptions Towards VR-Shuttlecock (RQ3)

Through our observations of participants during balance training, we gained insights into the performance of older adults throughout the training process. Additionally, semi-structured interviews conducted after the intervention helped us understand their perceptions of using VR-Shuttlecock for long-term balance training and the factors associated with it.

6.2.1 Older Adults' Performance in VR-Shuttlecock.

Our observations revealed that older adults' performance in VR-Shuttlecock could be described through two aspects: verbal discourse and body movements, both of which varied with different training difficulties.

Older Adults' Verbal Discourse. During balance training in VR-Shuttlecock, despite not engaging in dialogue with others, participants provided verbal evaluations about the training themselves. We identified several discourse themes among participants, including VR environment, interactive characters, countdowns and scores, training difficulty, and feelings.

Most participants expressed amazement upon viewing the environment in VR-Shuttlecock. For instance, P10 remarked, "Wow, this is a park! It's beautiful, with flowers, trees, and even sounds of birds and flowing water, just like a real park. The soothing music is lovely too…" When the interactive character began to lift its legs to trigger shuttlecocks, many participants noted it resembled a teacher demonstrating movements. For example, P1 said, "The kicking action of this character is so standard; should I learn its movements and lift my legs this high? It's like having a teacher." If participants missed a shuttlecock, they would analyze the reasons; P3 commented, "I missed that one again; it must be because my leg wasn't lifted high enough. I need to try different movements."

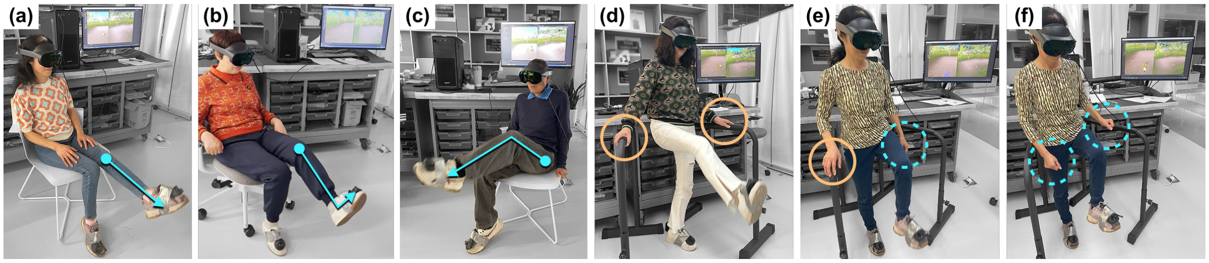

Fig. 9. Six types of participants' movements: (a) straightening the knee to lift the lower leg; (b) lifting the lower leg while flexing the foot; (c) bending the knee to lift the thigh; (d) both hands holding the support bars; (e) one hand holding the support bar; (f) neither hand holding the support bars.

After the training session, most participants (n=8) noted how quickly time had passed, finding the training enjoyable and nearly ignoring the countdown. Furthermore, all participants (n=10) checked the displayed game scores and accuracy rates on the character's head before removing the VR headset. P6 observed, "My accuracy today is lower than last time; I missed over a dozen today, while I only missed a few last time. I feel like my performance isn't great today." When the game difficulty increased, some participants (n=8) attributed their lower accuracy to this heightened challenge, noting increased soreness in their thighs after each session. At the final difficulty level, P2 said, "Kicking while standing feels much freer than sitting, but it's also tiring, especially with three characters randomly switching to kick the shuttlecock, requiring quick reactions. It's definitely challenging."

Older Adults' Body Movements. Throughout the training process across four different difficulty levels, participants exhibited variations in their body movements. These differences manifested in the actions of lifting their legs, the use of support bars, and their choices regarding which legs to employ.

While seated, participants' movements were generally relaxed and slow, characterized by three types: straightening the knee to lift the lower leg (Figure 9(a)), lifting the lower leg with a flexed foot (Figure 9(b)), and bending the knee to lift the thigh (Figure 9(c)). Participant P13 preferred flexing her foot during training to strengthen her ankles, while P5 focused on movements rather than scores, aiming to fully extend her legs for optimal exercise. When standing, movements were categorized into two types: straightening the knee to lift the thigh (n=9) (Figure 9(d)) and bending the knee to lift the thigh (n=5) (Figure 9(e)).

Some participants (n=11) kept both hands on the support bar for safety (Figure 9(d)), citing a need for security despite not being particularly worried about falling. Conversely, three participants used only one hand for support (Figure 9(e)) or chose not to use the bar (Figure 9(f)), trusting the VR-Shuttlecock and seeking to simulate a real shuttlecock kick for freer movements. We monitored their safety and provided assistance as needed.

