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DOCTORAL THESIS

Muhammad Asif Ahmad

DOCTOR DEGREE IN INFORMATICS ENGINEERING
SPECIALIZATION: SOFTWARE ENGINEERING

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Abstract

In most countries around the world, the population of older adults exceeds that of younger individuals. The ageing population has become a global challenge and is causing an increase in chronic diseases and associated health problems. This age group has been associated with conditions such as reduced mobility, prolonged hospitalisations, elevated morbidity rates, and an increased incidence of falls. A sedentary lifestyle has been correlated with numerous health conditions, making it essential to promote innovative health and fitness programs that encourage physical activity. According to the American College of Sports Medicine (ACSM), individuals should engage in 30 minutes of moderate exercise, five days a week, or 20 minutes of vigorous exercise, three times a week. The rapid growth of Information and Communication Technology (ICT) tools has led to a decrease in physical activity, contributing to various health and fitness issues. Balance assessment tools are used to evaluate postural movements, the risk of falls, and balance impairments. Using virtual reality (VR) technology in conjunction with balanced assessment tools may enhance the ecological validity of the instruments, increase performance and standardisation, and reduce administration time. Moreover, combining immersive virtual reality (IVR) with physical exercise, or exergames, enhances motivation and personalises training, effectively preventing falls by improving strength and balance in older adults. While many exergames and simulation applications have been introduced to help people engage in physical activity, limitations exist in user interest, consistency, achievement, and technology, particularly when targeting older adults and populations with specific deficits. Exergames often lack adaptability to individual fitness profiles and high-fidelity immersive virtual environments.

To address these limitations, we have created and validated a biofeedback-based spatial augmented reality platform that assesses physical and physiological fitness, as well as balance, in older adults through targeted interventions designed to promote wellness and reduce the risk of falls. Target heart rates are evaluated according to ACSM recommendations. The platform also offers simulations of diverse environments and fitness opportunities tailored to meet the specific needs of various populations. We have implemented standard fitness procedures in a virtual environment to assess lower-body strength and cardiorespiratory endurance in older adults.

Resumo

Na maioria dos países do mundo, a população idosa excede a dos indivíduos mais jovens. O envelhecimento da população tornou-se um problema global desafio e está a provocar um aumento de doenças crónicas e problemas de saúde associados. Esta faixa etária tem sido associada a condições como a mobilidade reduzida, hospitalizações prolongadas, taxas elevadas de morbilidade e maior incidência de quedas. Um estilo de vida sedentário tem sido relacionado com inúmeras condições de saúde, tornando-se essencial promover programas inovadores de saúde e fitness que incentivem a atividade física. De acordo com o Colégio Americano de Medicina Desportiva (ACSM), os indivíduos devem praticar 30 minutos de exercício moderado cinco dias por semana ou 20 minutos de exercício vigoroso três vezes por semana. O rápido crescimento das ferramentas de Tecnologia de Informação e Comunicação (TIC) levou à diminuição da atividade física, contribuindo para vários problemas de saúde e de fitness. As ferramentas de avaliação do equilíbrio são utilizadas para avaliar os movimentos posturais, o risco de quedas e os problemas de equilíbrio. A utilização da tecnologia de realidade virtual (RV) com ferramentas de avaliação equilibradas pode melhorar a validade ecológica dos instrumentos, aumentar o desempenho e a padronização e reduzir o tempo de administração. Além disso, a combinação da realidade virtual imersiva (URA) com o exercício físico, ou exergames, aumenta a motivação e personaliza o treino, prevenindo as quedas de forma eficaz ao melhorar a força e o equilíbrio nos adultos mais velhos. Embora tenham sido introduzidos muitos exergames e aplicações de simulação para ajudar as pessoas a praticar atividades físicas, existem limitações no interesse do utilizador, na consistência, na realização e na tecnologia, particularmente quando dirigidas a adultos mais velhos e a populações com deficiências específicas. Os exergames não têm, muitas vezes, capacidade de adaptação a perfis de fitness individuais nem a ambientes virtuais imersivos de alta-fidelidade.

Para abordar estas limitações, criámos e validámos uma plataforma de realidade aumentada espacial baseada em biofeedback que avalia a aptidão física e fisiológica, bem como o equilíbrio, em adultos mais velhos através de intervenções direcionadas, concebidas para promover o bem-estar e reduzir o risco de quedas. As frequências cardíacas alvo são avaliadas de acordo com as recomendações do ACSM. A plataforma oferece ainda simulações de diversos ambientes e oportunidades de fitness adaptadas para atender às necessidades específicas de diversas populações.

Implementámos procedimentos de fitness padrão num ambiente virtual para avaliar a força da parte inferior do corpo e a resistência cardiorrespiratória em adultos mais velhos.

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1 Introduction

1.1 Problem Statement

Working-age people are expected to decline steadily, leading to an increase in older people and a rise in the old-age dependency ratio. The number of people aged 85 years or older is projected to increase from 14 million to 40 million by 2050 (WHO). People who are less physically active have a higher risk of health problems such as high blood pressure, hypertension, being overweight, stress, etc. [1]. Falls are considered the second leading cause of death from unintentional injuries worldwide (WHO,2021), and the highest occurrences are found in adults aged ≥ 60 (WHO,2021) [2]. According to the World Health Organisation [3], approximately 684,000 fatal falls occur every year, making them the second leading cause of accidental injury death after road traffic accidents. More than 80% of fall incidents occur in low and middle-income countries. Some 60% of deaths occur in the regions of the Western Pacific and Southeast Asia [3]. One of the risk factors for falls is age [4], which leads to a decrease in muscle mass and strength, joint mobility, flexibility, balance, and agility [5], as well as reduced physical function and difficulty performing independent daily life activities. Medical conditions, such as neurological and cardiac, are well-known risk factors for falls [6].

Literature highlights that the older adults group who performed various types of physical activities (i.e., resistance training, endurance training, multi-component training, balance training, exergames) indicated an increase in balance from 16% to 24% [8] and reduced the prevalence of falls between 22% and 58% [9] [10].

A Sedentary lifestyle and obesity are the shared risk factors of Diabetes Mellitus [24]. Recent studies have shown that a sedentary lifestyle is one of the four major causes of death [25]. In some studies, it is estimated that physically inactive people are more likely to have diseases such as heart conditions (6%), breast cancer (10%), colon cancer (10%), and diabetes (7%) [26]. A sedentary lifestyle is a risk factor for developing heart failure [27] [28] and Colorectal cancer (CRC) [29]. Access to the internet and mobile devices has led to a decline in physical activity among people. People are more active on social media than they are in physical interactions [30].

More recent approaches aim to encourage physical activity through smartphone applications, video games, simulation applications, fitness apps, persuasive technology, and mobile devices [31]. Video games that require the user to interact and move physically, also known as Exergames, promote physical activity in different populations. They encourage higher interest and participation than typical cardio machines [32] [33]. However, most of these Exergames are not explicitly developed for older adults. They have been created for entertainment, commercial purposes, and for youngsters. The design of exergames for older adults presents a challenge, as they have varying needs depending on their physical and medical conditions. Hence, custom Exergames are needed to adjust training requirements to their physical condition [33] [34].

In developing custom Exergames, the design should support a high user interest and progression to promote motivation and adherence [35]. A solution is to employ Spatial Augmented Reality (SAR), developed by Raskar [36]. SAR promotes an increased physical involvement of the user by projecting virtual graphics on the surface and allows users to interact with virtual objects.

Exergames should maintain a user fitness profile and adjust the game's configurations accordingly [37] [38], enabling game mechanics to adapt dynamically based on the player's detected physical or cognitive states. The physiological inputs, such as Blood volume (Plethysmograph), are used to measure the heart rate and blood oxygen during the exergame play [39]. To achieve this, they require external hardware to record physiological characteristics that evaluate the performance of their physical activity, such as weight sensors, walking speed, and heartbeat, among others [39]. For instance, Kinect sensors have been used to analyse physical activity levels and motor rehabilitation [40] [41] as they enable quantification of player performance based on motor function during gameplay interaction. Literature also highlights that physiological characteristics, such as perception and emotions, can be modulated while playing Exergames [42] [43]. Biocybernetic Loop Systems (BLS) take physiological data from the user, convert it, and process it to act [44]. BLS is intrinsically adaptive and is modulated through physiological data from the user in runtime. Fewer exergames use BLS to adapt to the user's psychological state [45].

Although exergames have shown their potential to improve the cardiovascular system in seniors [46], the reached exertion levels are often below the fitness recommendations [47] [48]. To boost exergame effectiveness, novel approaches should be considered to optimise exercise personalisation through system adaptation. The biocybernetics loop is a modulation technique from the field of physiological computing, which utilises body signals in real-time to alter the system and assist users.

Despite this work, a lack of research combining these different approaches in Exergames for older adults remains, and further investigation is required to evaluate their impact [49]. Hence, we propose combining BLS and SAR based on closed-loop systems in a simulated platform. In a closed-loop system, the user's feedback is sent back to the system to adapt its behaviour, increasing the adaptive and responsive behaviour [50].

The primary objective of this research is to design a platform based on standard procedures to assess the functional fitness and balance of older adults, and to create an application that promotes wellness and reduces the risk of falls.

1.2 Research Question

To achieve our research objectives, we will address the following research questions:

1. How can traditional validated assessment tests (fitness/posturography / electrophysiological) be integrated into VR-based applications to assess fitness in older adults while maintaining validity?

2. Which VR technologies are most suitable for creating a VR-based fitness application?

3. Are personalised and adaptive SAR-CAVE-mediated applications feasible for fitness?

4. How can automatic physiological adaptation and user profiling be used to perform closed-loop VR-based fitness applications?

1.3 Contribution

The main contribution of this research is to propose novel solutions to prevent sedentarism and the risk of falls by creating adaptable simulated applications tailored to older adults’ requirements by addressing the following challenges:

1. Design and implementation of standard fitness procedures in simulations to assess fitness, balance, and enhance motivation in older adults require:
    a) Development of adaptive functional fitness assessment tools.
    b) Development of guidelines to develop SAR/VR-based applications for older adults’ fitness.
    c) Study the individuals' experience, usability, compliance, and exertion levels in the proposed VR simulations.
    d) Validate digital assessment against traditional assessment and compare VR simulation intervention to physical training.
    e) Assess the feasibility and efficacy of an HR-based adaptive training paradigm.

2. Integration of Virtual Simulation with Biocybernetic Loop Systems (BLS) to close the loop requires:

a) Validation of existing Biosignal Processing Matlab tools, which take physiological attributes in the form of musculoskeletal and cardiorespiratory fitness.
b) Development, validation, and integration of previously developed tools in BLS in different test scenarios.

3. VR experience with SAR to train fitness (endurance & balance):
    a) Design and development of multiple prototypes of adaptable VR Simulations tailored to the older adults’ requirements, which will implement standard scientific procedures to assess fitness and balance and features of SAR and BLS.

The thesis is organised into three primary chapters, each targeting specific objectives, and incorporates five published scientific articles. The first chapter focuses on the design and implementation of standard fitness protocols within simulations designed to assess fitness and balance, as well as enhance motivation among older adults. Each subchapter corresponds to one of the included articles. The second chapter explores the integration of Virtual Simulation with Biocybernetic Loop Systems (BLS) to establish a closed feedback loop, with certain sections tied to an additional set of publications. Lastly, the third chapter focuses on profiling and risk assessment related to falls. The thesis concludes with a final chapter that presents conclusions and outlines directions for future research.

2 State of the Art

2.1 Assessment of Functional Fitness

The Senior Fitness Test (SFT) is a well-known test battery that is widely used to assess the functional fitness of older adults [51]. The SFTS comprise seven tests to evaluate lower and upper body strength, aerobic endurance, lower and upper body flexibility, agility, and balance. Health and fitness professionals must conduct these tests while ensuring the integrity of the test data and safety. The SFTs have been used in many clinical studies [52][53][54]. The normative United States values are commonly used and compared closely, indicating US normative data would be appropriate for similar countries [55][56][57]. The SFTs are suggested to assess the functional fitness of older adults with no cognitive impairment and are suitable for research and clinical objectives. The results obtained from 7000 older adults in the USA set the performance standards for the SFTs and provide excellent normative standards for American older adults ranging from 60 to 94 years [58][55]. Similarly, normative standards for the Norwegian [57] and Madeiran [59] samples were also reported as reliable.

The following section is going to shed light on these tests:

- 30 Seconds Sit-Stand test (CST): To assess lower-body strength by counting the number of sit-to-stand positions with crossed arms folded across the chest in 30 seconds.
- Arm curl test (ACT): the upper-body strength is evaluated by counting the bicep curl positions with a hand weight of 2.3 Kg (3.6 Kg for men) in 30 seconds.
- Chair Sit and Reach test (CSAR): lower-body flexibility is assessed by measuring the distance between the extended fingers and the tip of the toe while sitting on the chair with an extended leg position.
- Back scratch test (BST): the upper body flexibility is assessed by measuring the distance between the extended middle fingers of two hands. One hand position must be over the shoulder and the other up in the middle of the back.

- 8-Foot Up and Go test (FUG): the dynamic balance and agility are evaluated by counting the number of seconds when a user stands up from the chair, walks 2.4 meters (8 feet), and returns to the seated position.
- Six-minute Walk test (6MWT): assesses aerobic endurance by counting the number of meters that can be walked around a 45.7-meter course in 6 minutes.
- Handgrip strength test (HANDG): A dynamometer is used to measure the force (in Kg) of the user’s hand while squeezing it for 5 seconds.

The SFTs can be automated using motion-tracking technology based on depth sensors, making the process quick and efficient and reducing the need for fitness professionals to conduct the tests. Many technologies in human body tracking systems include inertial and magnetic systems and markerless infrared systems. The marker-based optical systems are considered not feasible for low-cost and domestic applications because they require a multi-camera setup and plenty of markers to attach to the body [60].

The automation of SFT was previously developed at the NeuroRehabLab to assess the functional fitness of older adults [61]. The authors created a computer-based system to evaluate lower body strength, agility, dynamic balance, and aerobic endurance through a Kinect depth sensor for body and gesture detection. They compared it with the traditional SFTs and found 95% accuracy in identifying movement patterns and consistency. Although these tests were automated, they cannot provide user feedback during assessments and require ecological validity. This research will first validate them by integrating them into SAR and implementing the user's live feedback. We will incorporate this low-cost solution into our applications to assess the fitness of older adults.

2.2 Assessment of Cardiorespiratory Endurance

A cardiorespiratory endurance test is used to evaluate heart function using heart rate, including stepping, running, and walking [62]. It is defined as the capability of the heart and lungs to supply oxygen to the muscle group during physical exercise and is measured through maximum oxygen consumption (VO2 max). The VO2 max can be defined as the maximum oxygen consumption from the individual during intense exercise in one minute. It requires laboratory settings to estimate the maximum oxygen VO2 max, which is not feasible for fitness applications. Therefore, cardiorespiratory endurance can be measured based on the heart rate [63]

[64] [65] [66] [67]. The heart rate is the physiological signal identified before and after the exercise to determine the intensity of physical activity. The maximum heart rate (MHR) is defined as the maximum number of heartbeats per minute. It is used in physiology and clinical tools to diagnose and prevent health problems [68]. Other uses include aerobic fitness capacity, exercise prescription, and a criterion to evaluate maximum aerobic ability. There are several equations used to predict MHR. For example, the formula (220 − age) is commonly applied; however, it can underestimate or overestimate the measured MHR and is therefore not recommended. An equation recommended for healthy men and women is the one proposed by Tanaka et al. [69]. Equation 2.1 indicates the Tanaka formula [69] to estimate the maximum heart rate for different age ranges.

$$208 - (0.7 \times Age) \tag{2.1}$$

Similarly, resting heart rate (RHR) can be defined as the number of beats per minute when an individual is at complete rest i.e., no physical activity is performed. The range of RHR falls between 60-100 bpm (beats per minute) and is typically measured in the morning before leaving bed. RHR was found to be low in individuals who maintain a high fitness level, which changes according to age [70]. Healthy individuals have stronger hearts because exercise pumps blood effectively across the body and thus requires fewer heartbeats. After intense exercise, getting the heart to the normal stage is called heart recovery (HRR). Cardiac conditions or diseases can be diagnosed with the HRR. Most studies have measured current heart rate by subtracting the heart rate after two minutes of exercise from the MHR to calculate HRR and assess the efficacy of the physical activity. Healthy individuals with high fitness profiles (good cardiovascular condition) get a fast resting heart rate after exercise and acquire lower heart rates during intense physical activity [71].

Literature highlights some tests to assess aerobic fitness and cardiorespiratory endurance, such as the 12-minute run fitness test used to evaluate the fitness profile of military personnel by estimating VO2 max. Participants must run as long as they can in 12 minutes while the distance is recorded. However, different training and techniques can affect the participants' results. Fitness trainers have also used it to monitor fitness in multiple time intervals [72]. Saalasti introduced another cardiorespiratory endurance assessment method that used neural networks to analyze heart rate with time series. Participants’ VO2 max and HR data were acquired through cardiopulmonary function [73]. After conducting regression analysis, a nonlinear relationship was found between VO2max and HR with a polynomial fit to the data. Equation 2.2 [73]:

$$VO2 = 0.002 \times HR2 - 0.13 \times HR + 2.3 \qquad 2.2$$

The study reported a correlation between VO2 max and HR and applied it to real-world scenarios.

2.3 Ecological Validity and Virtual Reality

Ecological validity refers to "the extent to which the environment experienced by the subject in a scientific investigation has the properties it is supposed or assumed to have by the investigator" (Bronfenbrenner 1977). In other words, it is the process of finding the correlation between the activities of standard tests and real-life scenarios [75]. The ICT-based applications can increase the ecological validity of the standard instruments by creating more dynamic and motivated tasks according to real-life situations. They can increase the quality and performance of the tests by defining standards and acquiring comprehensive and objective data, reducing administration time. Virtual Reality (VR) has become a potential technology for increasing and validating ecological validity [76][77].

Novel tech-based applications can effectively promote these training programs. Recent reviews and meta-analyses exposed new technologies such as VR, artificial intelligence (AI), and exergames that introduced new training programs specially designed to avoid incidents of falls [21] [22] [23]. VR may increase older adults' motivation for their physical rehabilitation, which may be a valuable tool for achieving active aging goals [22]. VR applications are growing rapidly in medicine. The keyword "Virtual reality" was present in 1634 articles listed on PubMed in 2018, and later, those articles increased to 2949 in 2021. Recent progress in VR introduced portability and smart features to create more realistic virtual environments. The VR transitioned from the development of large-screen displays to head-mounted displays. Computer-based and standalone VR devices are being sold for commercial purposes [78]. Immersion can be described by the system's specifications. It is based on how large a computer has surrounding, comprehensive, realistic, and matching displays. Therefore, Immersion is a representation of a specific system, while presence refers to a person's involvement in a virtual environment [79]. Several studies have utilised VR for evaluating balance and rehabilitation. A VR simulation allows for controlling multiple factors, which can also potentially be used to assess users' behaviour more accurately. It also offers to create the latest generation rehabilitation tools and evaluate their efficacy [80]. The postural instability of a person can be triggered through VR [81][82]. For instance, for patients who underwent traditional assessment and were diagnosed with no symptoms, VR played an important role in diagnosing persisting neurological and balance impairments [83][84].

SAR [85], or projection mapping, is a well-suited technology that can be adapted to the requirements of exergaming, enabling users to visualize and interact with virtual information seen as situated in real space. Bright projectors [86], projectors enhanced with sensors, can adjust their projections to the surfaces' shapes, colors, and textures and are the best candidates for the development of such applications. In [87] the authors presented a system capable of real-time mapping of arbitrary indoor scenes using a handheld sensor and demonstrated its uses in geometry-aware augmented reality and physics-based interactions; [88] the system was enhanced by coupling the handheld sensor to a pico-projector (an arrangement known as ProCam) leading to the ability to visualize the interactions with the virtual world projected on the real environment; and in [89] the system was deployed in a ProCam installed on a motorized platform creating the possibility for hands-free interaction.

The use of ProCams for enhancing the viewing experience in gaming was demonstrated [90], where a system was developed to augment the area surrounding a television with projected visualisations. In related work [90], multiple ProCam unit systems were created, supporting full-room projection mapping and permanent motion tracking. These systems can now be built with affordable components, providing a way to display life-sized, interactive virtual environments. Such interactive environments create opportunities to engage players in more natural and novel ways that take advantage of their movements.

2.4 Exergames

Exergames (video games with physical activity) are becoming more popular because they feature physical activity [91]. A ten-minute exercise session can increase concentration and provide cognitive benefits [70]. According to the United States National Heart, Lung, and Blood Institute, physical activity limitations include lifestyle, limited access to recreational facilities, age, and health conditions [92]. Combining exercise and video games increases the player's interest and motivation [93]. VR technology has made exergames successful [93]. Nintendo Wii [94] and the Microsoft Kinect [95] introduced exergames commercially and confirmed a high interest and able to induce physical activity. Both Wii Fit (wiifit.com) and Microsoft Kinect (microsoft.com) have been well accepted as exergame input devices.

Exergames can help overcome a sedentary lifestyle [70]. Some examples include Swan Boat, where the virtual boat is controlled by the running speed and arm movements [96], and Liberi, a cycling-based exergame that promotes cardiovascular fitness in youth with cerebral palsy [97]. Although exergames can increase heart rate, they lack the ability to modulate the intensity of physical activity according to the player's cardiovascular health [98] [99]. However, immersion and motivation of the exergames were observed to be low, with lower physical involvement [100]. Another study developed a cycle-based exergame that included badges and prizes to motivate players [101]. Ville Nenonen and co-authors created Pulse Masters Biathlon exergames, utilising heart rate to control shooting and skiing speeds. They reported that heart rate interaction was a fun and usable method of interaction [102]. Another study developed an exergame, Vrun, in which players physically run in place to interact with the virtual environment. They compared laptop display and large-screen display setups and reported that large-screen displays had high immersion [93]. The main goal in the design of the exergames is to keep players motivated during gameplay and physical activity [103] [97].

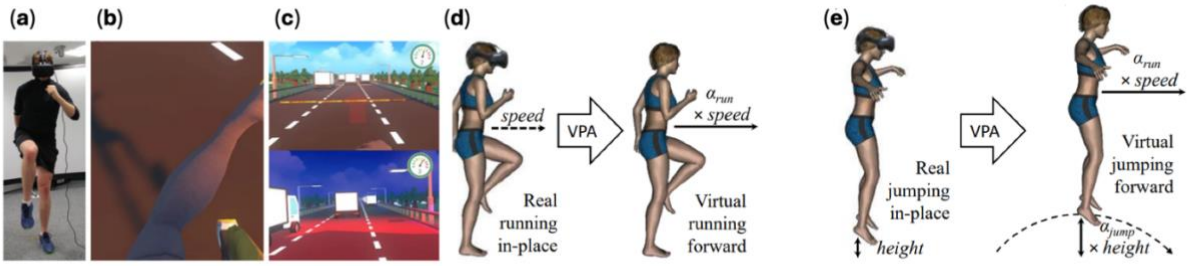
2.4.1 Effectiveness of Exergames

Grab Apple exergame elevated 72% of the maximum heart in ten minutes, which allows players to play at multiple intervals of the day [103]. This exergame was considered helpful for those who could not perform prolonged exercise. Moreover, Shaw et al. used an HMD environment to simulate an exercycle game where players have to pedal to move in a virtual environment [104]. The authors reported a statistically significant increase in exertion and motivation when playing the game. However, a slight increase in motivation and no difference in exertion were found in the HMD environment.

Jeff et al. [105] indicated one limitation of designing physical activity in a particular exergame, that gameplay and exercise may not be synchronized to acquire the target heart rate. Finkelstein and Suma [106] developed the immersive VR exergame "Astrojumper" and reported a significantly increased user heart rate after gameplay. The exertion level of the participants was correlated with their level of motivation.