Additionally, there were differing frequencies in leg utilization. Some (n=8) alternated between lifting their left and right legs. In contrast, another group (n=6) focused on exercising the leg with poorer balance, consistently lifting one leg to catch the shuttlecock and only switching after experiencing fatigue.

6.2.2 Older Adults' Perceptions Towards VR-Shuttlecock.

The results of the semi-structured interviews with all participants (N=14) in experimental group revealed a positive attitude toward long-term balance training using VR-Shuttlecock, which they found superior to traditional methods in functionality, enjoyment, and safety. Feedback on the core design elements was categorized into four dimensions: subjective perception of balance improvement, motivation from multi-sensory feedback and gamification, adaptability to progressive difficulty, and psychological safety.

Subjective Perception of Balance Improvement. The majority of participants (n=9) actively reported improvements in their balance abilities after training, particularly reflected in enhanced stability during daily activities

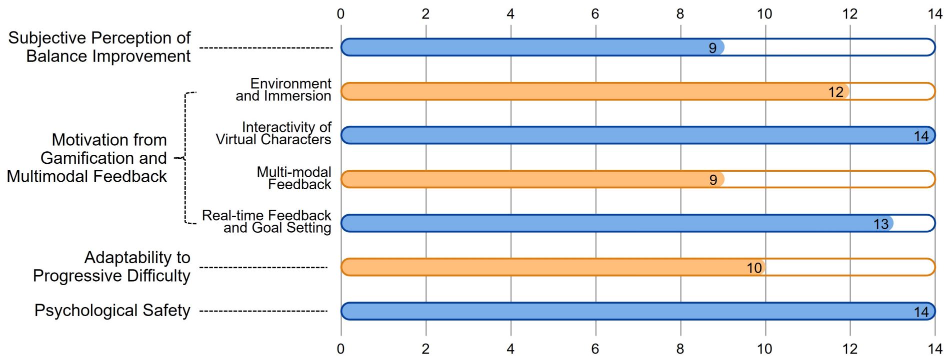

Fig. 10. Participants' Perceptions Towards VR-Shuttlecock: subjective perception of balance improvement; motivation from gamification and multi-sensory feedback, including environment and immersion, interactivity of virtual characters, multi-sensory feedback, real-time feedback and goal setting; adaptability to progressive difficulty; psychological safety. Each subplot is composed of a horizontal bar chart to show the number of participants.

(e.g., standing, walking). For instance, P11 mentioned, "My single-leg standing time has noticeably increased, and I feel more confident when walking." Some participants (P1, P6) did not explicitly perceive objective improvements but experienced a significant boost in their confidence regarding their balance abilities. P1 stated, "I now pay more attention to balance exercises like single-leg standing."

Motivation from Gamification and Multi-sensory Feedback. Most particioants (n=12) appreciated **the environment and immersion**, the virtual park environment and natural sound effects (e.g., birds chirping, water flowing), as they felt these elements created a relaxing atmosphere that enhanced immersion. P3 suggested, "The color of the grass could be more varied, and the dynamic presentation could be more diverse." P8 hoped the type of music could change with the training phases, matching the frequency of leg lifts.

All participants (n=14) acknowledged **the interactivity of virtual characters**, stating that despite the absence of family or friends in VR-Shuttlecock, they did not feel lonely due to the character's interactivity. However, P12 expressed a desire for the character to have more functionalities, such as providing verbal encouragement and movement guidance. Additionally, P9 noted that while she mimicked the virtual character's actions, she wished the character could also replicate her movements to enhance interaction and enjoyment, as this would signify that the character recognized her presence.

Most participants (n=9) regarded **the multi-sensory feedback** comprising haptic (controller vibrations), visual (particle effects), and auditory (impact sounds) elements as effectively simulating the experience of kicking shuttlecock. P3 noted, "The pleasure from the vibrations on my feet is stronger than the other two sensations." However, most participants (n=8) indicated that they were most focused on the visual feedback from the particle effects after hitting the shuttlecock. P6 explained, "I need to visually track the shuttlecock's position and predict when to lift my leg to make contact and determine the angle and height. The particle effects' visual feedback is the most direct, while auditory and haptic cues serve as supplementary sensations." Nonetheless, P7 remarked, "Both the auditory and haptic simulations can replace the experience of kicking a shuttlecock in reality, even though the haptic feedback only simulates vibrations without the weight of the shuttlecock." Overall, participants prioritized the enjoyment from multi-sensory feedback over complete authenticity.