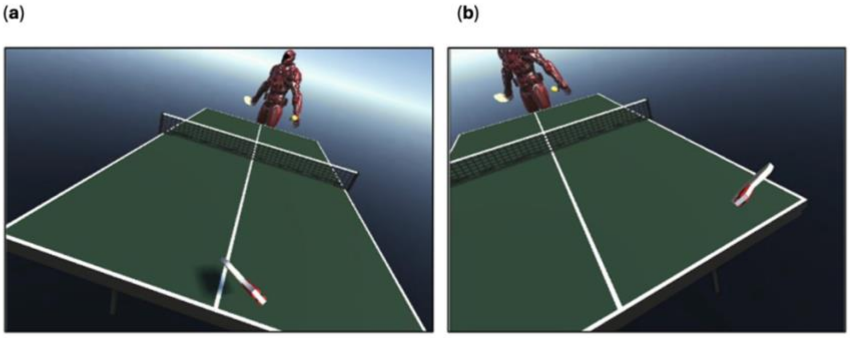
Another study reported that direct competition in exergames increased the exertion level of the players. However, less enjoyment and motivation were found in non-competitive players [107]. Sell et al. [108] investigated the effect of the player's experience on exertion level and motivation. The authors used the "Dance Dance Revolution" game and reported that experienced players who played exergames with hard difficulty achieved high exertion levels on the cardiovascular metric. The high experience of the players was associated with a high level of fun in the exergame.

Ioannou et al. [109] proposed virtual performance augmentation of in-place running and jumping and assessed a VR exergame effect. They found that in-place running and jumping in a VR can be used to create a natural experience and induce moderate to high physical activity (Figure 2.1).



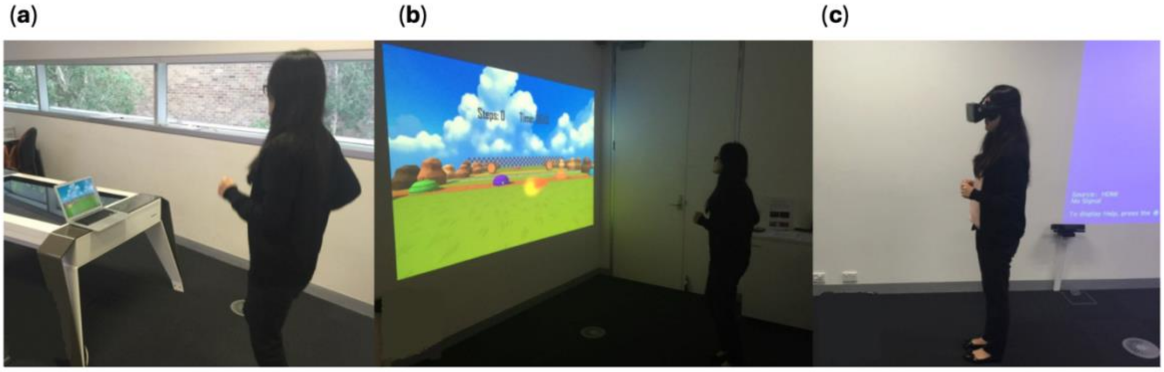
2.1: The exergame is played by running and jumping in place while wearing a head-mounted display. b) A sense of embodiment is created through visual-motor synchronicity with an avatar. c) Running, jumping over "lava gaps", and avoiding trucks during gameplay. d) In-place running with estimated speed is used to simulate forward running in VR with the speed augmented by a factor run. d) In-place jumping is used to simulate forward jumping in VR with the height augmented by a factor jump. Adapted from [109].

Another study developed a VR table tennis exergame and compared the participants' heart rates generated through traditional and VR-based table tennis [110] (Figure 2.2). They reported a decrease in the participants' heart rate in the VR version, which indicated that VR-based table tennis was not suitable for inducing physical activity.



2.2: Scene of the exergame. Adapted from [110].

A recent study built a bike, 'Greedy Rabbit,' adopting a design-based exergame approach to assess young adults' physical activity and situational interest [111]. They found that a design-based exergame approach is an excellent method to elevate the player's physical activity and situational interest. Another study created an exergame VRun in which players physically run on the spot to interact with the virtual environment [93]. They compared laptop display and large-screen display setups and reported that large-screen displays had high immersion (Figure 2.3).



2.3 (a) Laptop display; (b) Large display; (c) Head-mounted display(HMD). Adapted from [93].

Ketcheson et al. [91] introduced and assessed heart rate power-ups' novel game concept to induce higher physical activity during gameplay. The heart rate power-ups encourage players to elevate their heart rate to the target level by providing those rewards in the game. They developed three exergames and found a significant increase in the players' exertion level and enjoyment level. Authors reported that a school-based exergaming program induced children's moderate-to-vigorous PA (7–10 years old) over two years in overweight and obese adolescents [103]. Another study found an increase in PA during a 12 weeks dance exergaming intervention program in overweight and obese adolescent girls [112]. Grab apple exergame elevated 72% of the maximum heart in ten minutes, making players play at different intervals of the day [103]. This exergame was considered useful for those people who were not able to perform a long exercise.

Moreover, Shaw et al. [104] used an HMD environment to simulate an exercycle game in which players must pedal to move in a virtual environment. The authors reported a statistically significant increase in exertion and motivation when playing the game. However, a small increase in motivation and no difference in exertion level were found in the HMD environment.

Sinclair stated that one limitation of designing physical activity exergames is that gameplay and exercise may not be synchronized to acquire a desired target heart rate [113]. Huang et al. [7] assessed the effect of immersion on the perceived exertion by using a stationary bicycle-based training system. The authors compared perceived exertion in a PC desktop screen, a projector, Head Mounted Display (HMD), and a non-VR system. A significantly lower perceived exertion was found in the HMD and projector conditions when compared to non-VR. No significant difference was found between HMD and projector conditions. The outcomes of this study were consistent with [114], who compared immersive VR with virtual feedback and no 3D computer-generated feedback setups. They reported lower perceived exertion and higher excitement in the immersive VR environment.

2.5 Computer-Mediated Balance Assessment Tools

Balance can be defined as the capacity to sustain an upright body posture with minimal body sway and a straight back. It can also be characterised as maintaining the body's centre of pressure without external support [115]. Balance disorders, mainly in standing, may affect daily activities [116]. The feedback obtained from balance tests serves as a valuable foundation for establishing standards to assess functional recovery and predict the risk of falls [117]. While age is a well-recognized factor that significantly influences balance, it is worth noting that extreme body weight can also have a notable impact on an individual's ability to maintain balance. A recent study reported that stress, depression, obesity, and physical overload are the main factors of impaired balance in older people [118]. Balance assessment has greater importance because of the increase in balance disorders after age-related conditions such as stroke [119]. Balance disorders have been assessed using clinical tools, which take time and effort [120].

Balance assessment tools and instruments are fundamental to assessing postural movements. In the last ten years, quantitative assessments have been used to test static and dynamic posturography, such as weight distribution or postural sway measures that measure balance impairments (WHO, 2001) [121]. Posturography is one of the medical procedures where balance and posture are assessed through the central nervous system [122].

Posturography systems use force-plate platforms to measure the center of pressure of the subjects and compare it with the healthy sample. The automated posturography systems can evaluate balance and postural control with higher sensitivity and objectivity than traditional clinical tools while computing responses under modulated sensory conditions [123]. It can assess postural balance in static and dynamic conditions. In a static condition, the subject is placed on the force platform in an upright standing posture to monitor the body's oscillations. These oscillations are described as the excursion of the center of pressure (COP), measured by the force platform. The COP is considered an imaginary point where the impact of the body weight is similar to the pressures of the body over the feet.

Several traditional clinical tools have been used to assess the risk of falls and balance impairments [121]. Some of the tools include Wolfson's postural stress test (PST), the COP excursion [53] and the platform perturbation test [124] [125] [126]. The PST uses the ordinal scoring method, which may not measure postural impairment levels precisely. The other two tests, perturbation and COP, require state-of-the-art laboratory equipment, creating a barrier to clinically accessing them. Moreover, these tests evaluate postural responses to artificially created external inspirations rather than voluntary movements performed during daily activities. However, these tools and tests are subject to bias and reported limited sensitivity to change, information about, and sensory integration [121].

The Tinetti Balance Assessment Tool (TBAT) is a clinical balance tool with high usability. It mainly measures static and dynamic balance in older people [127]. TBAT has high reliability and is considered specific to detect the risk of falls, with moderate intensity, with an intra-class correlation coefficient>0.80 [128] [118]. However, it requires an experienced person to operate and has limited reproducibility [129]. The Romberg test, also known as the Romberg maneuver, is used by healthcare professionals for drunk-driving tests and neurological examinations. This test assesses the body's sense of movement and position (proprioception), which is based on the condition of the upper spinal cord. The primary condition for conducting the Romberg test is that the subject needs to have at least two of the three senses: proprioception, vestibular, and vision. A person who has lost proprioception can maintain balance if the vestibular and visual senses are well-functional. The subject must stand upright with straight arms and eyes closed to conduct the Romberg test, and a positive Romberg sign indicates a loss of balance [122] [130].

Some advanced posturography tests have been introduced and can only be run by healthcare professionals at health centers. Some drawbacks of posturography systems are that they are costly and space-dependent, making them less available for use [123]. However, low-cost, platform-based posturography tests have been developed and might not require healthcare professionals or a clinical environment to conduct them for older adults [129].

The Nintendo Wii Balance Board^{TM} (WBB) is a cheaper, Japanese-manufactured gaming platform (Nintendo Co. Ltd, Kyoto, Japan) and a more portable force platform for users to integrate with video games and interact through postural movements [131]. WBB is widely used for research purposes such as balance assessment by neuro-otologists and neurologists [132]. The WBB is used for commercial games such as WII and WII U. It uses Bluetooth to connect with the personal computer and consists of four pressure sensors to estimate the COP. The WBB has two variants: maximum weight supports up to 136 kg and 156 kg. However, both have similar features. It is also stated that the structure of the Wii balance can support greater force up to 300 kg [133] (Figure 2.4).

Figure 2.4: WII Balance Board.

The WBB is more useable than the conventional clinical force platforms used in posturography systems, which are far more expensive than the WBB [117] [134]. The use of WBB in studies has been increasing as an assessment or rehabilitation [131] instrument because of its potential benefits [117] [135]. The path distance and the velocity of the COP assessed through WBB have indicated a high correlation with clinical-based platform tools [132] [134] in different demographics and activities [136] [94].

2.5.1 Studies on Balance Assessment

The WBB can be used with personal computers to assess balance in home environments [132][94]. This device has been validated to improve balance with the training sessions and the evaluation of the balance tests. The COP can be obtained at runtime, which avoids the chance of biased evaluation of posturography metrics [137]. WBB has shown the reliability of measurements from moderate to excellent [94] [138]. One initial study assessed the balance and weight-bearing asymmetry of the subjects after stroke and reported that all WBB-based outcomes were found to be highly reliable between testing occasions (ICC =0.82 to 0.98) [138].

In one study, WBB was used to measure postural equilibrium. The researchers developed an open-source computer-based application compatible with macOS, which operates in conjunction with the WBB. They compared the results obtained with this setup against those from a traditional clinical-grade posturographic platform. Their findings revealed a positive correlation, validating the utility of the WBB for assessing static balance [139]. Subsequently, a systematic review was conducted to assess the validity and reliability of the WBB. This review identified 21 relevant articles, of which 12 focused on validating the reliability of the WBB. However, the remaining literature revealed certain limitations, including issues related to poor quality and validity. While the results from the WBB were generally deemed valid, due to these constraints, it is not advisable to replace clinical-grade posturography platforms entirely [140].

The literature lacks in highlighting the abnormal postural sway by using a WBB. The BioSway Balance System was designed to conduct the Modified Sensory Organization Test (MSOT) to measure mean velocity and maximum excursion of COP with eyes open and closed on a stable and non-stable platform. The authors reported that the test was reliable and valid, with high sensitivity and specificity [141]. Llorens et al. validated a WBB-based posturography tool to assess balance, including tests such as the modified Clinical Test of Sensory Interaction on Balance (mCTSIB), the Limits of Stability (LOS) test, and the Rhythmic Weight Shift (RWS) test. The freeware application requires Bluetooth, a personal computer, and no internet connection. They evaluated the balance of stroke and health subjects and validated the tool with high reliability and feasibility [142].

Despite advancements, the common balance assessment procedures are task-specific, not designed for specific postural demands, and do not transfer effects to performance to evaluate the balance [143] [144] [145].

These balance tests do not reflect the postural control demands of real-life situations, which often involve dynamic environments, interaction, and multitasking. Hence, more ecologically valid balance tests are required for balance evaluation based on the postural control needs according to the daily life situation[146].

3 Proposed Strategy

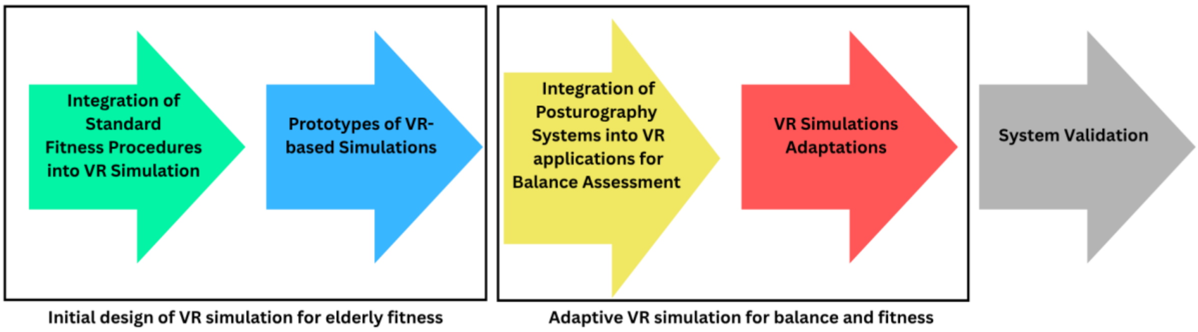
Physical exercise helps combat sedentary lifestyles while improving fitness and balance. Standard fitness procedures, such as the Senior Fitness Tests (SFTs) and posturography, are commonly used to evaluate the functional fitness and balance of older adults. Other tests, like the cardiorespiratory endurance test, assess heart function by monitoring heart rate [62]. Physiological signals, such as heart rate, can be utilized to assess cardiorespiratory endurance. People who are older than 85 years old will rise from 14 million to 40 million by 2050, as shown by SOA (WHO,2021). The highest occurrence of falls is found in adults aged above 60; thus, more research is required on older adults' fitness, risks of falls, and reducing sedentary behaviour. We will conduct our research with a large sample of older adults.

Recent advancements in Information Communication Technology (ICT) have enabled researchers to develop computer-based assessment applications to evaluate fitness and encourage physical activity. For instance, exergames have been used to promote physical activity and increase motivation. However, most exergames are commercially designed rather than explicitly tailored for the fitness training of older adults, highlighting the need for further research on custom exergames for this demographic. While the literature addresses computer-based fitness applications for functional fitness assessment and balance, most require laboratory setups and trained professionals, needing more ecological validity in real-world scenarios.

Virtual reality has emerged as a promising technology for assessing fitness and balance. The most common VR setups used in various studies are Cave systems and Head-Mounted Displays (HMDs). VR has the potential to enhance the ecological validity and effectiveness of assessment procedures. Additionally, a person's posture can be monitored and controlled through VR environments [81][82]. Several studies have utilized and validated low-cost Nintendo WBB for balance assessments. However, the literature lacks sufficient focus on detecting abnormal postural sway using WBBs. Additionally, the commonly used balance tests lack ecological validity, emphasising the need for more research on automated balance assessment procedures.

The literature should emphasize VR-based automated fitness procedures and simulation applications that offer high ecological validity for profiling fitness and balance. These approaches aim to increase physical activity and reduce the risk of falls among older adults. Therefore, our primary research objective is to develop a SAR platform that leverages biofeedback for fitness assessment and intervention, enhancing the overall fitness of older adults.

Motivation and physical exertion in older adults can be improved through VR-based simulations by designing applications tailored to their interests, needs, and physical fitness profiles. This thesis aims to develop a framework to assess the fitness and balance of older adults and deploy a VR training methodology oriented to reducing the risk of falls by increasing fitness and minimising sedentary behaviour. Figures 3.1 and 3.2 illustrate the proposed methodology



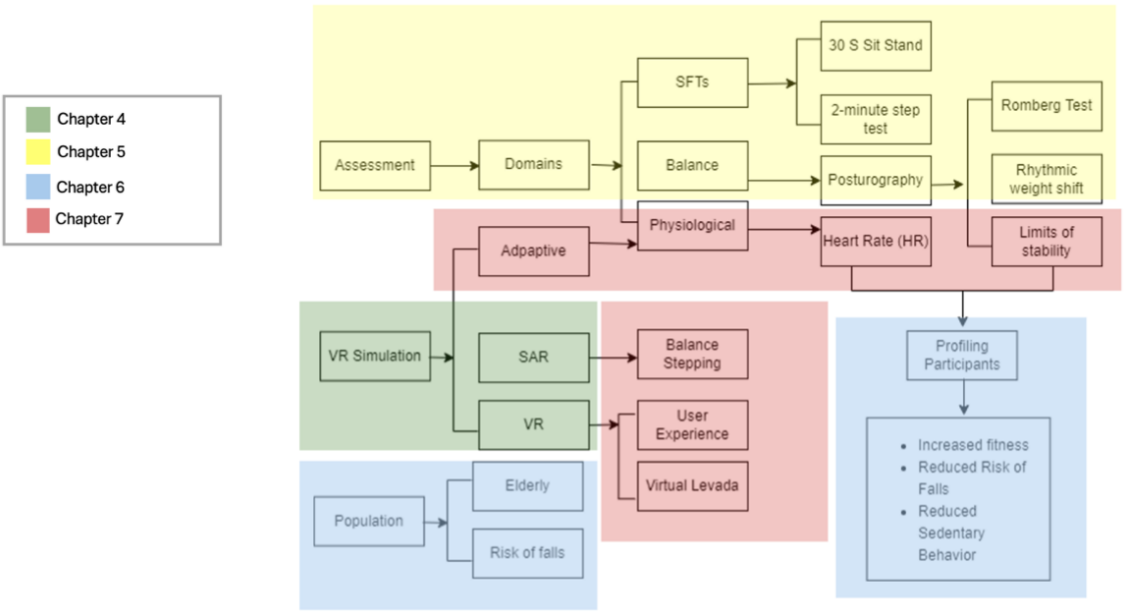
3.1: Proposed Methodology

and the conceptual framework of our research, emphasising three main components: Assessments, VR Simulation/Training, and Profiling and Fall Risk Assessment:

- The Assessment component encompasses functional fitness tests, such as the Senior Fitness Tests (SFTs), and balance assessments, including Posturography (Romberg Test, Rhythmic Weight Shift, and Limits of Stability), all of which will be implemented within VR setups.

- The second component, VR Simulation, features a virtual hiking application for fitness training, using physiological signals (heart rate) to track and enhance cardiorespiratory endurance.

- The final component is dedicated to evaluating the developed system, drawing on the fitness and balance assessment procedures.



3.2: Concept Diagram

Our work will be developed in the following four chapters. Chapter 4 evaluated the effectiveness of SAR environments in developing VR-based applications that have the potential to be integrated with traditional fitness and balance assessment tests. This served as an initial step toward creating an ecologically valid SAR-based simulation and testing our VR setup, the KAVE. In Chapter 5, a SAR-based simulation application was developed to evaluate the feasibility of the system to assess users' cardiorespiratory endurance (fitness) by implementing senior fitness tests, including the two-minute step test, 30-second Sit-to-Stand test, and six-minute step test. Chapter 6 presents a custom immersive VR-based platform built on validated protocols, aiming for high ecological validity to assess static balance in older adults. This platform facilitates profiling and fall risk assessment. Finally, Chapter 7 introduces a SAR application for fitness training, utilising physiological signals within the SAR simulation to control and adjust the intensity of participants' physical activity. Adaptation rules were established in a closed-loop system based on participants' heart rate (HR), using BLEngine [147] to maintain them within the target heart rate zone.

4 Design to increase ecological validity (Cave vs HMD)

This chapter evaluates the efficacy of HMD and Large Screen environments (CAVE) in creating ecologically valid VR-based applications [148]. A simulation application was developed to assess efficacy in terms of immersion within the two most common VR environments. It served as our initial step toward developing an ecologically valid SAR-based simulation and validating our VR setup, the KAVE.

4.1.1 Introduction

Walking is an eco-friendly mode of transportation that also serves various other purposes, such as travel, exercise, rehabilitation, social connection, relaxation, and improving emotional well-being [149]. Walking is widely recognized as an important factor in reducing the risk of coronary heart disease in older adults [150]. Pedestrians aged 65 and older are at a higher risk of serious injury on the road compared to younger adults [151] [152]. Aging causes a decline in functions, such as vision [153], hearing [153], visual perception [154], motion sensitivity [155], the ability to estimate time to contact [156], and general executive function [157][158] may affect the ability to perceive approaching traffic and make quick, accurate decisions when crossing the road. However, pedestrians walking along the roadside face a high risk of injury [159]. Moreover, movement time increases [160] with age due to a decline in stability [161], leading to a higher risk of road crossing accidents. Older adults also tend to look down while walking, which can distract them from noticing oncoming traffic [162].

The increasing number of vehicles and traffic in the last decades is leading to a higher number of casualties on the road, particularly of pedestrians, who account for about 20% of all deaths in the USA. In Europe, 5320 pedestrians were killed in road accidents in 2016, which corresponds to 21% of all road fatalities [163]. In the case of Portugal, in 2016-2017, there were approximately 10,000 accidents involving pedestrians [163]. A survey on pedestrian and bike rider activities in 2012 showed that some of the reasons for traffic accidents are related to low-standard traffic services, such as the unavailability of footpaths and dark streets (Schroeder, 2013)

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[1] The content of this chapter has been published in the proceedings of the 13th International Conference on Disability, Virtual Reality & Associated Technologies [148].

and lack of traffic lights [164]. Interestingly, in 80% of the cases, the behaviour of pedestrians is the cause of collision between vehicles and pedestrians [165]. Therefore, more research is required to examine pedestrian behavior and to develop training procedures that could be used to train pedestrians [166]. There are, however, limitations to conducting real-world studies on pedestrians, such as creating a special risk-free traffic environment for an experiment and ensuring pedestrian safety.

4.1.2 VR Simulations

Users can benefit from SAR because it not only provides a virtual environment but also provides characteristic features of Augmented Reality (AR) and Virtual Reality (VR) without wearing any complex head-mounted displays. The main components of creating a SAR environment are projectors, which do not require any particular display but can project virtual environments on real-world surfaces. Due to the projection features of SAR, users require minimum input devices to interact with the environment. SAR may be used in many areas, such as public spaces, where social and networking features of the technology can be applied [167].

In recent years, VR technologies have made much progress, and many VR systems have been introduced. The usage of VR technology is trending because it provides a high level of immersion - the extent to which the VR system delivers sensations from the real world to the virtual world [168] [169]. In particular, CAVE (Cave Automatic Virtual Environment) systems have been reported to immerse and engage participants during VR experiences effectively [170].

4.1.3 SAR Setup

Multiple prototypes of VR simulation were developed in Unity 3D cross-platform gaming engine, which implements both features of HMD and SAR. Desktop-based systems initially introduced immersive VR. Specialized hardware such as CAVE, HMD, and sensor gloves are required to create an immersive VR with a high sense of presence [171]. The VR companies and edutainment industries used the most common VR devices, such as HMD and CAVE. The CAVE was developed in the early 1990s as a large-scale projection tool that supported computational scientists in presenting their research in advanced interactive systems [172]. Krijn et al. [173] reported a greater presence, immersion and emotion for the CAVE, greater skills and less experienced [174] as compared to HMD.