The majority of participants (n=13) expressed interest in **the real-time feedback and goal setting**, except for P5, who focused solely on movement accuracy and not on scores. P4 highlighted a competitive spirit, wishing to compare her score with those of other participants, while others were more concerned with their own scores, favoring self-comparisons over competition with others.

Adaptability to Progressive Difficulty. Most participants (n=10) felt the difficulty was appropriate, with progressive challenges that provided enjoyment and a sense of achievement. However, four participants expressed a desire for increased difficulty. P13 and P14 suggested, "The speed of the shuttlecock could be faster, and the intervals shorter, which would accelerate the frequency of leg lifts and thereby increase training intensity." P5 also wished for a greater variety of movement types, such as using the knee to receive the shuttlecock with high leg lifts. P9 proposed, "A resistance training mode could be added, for example, by attaching sandbags to the legs, as weighted leg lifts would significantly enhance leg training effectiveness."

Psychological Safety. All participants (n=14) believed that the VR environment and safety measures such as the support bars significantly reduced the risk of falls while kicking shuttlecock in VR. P3 pointed out, "I worry about falling when kicking shuttlecock in reality, but in VR, I'm not afraid even if my movements are large." P11 noted, "Kicking shuttlecock in VR-Shuttlecock is fixed-point, allowing me to focus more on lifting my legs rather than moving around." This sense of safety directly enhanced training adherence, with P6 stating, "It's safe enough so I'm more willing to attempt high-difficulty leg lift."

7 DISCUSSION

The purpose of this study is to provide older adults with an engaging, effective, and safe tool to improve their balance. To achieve this, we designed a customized VR exergame, VR-Shuttlecock, that integrates a traditional recreational activity with VR technology. In this section, we discuss the significance of VR-Shuttlecock and summarize design guidelines for VR exergames.

7.1 The Spiritual Significance of VR-Shuttlecock

Previous research has found that older adults tend to engage in VR activities that evoke nostalgic memories [2, 40, 90]. We selected kicking shuttlecock as a traditional activity that aims to improve balance while allowing older adults to recall past experiences. Many older adults had previously enjoyed kicking shuttlecock but had to abandon it as they aged. Within VR-Shuttlecock, they can recall these movements and reminisce about the joys of their youth, ultimately restoring their confidence in body control through the immersive experience of kicking shuttlecock in a safe virtual environment.

Furthermore, prior studies have indicated that VR can help reduce feelings of loneliness and isolation among older adults [22, 33, 59]. Previous VR experiences designed to alleviate loneliness among older adults have included reminiscence therapy (i.e., activities that evoke memories) [22, 52] and group activities [22, 59, 98]. In this study, we introduced interactive characters as substitutes for family members and friends to enhance the experience of kicking shuttlecock. Future research could investigate the design of multi-user VR experiences, which may further enhance social engagement by reinforcing existing social connections among older adults.

7.2 Design Guidelines for VR exergames Aimed for Balance Training

While previous research has explored the potential of exergames to support home-based exercise among older adults [92], their effects on functional balance abilities remain to be validated. Some studies have explored the potential of VR exergames to improve balance abilities [9, 12, 13, 17, 36, 83]. However, due to potential cybersickness or a higher physical workload, these VR exergames may not be suitable for long-term balance training [45]. Our study is the first to customize a VR exergame specifically for long-term balance training. Based on our findings, we propose design guidelines addressing gamification design, multi-sensory feedback, progressive difficulty, and psychological safety.

7.2.1 Gamification Design.

Providing a Natural and Open Outdoor Environment for Balance Training. Our findings indicate that a natural and open environment enhances participants' motivation to exercise. Auditory elements also play a crucial role in creating an immersive atmosphere. Older participants noted that background music and sound effects enhanced immersion, especially when the rhythm adapted to game difficulty. Designing a vibrant outdoor environment can effectively improve engagement and motivation.

Using Interactive Characters to Encourage Participation. Participants responded positively to interactive characters that demonstrated movements and provided emotional support. Future designs could incorporate chat features for praise or encouragement, enhancing interaction and motivation among older adults.

Establishing a Dynamic Personal Database for Tracking Changes in Balance Ability. Most participants focused on their individual scores and balance changes rather than comparing themselves to others. Therefore, the design should emphasize personalized database visualization with a timeline to help participants see their progress, enhancing self-efficacy and motivation.

7.2.2 Multi-sensory Feedback.

Utilizing Multi-sensory Feedback to Enhance VR Experience and Realism. Multi-sensory feedback can create a more immersive experience through sensory feedback [49, 102]. We simulated kicking shuttlecock using visual, auditory, and haptic feedback, with participants reporting a strong sense of realism. Future designs should incorporate a broader range of feedback, including enhanced visual effects, auditory encouragement through voice agents, and haptic sensations that simulate gravity, temperature, and texture.