4.1.4 Method

4.1.4.1 Participants

A convenience sample of 20 participants (10 females, ages: M=29.37 SD = 6.49) participated in this study. The participants were undergraduate and graduate students, and research assistants with no physical disabilities and were able to understand and speak English. They were Recruited at the University of Madeira and the NeurorehabLab. One participant was removed because of the data storage problem. All participants provided written informed consent and received no compensation for their participation. Participants were randomly assigned to HMD and Cave groups.

4.1.4.2 Hardware

The primary goal of our work was to create a safe, user-friendly, and cost-effective virtual reality environment for road-crossing training. To achieve this, we developed a VR simulator implemented in two configurations: a VR CAVE and a HMD. Both CAVE and HMDS are highly immersive systems that offer realistic traffic simulations while reducing spatial and movement limitations. The following sections describe the hardware and software of our study.

4.1.4.2.1 KAVE

The first hardware component of our experimental setup is the KAVE, an immersive VR system based on CAVE technology, developed previously at our research lab [175][170]. KAVE consists of large-screen displays, speakers, and four Hitachi projectors arranged to project onto the floor and walls.

KAVE Unity Plugin

The KAVE runs on a Unity plugin for CAVE systems previously developed at our research lab. It comprises scripts, objects, and prefabs that use a 140$ Kinect V2 tracking sensor (Microsoft, Redmond, USA) to add a parallax effect and full-body tracking for interaction with virtual objects.

The motion parallax effect is the core feature of the cave plugin, and It is achieved by monitoring the positions of the user’s viewpoint, projection surfaces, and virtual environment objects. The projection images from the virtual environment are projected on the surfaces dynamically for the user to perceive like the real-world environment objects. The parallax effect can not be achieved without tracking the size and position coordinates of the projection surfaces and the user’s avatar and mapping the CAVE projectors’ images to the surfaces accurately. A maximum of 8 projectors and the surfaces can be added dynamically. Their size, position and orientation can be altered according to the physical cave configurations. Therefore, the KAVE calibrator was created to map the projections on the cave walls correctly. It creates a configuration file (XML file) at run time, which allows the KAVE plugin to create a virtual environment for a physical cave setup. After implementing the KAVE plugin into the Unity project, the following components are created in the Unity scene at run time:

- Kinect v2: A virtual Kinect v2 sensor is created in the scene that tracks a maximum of 6 users with their avatars having 25 joints, skeleton positions and orientations through Kinect SDK. The avatars have colliders so that users can interact with virtual objects.
- Surfaces and User View Cameras: The unity planes are created without rendering their textures (invisible) to simulate the cave’s walls and floor as reference targets for the user view cameras. The user view cameras are the unity cameras that are created for each surface and attached to the v2 sensor for tracking the user’s head position.
- CAVE Projectors: The virtual cave projector is created in the unity scene that wraps the images from the user view cameras to map into the required physical projection surfaces correctly. The wrapping process is done by mapping each of the four corners of the image to the new viewport locations matching the physical wall corners. This allows to creation of customized configurations when the aspect ratio of the projection surfaces and projector are different or when projectors are not oriented correctly. Each projector can receive multiple user-view cameras simultaneously, avoiding physical projector calibrations (Figure 4.1).

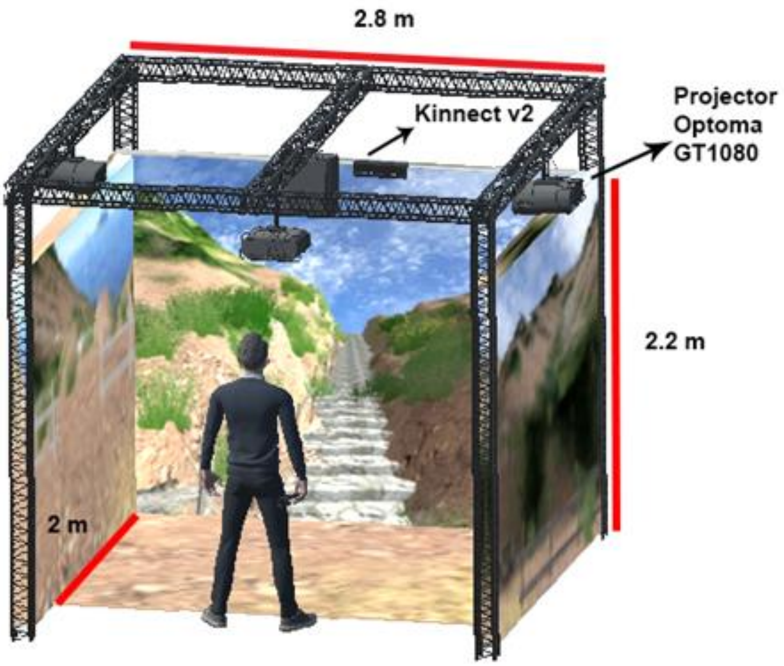


Figure 4.1 Schematic diagram of Kave Setup

The KAVE plugin is comprised of prefabs, such as 'Cave Manager', which is placed as a child object of the game player object. The existing Unity scene camera should be turned off after importing the KAVE plugin package.

The image projections can be done on multiple configurations as follows:

- Interactive Floor: The floor surface with one projector facing downwards is used to create an interactive floor, allowing a direct interaction with a parallax effect. It is a simple configuration and It could be effective for exergames or simulations where direct floor interaction is required.
- Large Screens: A large interactive wall is created using multiple projectors, which project images on adjacent areas. The parallax effect can also be created by placing a Kinect sensor behind the user. However, the Kinect sensor does not detect users from the back and creates interaction problems. The best practice is to place the Kinect sensor in front of the user's wall.
- Corner Projection: A small corner cave can be created by using two walls and a floor (corner) of the room. One projector is used to project multiple walls simultaneously. The projector is required to be placed at high angles due to less brightness and resolution. Another limitation is the position of the Kinect sensor relative to the user's position.

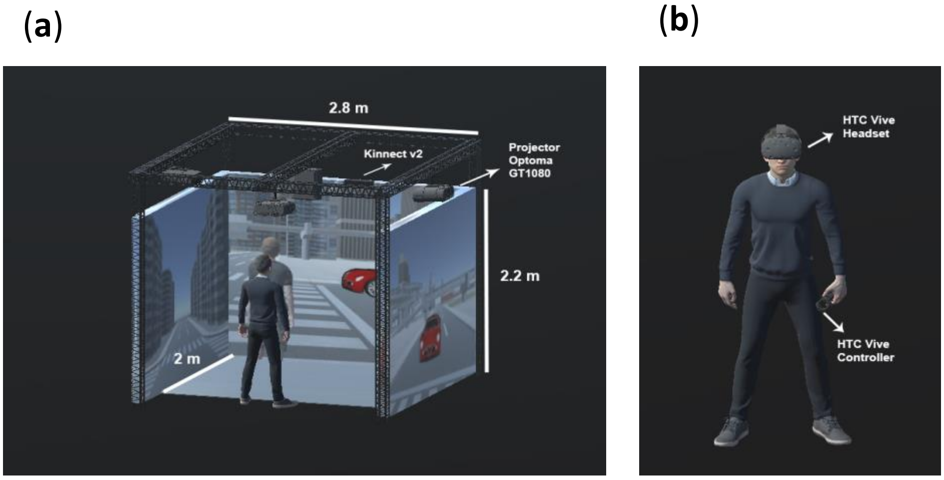
- Small /Desktop Screens: The KAVE plugin can also be used for small screen setups or desktop applications. However, the calibrator does not support that configuration and can be done by modifying the configuration xml files manually.

Physical Cave and Configurations

The height and width of our CAVE walls are 2.2 and 2.8 meters, respectively, made with three wooden sheets (1.2 cm thick). The floor is made of a rigid white vinyl sheet. A Kinect V2 sensor is installed at the front wall to detect full-body gestures. The latest Azure Kinect DK can be used with the KAVE plugin, as Kinect V2 is out of production. External speakers and four HD projectors (Optoma GT1080, 1080p image resolution and throw ratio of 0.5:1) are positioned in a way to project on walls and floors (Figure 4.1(a)). The low throw ratio of the projectors minimizes the user shadows during the projections inside the cave. A metallic frame was built to provide support to projectors, Kinect sensors, and cave walls. The frame can be used to support other sensors, such as HTC base stations (vive.com), which are also installed at the corners of the cave. The price of the CAVE (structure, projectors, and Kinect) was just under 3,800€ (projectors costing 3,200€).

4.1.4.2.2 Head Mounted Display

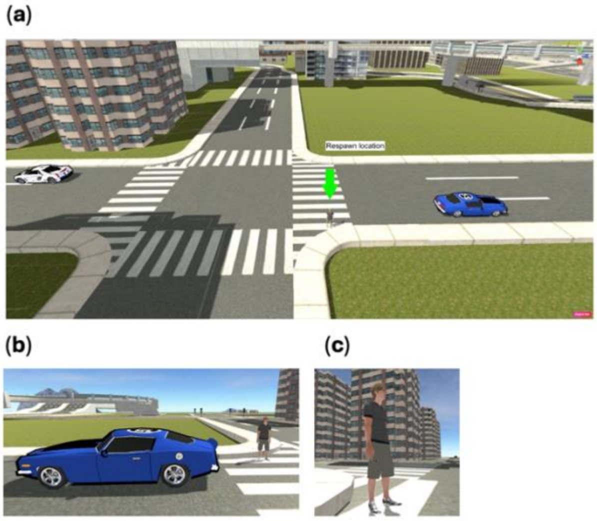
The second setup consisted of an HMD, namely an HTC Vive headset (vive.com) (Figure 4.1(b)). Vive renders stereoscopic textures of 3D models, which are generated at specific angles to create an immersive effect. Vive also has supporting features such as lighthouse sensors for tracking the position and rotation of the headset, allowing interaction with the virtual environment more efficiently. Our setup used two lighthouse sensors that were facing each other, placed at the corners of the CAVE. To help prevent sickness, Vive provides a high refresh rate to reduce lag in rendering graphics.



4.2*: (a) CAVE setup (b) HMD setup*

4.1.4.3 Software

For the development of our system, we used the Unity 3D game development platform (unity3d.com), which is a powerful tool for creating 3D virtual environments. It has special features such as a particle system, animations, and physics for more realistic applications. The virtual environment includes a 3D city with roads, downtown buildings, zebra-crossings, and traffic that simulate real-world conditions were created in Unity 3D and Blender creation suite (Blender Foundation, Amsterdam, Netherlands) to create a simulation experience. A user avatar with multiple animations, such as standing, walking and falling, was also created to develop a virtual road-crossing simulation for the pedestrians. The city environment was the same for both VR setups. The two different traffic speed limits were used, namely 40km/h and 60 km/h, to assess how participants behave in different speed limits when they have different gaps of time to cross (Fig. 4.2). Vehicles were spawned at different time intervals for the users to estimate valid gaps. A user could see his/her avatar in the VR environment, in front of him/her, standing at the curb of the footpath. Participants held a Vive controller or a joystick that they should press when they decided to cross the road. The avatar walked at the speed of 1.20 m/s, which is the average speed of a pedestrian [176]. In case of a collision or completion of the street-crossing session, the application re-spawned the avatar to the starting position. The decisions of participants to cross the road and the total number of collisions (Invalid decision) were logged during the live simulation for both speed limits (40km/h and 60 km/h).



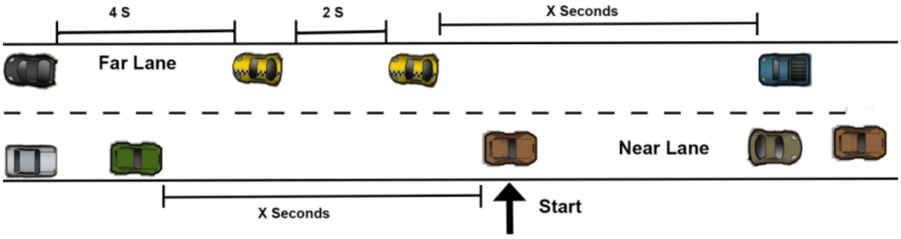
4.3*: Road crossing simulator for pedestrians: (a) City Environment (b) Vehicles (c) Pedestrian Avatar*

4.1.4.4 Questionnaires

As most of the literature uses the Witmer and Singer Presence Questionnaire (WSPQ) [177] to measure participant’s level of presence in a VR environment [178][179] (Appendix B); the WSPQ was used to measure the level of presence. The version used included 24 items addressing Involvement, Immersion, Visual Fidelity, Interface Quality, and Sound [177]. Items 1-22 were rated on a 7-point scale. Sound items (20-22) were not included in the computation of the overall WSPQ score for comparison with other studies. Items 23 and 24 were removed because the application does not have haptic feedback.