7.2.3 Progressive Difficulty.

Designing Gradual Difficulty Changes to Improve Player Adaptability. This study provided training across four difficulty levels, with results indicating that most players found the difficulty acceptable and were motivated by challenges. However, since players were focused on their movements, future designs should allow players to select difficulty levels and customize training durations based on their capabilities.

7.2.4 Psychological Safety.

Providing Relevant Safety Measures to Enhance Players' Psychological Safety. Safety measures are essential as exercising in VR may induce cybersickness or a higher physical workload [45]. In this study, we provided chairs and support bars for fixed-point movements. Future designs should explore more flexible safety options, which could accommodate a broader range of physical activities while enhancing psychological safety.

8 LIMITATION AND FUTURE WORK

Our study acknowledges certain limitations and outlines potential future research directions. Firstly, the universality of the findings is limited due to the small sample size. Our experiment recruited only 14 older adults for the experimental group and 13 older adults for the control group, all of whom are relatively healthy without mobility impairments. While the effectiveness of VR-Shuttlecock in enhancing participants' balance abilities has been validated, it remains uncertain whether the benefits apply to older adults beyond this group. Despite healthy older adults needing preventive balance exercises to reduce fall risks, future work should involve collaboration with hospitals or elder care facilities to recruit participants with mild to moderate mobility impairments, as this group stands to benefit the most. Additionally, although most participants haven't kicked shuttlecock for decades, the sample's familiarity with shuttlecock kicking may introduce cultural bias in the results. The effectiveness of VR-Shuttlecock needs to be tested in a broader population.

Another limitation is related to the short duration of the experiment. The balance training in this study lasted only four weeks. Although assessments of players' balance abilities (Single Leg Stance Test, Timed Up and Go Test, Functional Reach Test, and Y Balance Test) showed varying degrees of improvement after four weeks, the long-term impact on participants' balance abilities remains unclear. Future research should reassess the balance abilities of participants who have ceased balance training using these four assessments to explore whether the effects of VR-Shuttlecock on balance ability are temporary or lasting. In addition, the effectiveness of VR-Shuttlecock in promoting long-term balance training among older adults has yet to be confirmed. Although the current study observed high levels of engagement and positive feedback, these responses may be attributed to the novelty of the VR experience. Over time, this initial enthusiasm may diminish, potentially leading to reduced adherence or increased boredom. Therefore, future research should include extended experimental periods to gather longitudinal feedback from participants and identify potential strategies for improvement.

Furthermore, some participants mentioned that while interacting with virtual characters in VR-Shuttlecock reduces feelings of loneliness, they would appreciate additional functionalities such as voice encouragement, motion guidance, and personalized training plans. Addressing these requests could enhance user engagement and motivation. Additionally, the current static difficulty levels in the game were noted by some players as needing more variability. Implementing dynamic difficulty adjustments based on daily performance could improve the game's adaptability to individual needs.

Despite these limitations, the current study highlights the significant potential of VR-Shuttlecock as a viable alternative to traditional balance training methods. By leveraging immersive technology, this approach not only addresses adherence challenges but also promotes social interaction and psychological well-being among older adults. As the field of VR exergames continues to evolve, ongoing research will be essential in refining these tools, ensuring they meet the unique needs of older populations, and exploring their broader applications in promoting physical health and independence.

9 CONCLUSIONS

In conclusion, this study designed the VR exergame, VR-Shuttlecock, integrating the recreational activity of kicking shuttlecock with VR technology, providing an effective, enjoyable, and safe tool for long-term balance training among older adults. To meet the needs of older adults in long-term balance training, the game design considered four key aspects: 1) simplified exercises to enhance training efficiency; 2) diverse gamification designs to enhance motivation; 3) customized progressive difficulty for adherence; 4) corresponding protection measures for safety. Subsequently, a four-week controlled experiment consisting of eight sessions was conducted. The experimental group included 14 older adults from the formative study, while the control group comprised 13 older adults with similar physical conditions to those in the experimental group. This was designed to demonstrate the effectiveness of VR Shuttlecock in improving balance. Quantitative results from the four assessments (Single Leg Stance Test, Timed Up and Go Test, Functional Reach Test, and Y Balance Test) indicated that older adults' balance showed significant improvements after the intervention of VR-Shuttlecock. Additionally, qualitative results based on observations and semi-structured interviews conducted at the end of the experiment revealed that older adults held a positive attitude toward using VR-Shuttlecock for long-term balance training. The design elements based on our considerations were identified as key factors influencing their attitudes and perceptions.

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