4.1.4.5 Procedure

Participants were randomly allocated to one of the two conditions: HMD or VR CAVE. After being informed of the context of the study and signing the informed consent, the participants performed a training trial to familiarise themselves with the VR environment and to learn how to perform the task. After training, each participant executed two trials of 2 minutes each with different speed limits (40 km/h and 60 km/h). The number of times the avatar was hit by a vehicle (collisions) was recorded by the VR application. After the task, participants answered the WSPQ [180]. A full session took about 10 minutes to complete (Figure 4.3).



4.43: Schematic Diagram of the Street Crossing Task

4.1.4.6 Statistical Analysis

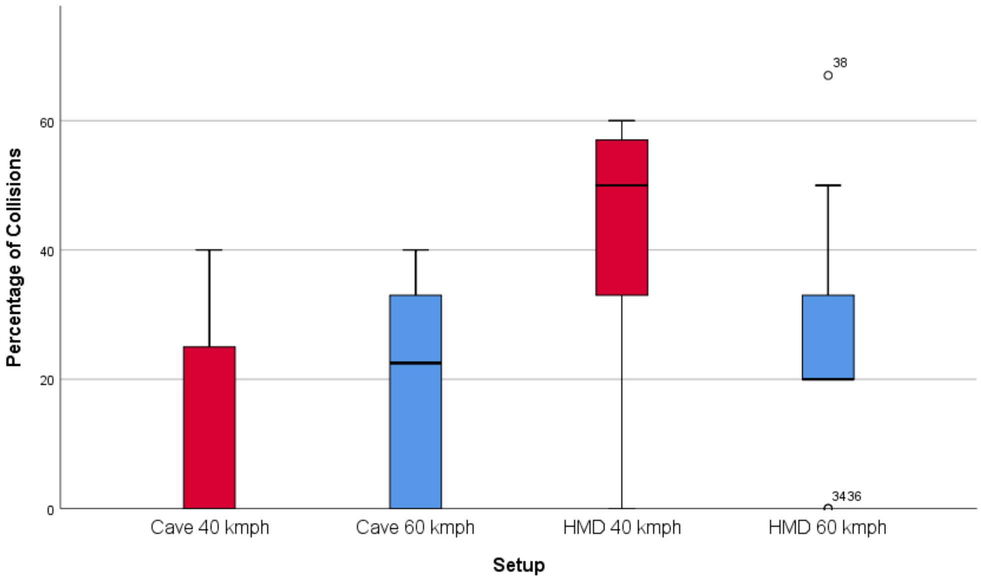
From the number of collisions, we computed the percentage of collisions for the two different speed limits, 40 and 60 km/h. The normality of the distributions was assessed using the Kolmogorov-Smirnov test. Data were considered normal for the 60 km/h speed limit but not for 40 km/h. Hence, we decided to use nonparametric tests for both limits also because of the small sample size. Nonparametric tests were also used for the WSPQ because of their ordinal nature. For between-group comparisons, we used the 2-tailed Mann-Whitney test. Central tendency and dispersion measures are presented as a median and interquartile range, respectively, Mdn (IQR). For the WSPQ, we present the mean (M) and standard deviation (STD) for comparison with the literature. The threshold for significance was set at 5% (α=0.5). Data were analyzed using SPSS version 26.

4.1.5 Results

The data of 1 participant was not included in the analysis because of technical difficulties with the setup during acquisition. For the remaining sample of 19 participants, we compared the percentage of collisions between the two conditions (CAVE and HMD) for the speed limits (40 and 60 km/h) (Table 1). When vehicles were moving at a speed of 40 km/h, participants in the HMD group displayed a significantly higher percentage of collisions when compared to participants in the CAVE group (CAVE: Mdn=0 (22.5), HMD: Mdn=50.0 (42.0); U=17.0, p=0.02, r=0.31). For a speed limit of 60 km/h, no significant difference was found between conditions (CAVE: Mdn=20.0 (33.0), HMD: Mdn=20.0 (31.5); U=41.5, p=0.77, r=.004) (Table 4.1) (Figure 4.4).

Table 4.1: Median (IQR) percentage of collisions per condition

Speed	**CAVE (N=10)**	**HMD (N=9)**	**Mann-Whitney Test**
40 km/h	0 (22.5)	50.0 (42.0)	U=17.0, p=0.02
60 km/h	20.0 (33.0)	20.0 (31.5)	U=41.5, p=0.77



4.54: Collisions in percentage for speed limit 40 and 60 kmph

The mean total score in the WSPQ for the CAVE group (M=122.7 (12.2)), although higher, was not significantly different from the HMD group (M=115.8 (17.5)), (U = 34, p=0.36, r=0.045) (Table 4.2). When analyzing the separate items of the WSPQ, no significant differences were found between conditions (Table 4.2). The high average score for the subdomains of the WSPQ, such as involvement, immersion, visual fidelity, interface quality, and sound, indicates that the user perceived high presence, realistic environment, reliability, and user-friendly (Table 4.2).

Table 4.2: Mean (SD) scores in the Presence Questionnaire

WSPQ	**Items**	**CAVE (N=10)**	**HMD (N=9)**
Total score	All except 20,21,22	122.7 (12.2)	115.8 (17.5)
Involvement	1,2,3,4,5,6,7,10,13	5.2 (0.6)	5.0 (1.2)
Immersion	8,9,14^a,15,16,19	6.1 (0.6)	5.6 (0.5)
Visual Fidelity	11,12	5.0 (1.1)	4.6 (1.3)
Interface Quality	17^a,18^a	6.0 (0.9)	5.4 (1.9)
Sound	20,21,22	5.5 (1.2)	5.5 (0.8)

^{a} Reversed items

4.1.6 Discussion

The goal of this study was to evaluate the feasibility of two primary VR environments (KAVE vs HMDs), based on the level of presence and realism they offered during the experiment, which addresses our subsection of the first research question: 2. Which VR technologies are more adequate to create a VR-based fitness application? Therefore, we created a road-crossing simulation with realistic virtual traffic environments for creating more dynamic and motivated road-crossing tasks based on the traffic speeds and gaps according to real-world traffic situations.

Here, we investigated and compared the effectiveness of a street-crossing task based on valid crossing decisions, measured by the percentage of collisions and the user perception of the presence within a VR environment deployed in two different setups: CAVE and HMD. Our results showed that the percentage of collisions is modulated by the speed at which vehicles move. With lower traffic speeds, participants in the HMD group had a significantly higher percentage of collisions than those who were in the CAVE group and experienced a stronger sense of presence in the CAVE-based environment compared to the HMD. This suggests that the CAVE system may be more feasible, as higher presence can lead to better performance and improved training outcomes [181]. Fewer collisions indicate a better performance, as participants made more valid street-crossing decisions, suggesting its suitability for pedestrian training [164]. This could indicate that participants who used the HMD setup had more difficulties in deciding when to cross the street. The difference was, however, not significant at a higher speed (60 km/h). Although HMDs have higher immersion than a CAVE, they might somewhat restrict looking at both sides of the street while wearing them.

In contrast, the CAVE has larger screens, and users can more easily look around. On the influence of the speed of the vehicles, it is important to note that pedestrians often judge the physical distance, not considering the speed, leading to a poor estimation of the available time frame to cross the street. Other authors compared HMD with CAVE setups and found that participants took smaller gaps and performed faster in HMD when compared to the CAVE, suggesting that the HMD makes the scenario less threatening, which leads to users taking more risks [182]. This is a plausible explanation to justify the higher number of collisions in the HMD setup. Another study where participants performed a train boarding task showed that the performance was better in a CAVE when compared to an NVIS nVisor ST HMD [181].

Concerning the WSPQ [180], when comparing the total score over the 19 items in the two conditions, we observed that the mean score was slightly higher in the CAVE condition when compared to the HMD setup (122.7 (12.2) against 115.8 (17.5)), but not significantly different. Other studies that measured presence using the same version of this presence questionnaire on VR environments for pedestrians reported lower total scores. For example, a recent study reported a mean score of 109.35 (13.65) using an HMD [179]. In another study, authors reported a total presence score of 93 (1.23) in an HMD setup [178]. Our results indicate that both the CAVE and the HMD induced a stronger sense of presence when compared to the literature. On the subdomains of WSPQ, irrespective of the setup, we observed high scores for involvement and immersion, indicating the presence and realism of the virtual environment. We also observed high scores for visual fidelity and interface quality, suggesting the reliability of the simulator. The average sound score also indicates realistic sound effects in the virtual environment for both setups.

Following the popularity of driving simulators, several studies developed pedestrian simulators through VR environments for street crossing training [164]. VR simulation has the advantage of training pedestrians in a safe environment that would not be achieved in real traffic conditions.

4.1.7 Conclusion

Our study compared the efficacy and presence of two VR environments by using the latest VR technology for pedestrian safety applications. Although the latest VR technology has removed barriers, there are still space constraints. To address this issue, our application represents the pedestrian as an avatar that the participant controls using a joystick/controller. This pedestrian simulator also includes sound effects to simulate real-world traffic experiences. Both setups offer low-cost solutions with flexible and customizable traffic scenarios. However, considering that the CAVE (SAR) elicited a higher sense of presence and considering that participants showed fewer collisions with vehicles, our results indicate that the CAVE is more effective as a simulator for street crossing.

The main limitation of this study is the small sample size and its lack of representativeness because all participants were young, healthy adults. Children, older adults, and people with motor and cognitive deficits are at higher risk of traffic accidents. Hence, further studies should be done on these specific populations.

This study suggests that the KAVE can be a promising technology for implementing ecologically valid VR environments to integrate standard fitness procedures and create a SAR platform for fitness assessment, profiling, and intervention using biofeedback to enhance the fitness of older adults.

5 Assessing Fitness in SAR

In our previous study, we found that CAVE systems (SAR environments) may be feasible for ecologically valid simulation applications, as they provide a strong sense of presence for users. In this chapter, we will introduce several SAR-based simulation applications for fitness assessment and cardiorespiratory endurance (fitness) training by implementing validated fitness tests described in the State of the Art [183].

The assessments consider three different assessment approaches: SFTs, balance and electrophysiological recordings. The combined assessment procedures will enable us to develop a fitness profile of the individuals and provide them with appropriate tools for personalized physical activity training. The SFTs have been used in many clinical studies, as shown in the State of the Art by [52][52][53][54], and they are recommended instruments to assess the physical fitness of older adults (see chapter 2.1 for more details).

Similarly, clinical instruments have been developed to assess balance disorders [120], and posturography assessments have been used to measure balance disorders, as shown in SOA accurately [184][121]. Therefore, relying on low-cost hardware, we will implement a posturography system that will evaluate balance and postural control and compare to validated systems [123].

Through exercise, physiological responses are altered by playing, as shown in the introduction chapter by [42]. Thus, to maintain the player's physical activity, one possible solution is to adapt the VR application to the user in real-time. This adaptation can provide the training load required to achieve the desired exertion levels [185]. Here, we will use a closed-loop control approach, which will be implemented through a biocybernetic-loop-engine (BLEngine) [186] monitoring the heart rate (HR) to control the intensity of cardio-respiratory training. The adaptation feature provides live feedback on the participant's performance during execution, which keeps them motivated, and optimized exertion levels can be achieved.

[2] The content of this chapter has been published in the proceedings of the 14th International Joint Conference on Biomedical Engineering Systems and Technologies [166].

5.1 Senior Fitness Tests

5.1.1 Introduction

Exergames (video games with physical activity) are becoming more popular because of their reported benefits [91]. The main goal in the design of exergames is to keep players motivated during gameplay and physical activity [103] [97]. An exercise session of ten minutes can increase concentration and provide cognitive incentives [70]. The combination of physical activity and video games increases player interest and motivation [93]. Exergames can help to overcome a sedentary lifestyle [70]. According to the US National Heart Lung Blood Institute, the limitations of inadequate physical activity levels include lifestyle, fewer recreational facilities, age, and health conditions [92].

SFTs were introduced to assess lower-body strength, agility dynamic balance, and aerobic endurance among older adults [58]. The SFTs have been used in many clinical trials as a tool to assess the physical function of older adults [187]. The SFTs are easy to use and do not require any special technical skills, infrastructure, or setup [57]. We implemented automated senior tests - the 30-second sit-stand (30SSTS) and 2-minute step test (2MST) [61] - in a SAR simulation of Madeira's natural environments and compared them with traditional fitness tests. We hypothesize that the VR-based SFT will correlate with the conventional tests, being a feasible alternative for fitness assessment.

We implemented this system in a SAR setup simulating the Madeira Levada tracks to enhance the sense of presence, realism, and usability. As part of this, we adapted the 2MST, originally introduced by Rikli and Jones in 1999 as part of the Senior Fitness Test [42]. In our virtual Levada simulation, participants were required to march in place as fast as possible for 2 minutes, lifting their knees to a predefined criterion height.

Additionally, we hypothesized that a 6-minute stepping exercise in a VR environment could effectively induce physical activity by increasing participants' heart rates, like the physiological effects of the 6-Minute Walk Test (6MWT). To test this, participants performed a 6-minute stepping exercise in SAR with three variations of knee height, simulating walking in a VR environment. Finally, we developed and implemented a SAR version of the 30SSTST.

With this work, we intended to address the following sub-research questions:

RQ1.1 Which VR environment induces more presence?
RQ1.1 Does a cave-based VR system offer high presence and usability for simulating a virtual environment?
RQ1.3 Can a stepping exercise in a Virtual environment be used to induce adequate physical activity?

5.1.2 Method

5.1.2.1 Participants

The participants were a convenience sample recruited at the University of Madeira campus. It consisted of 13 participants (females =8, ages: M=30.29 SD =6.4). The sample comprised graduate students and research assistants who had no physical disabilities, could understand and speak English, and received no compensation for their participation. Three participants were removed because of technical problems with the accelerometer.

5.1.2.2 Technical Setup

We used the NeuroRehabLab's KAVE system [175][170] to create the SAR environment (For more details, see Chapter 4.7). The SFT simulation has two parts. The first part includes the 2MST and 30SSTST SFTs, while the second part comprises the 6-minute virtual levada track with three difficulty levels.

The VR environment contains computer-generated 3D objects, such as mountains, trees, grass, birds etc., created in Unity3D and the Blender creation suite (Blender Foundation, Amsterdam, Netherlands). Virtual steps were created for the 2MST simulation, that the user can climb by performing a stepping exercise (Figure 5.1(a,c)). Relying on the KAVE plugin described in chapter 4.1.4.1.1, the simulation tracks the user stepping activity through the Kinect sensor at run time and updates the scene accordingly. A virtual avatar and chair were created for the 30SSTST (Figure 5.1(b,d)). When the user performs a sit-to-stand activity, the avatar synchronizes its movement with the user. The purpose of avatar creation was to provide feedback on the activity to the user during performance.

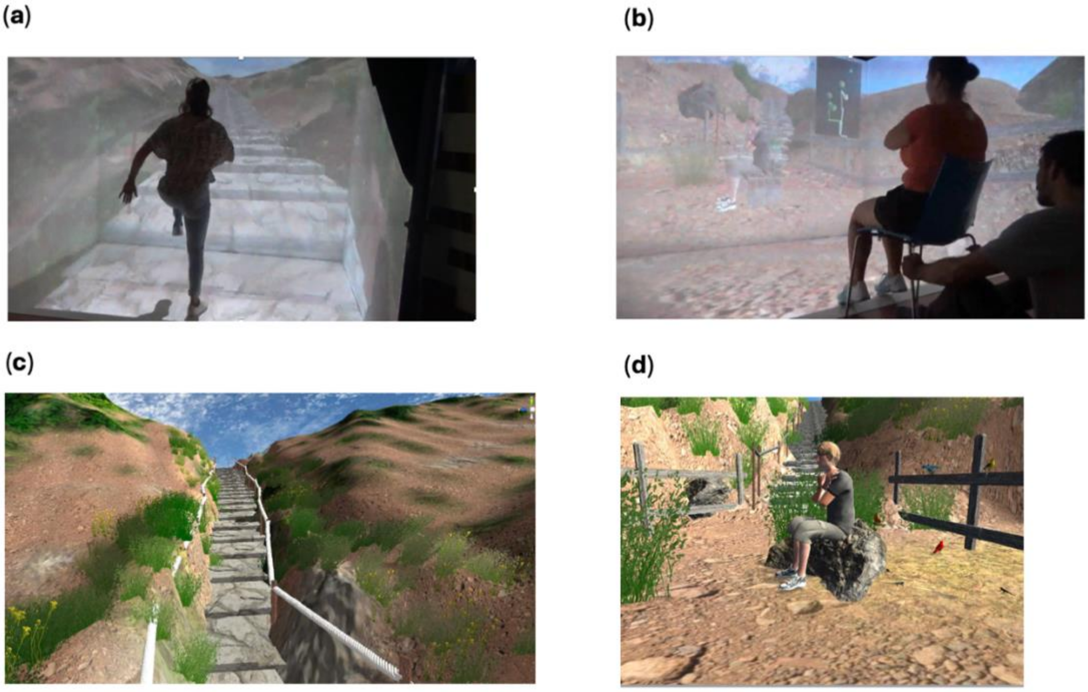


Figure 5.1: (a) 2MST (b) 30SSTST (c) Steps in VL (d) Avatar in VL

In the second part, four types of virtual Levada tracks (Figure 5.2(a), 5.2 (b), 5.2 (c), and 5.2 (d)) (Figure 5.3) were created in Unity 3D to simulate a 6-minute hiking experience (Figure 5.4). The VR environment features computer-generated 3D objects, including mountains, trees, grass, birds, and irrigation canals. The user moves through the hiking trail by stepping in place. The Kinect V2 is used to detect the knee height and trigger the virtual movement. Three different difficulty levels were created by modulating the required stepping height of the knee.

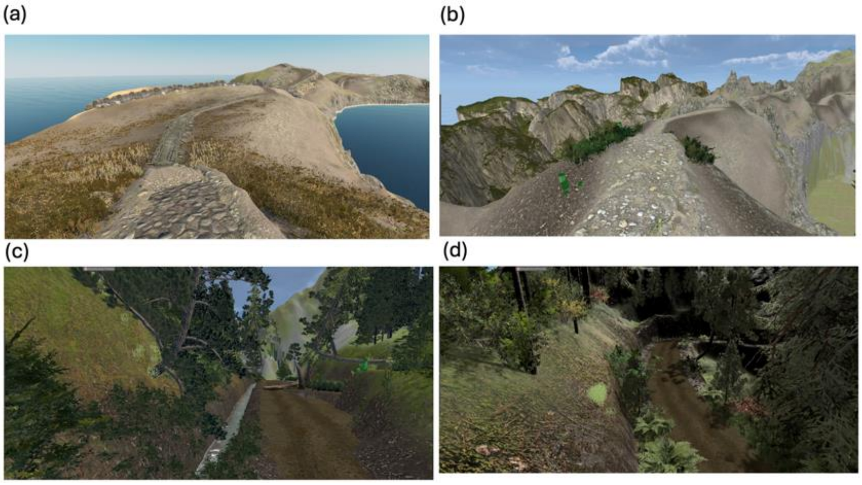


Figure 5.2: (a) Virtual Sao Lourenco (b) Virtual Pico do Arieiro (c) Virtual Caldeirao Verde (d) Virtual 25 Fontes Falls

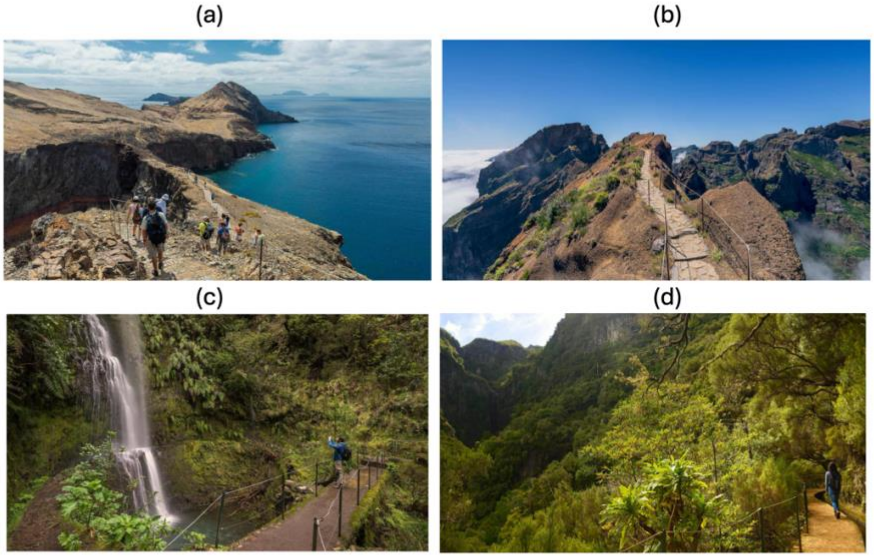


Figure 5.3: (a) São Lourenço (b) Pico do Arieiro (c) Caldeirão Verde (d) 25 Fontes Falls

Figure 5.4: 6-minute walk simulation in our Virtual Levada

5.1.2.3 Instruments

We used ActiGraph's WGT3X-BT activity tracker, which is a validated small, lightweight, portable device that measures body acceleration and energy expenditure associated with movement ("ActiLife 6 User's Manual", 2020) and magnitude vector. The vector magnitude is the magnitude of the resulting vector obtained by combining the sampled acceleration values from all three device axes. Also, the WGT3X-BT was paired with a heart rate chest band Polar H10 (Polar Electro Oy, Kempele, Finland), and hence, heart rate data were collected synchronously with the ActiGraph system. ActiLife6 software (version 6.13.4, ActiGraph, Cary, NC, USA) was used to process data and calculate the vector magnitude.

WSPQ was employed, which includes 24 items addressing Involvement, Immersion, Visual Fidelity, Interface Quality, and Sound [177]. Items 1-22 are rated on a 7-point scale. Sound items (20-22) were not considered for the overall WSPQ score's computation, consistent with other studies [177].

Items 23 and 24 are not applicable, as the application does not have haptic feedback.

Our study also used the System Usability Scale (SUS), created by [188], to assess the application's usability. SUS comprises ten items with five response options from strongly disagree to agree strongly. It allows a quick evaluation of the usability of various products and services, including hardware and software.

5.1.2.4 Procedure

Before starting, the study protocol was provided. Participants provided informed consent and were randomly assigned to one group. A repeated measures experimental design was used, and a two-minute demo session was provided to familiarize them with the application and task. After the demo session, participants were asked to wear the Actigraph accelerometer and the heart rate chest band.

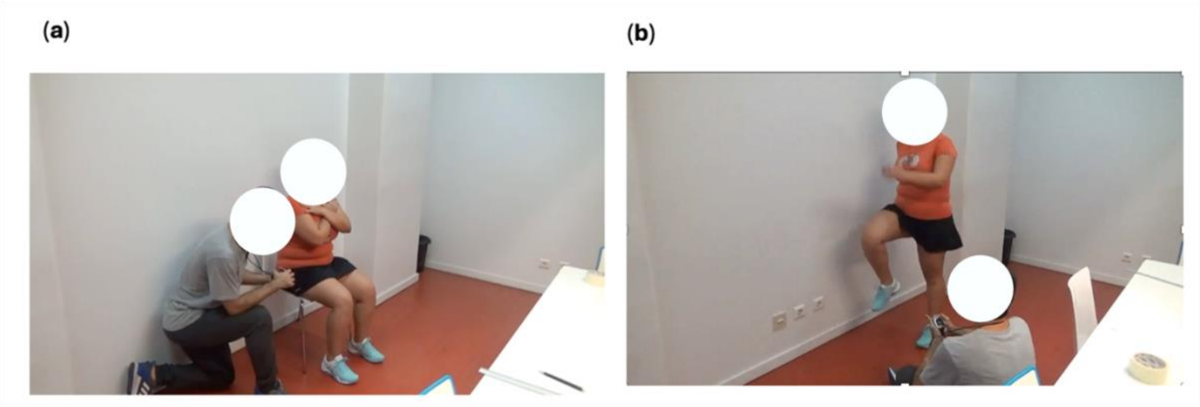


Figure 5.3: (a) 30s Sit-Stand Test (b) 2MST

Participants performed 2MST and 30SST in VR and non-VR environments (Figure 5.1 and 5.3). Five minutes of rest were provided after each 30SST. Likewise, participants had a 5-minute break between each 2MST (VR and NonVR). The time, number of steps and SitStands were recorded during the tests. Finally, a 6-minute walk was implemented were participants executed three blocks of 2-minute of increasing difficulty level (easy, medium, and hard) based on the knee’s height. One minute rest was provided after each block. After the experience, participants answered the WSPQ and SUS questionnaires.

5.1.2.5 Statistical Analysis

The number of steps, magnitude vector, and heart rate were computed as median and standard deviation, Mdn (IQR). For the WSPQ and SUS, we calculated the total mean score and standard deviation M (SD) to compare with related work. The normality of the distributions was assessed using the Kolmogorov- Smirnov test. Data were considered not normal for all three parameters, and nonparametric tests were used. The Friedman test was used to evaluate the impact of different experimental conditions. The threshold for significance was set at 5% (α=0.5). The post hoc 2-tailed Wilcoxon signed-rank test was used for pairwise comparisons. Because of multiple comparisons, Bonferroni correction was applied. Data analysis was performed using SPSS version 26.

5.1.3 Results

5.1.3.1 Fitness

The number of steps in the VR 2MST (M = 86.43, SD = 6.25) was significantly correlated with the number of steps in the non-VR 2MST (M = 109.29, SD = 4.30), showing a strong correlation coefficient of r = 0.735, p < .05. However, the number of SitStands was observed to be slightly higher (M= 16.50(0.41)) for the non-VR condition (Figure 5.5).

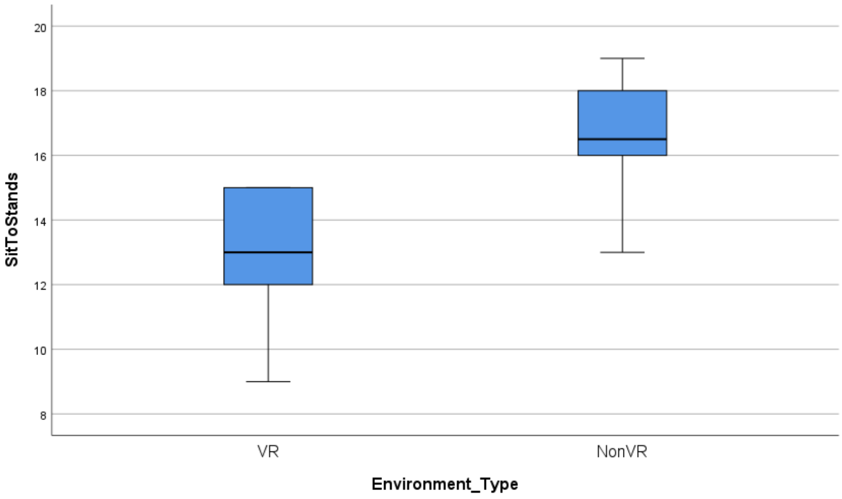


Figure 5.4: Box Plot Indicating the SitStands difference between VR and Non-VR conditions

Three levels (conditions) of difficulty were implemented in the 6-minute walk to elevate the user's heart rate and analyze the number of steps and vector magnitude. There was a statistical difference in all parameters over three conditions of Levada FR (2)=0.20, p<0.001 (Figure 5.6). Post hoc analysis with the Wilcoxon signed-rank test was used with a Bonferroni correction applied. Median (IQR) number of steps for the easy, medium, and hard were 113.0 (27), 96.0 (19), and 83.5 (24), respectively. There were significant differences in all three conditions for the number of steps, which were easy and medium (Z = -3.29, p = 0.0005), easy and hard (Z = -3.29, p < 0.001), and medium and hard (Z = -2.22, p = 0.013). The number of steps decreased at each difficulty level, which suggests that our simulation impacted the participant's exertion level. Similarly, median (IQR) average magnitude vectors for the easy, medium, and hard were 371.1 (253.15), 394.4 (327.52), and 789.6 (360.18), respectively. There were no significant differences in vector between easy and medium after Bonferroni correction (Z = - 1.97, p = 0.024). However, statistically significant differences were found between the easy and hard (Z = -2.73, p = 0.003) and medium and hard (Z = -2.85, p = 0.002). Median (IQR) heart rates for the easy, medium, and hard were 125.0 (54), 126.5 (53) and 138.0 (40), respectively. Significant differences were found in all three conditions for the heart rate, which were easy and medium (Z = -3.11, p = 0.001), medium and hard (Z = -2.27, p = 0.011), and easy and hard (Z =-2.41, p = 0.008). The participant's heart rate supports the idea that an adaptation of the simulation based on the participant’s heart rate could be effective at inducing different physical activity levels.

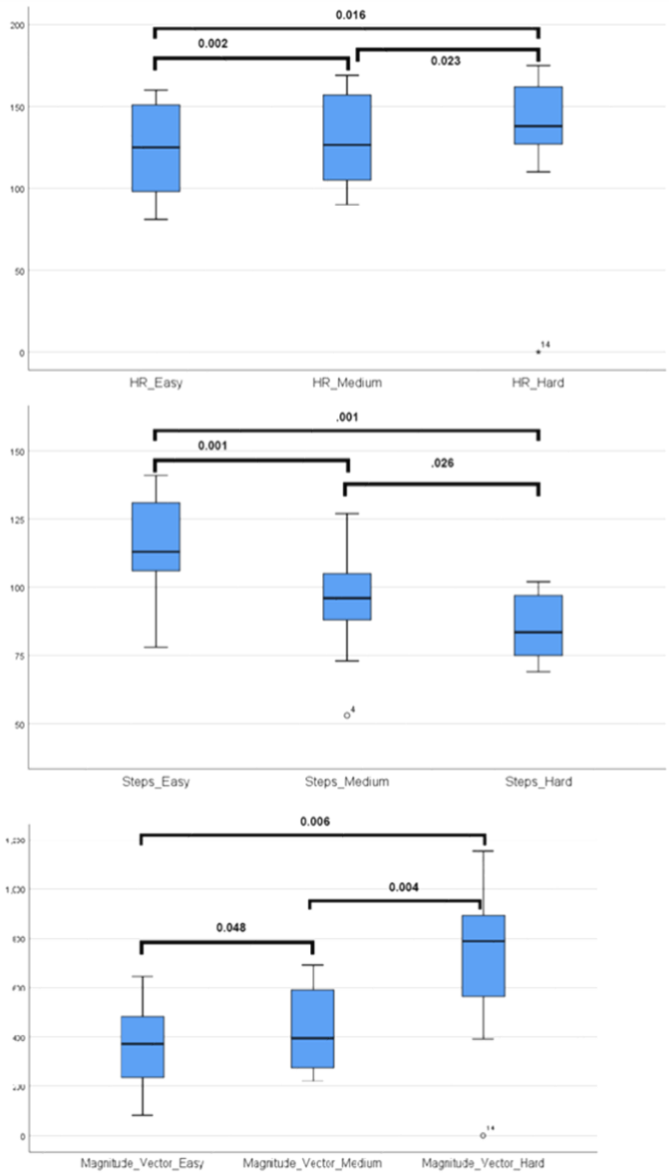


Figure 5.5: Boxplot from post hoc results of Heart Rate, Magnitude Vector, and number of steps. The black lines show the difference between easy, hard and medium conditions.

5.1.3.2 Usability and Presence

The virtual environment was created to resemble the real Levadas of Madeira closely. The hiking tracks with irrigation canals, trees, birds, grass, and plants, and audio, and visual effects were implemented to achieve high visual fidelity, immersion, and presence. The total mean score of the WSPQ questionnaire was M=99.6 (20.3), which indicates a high sense of presence. There were high average scores for all the subdomains of the WSPQ, such as involvement, immersion, visual fidelity, interface quality, and sound, as indicated in Table 5.1. The high SUS scores reported (M=79.2(16.3)), graded as good (near to excellent) according to [189], suggest that using SAR technology for fitness assessment and training is feasible and has good acceptance and usability.

Table 5.1: Mean (SD) scores

WSPQ	Items	Scores
Total score	All except 20,21,22	99.6 (20.3)
Involvement	1,2,3,4,5,6,7,10,13	5.1 (0.98)
Immersion	8,9,14[a],15,16,19	5.0 (0.98)
Visual Fidelity	11,12	4.2 (1.5)
Interface Quality	17[a],18[a]	5.8 (1.5)
Sound	20,21,22	4.6 (1.7)

5.1.4 Discussion

5.1.4.1 Fitness

In this study, we compared our SAR-based SFTs with the traditional ones. Results indicate that the SAR-based 2MST may be confidently used to assess aerobic endurance reliably, autonomously relying on Kinect motion tracking. However, the SAR-based 30SST showed differences from its traditional counterpart. The reasons can be several. This could be due to the intrinsic tracking limitations of the Kinect sensor. Some participants wore black clothes during the test, which can cause the Kinect to fail to track some movements. Also, the presence of an avatar movement as a feedback mechanism could induce slower movements due to Kinect latency in detecting complete standing and sitting poses.

We also assessed the viability of the SAR simulation to induce different levels of exertion by measuring heart rate at various difficulty levels. The difficulty level of the application was associated with the participant's knee height during the stepping exercise. We observed a significant increase in heart rate at each difficulty level, suggesting that a desired target heart rate could be achieved by modulating the application's duration and difficulty. A recent study compared the 2MST with a 6MWT, and they reported higher fatigue and leg fatigue after the 2MST [190]. Another recent study assessed the average exertion level of multiple exergames by measuring participants' heart rates and found an elevation in heart rate [91].

5.1.4.2 User Experience

The usability and user perception of the application's presence were also assessed using the SUS and WSPQ instruments. Our study reported an SUS score of 79.2, which suggests users find the system relatively easy to use and efficient (scores above 68 are considered good). Similar studies have also reported SUS scores; for example, Yoo and Kay reported SUS scores of 75 and 65 for HMD and large-screen displays, respectively [93]. The highest SUS score reported in the literature for exergames is M = 87.0 (11.1), using the Mole exergame developed by SilverFit [191].

A total score of 99.6 (75%) over the 19-item presence questionnaire WSPQ is considered a moderate to strong sense of feeling present within the virtual environment, supporting that our application can induce reasonable and strong immersion and involvement. For example, a recent study reported a mean score of 109.35 (13.65) using an HMD [179]. In another study, Feldstein et al. reported 93 (1.23) presence scores in an HMD setup [178]. The high scores in the subdomains of involvement and immersion indicate that participants experienced a strong sense of presence and a realistic environment. In contrast, the fidelity score highlights the application's reliability. The mean score for interface quality suggests that the application's interface was user-friendly. The average score for sound reflects the realistic ambient sound of Levadas. Gonçalves et al. designed and developed four exergames for older adults using a human-centred approach that actively involved users and health professionals [172][173]. The authors system utilized a Kinect V2 camera to track body movements and floor projectors for interaction and feedback. In contrast, we implemented Cave-based VR systems, offering greater immersion and a stronger sense of presence than large-screen displays.

5.1.5 Conclusion

In this study, we designed and developed a SAR simulation in a CAVE-based VR environment to provide a virtual simulation of Levadas. They are the main attraction for tourists in Madeira, and our simulation can bring more awareness and promote our region while offering fitness training and assessment possibilities. We also assessed the exercise's average exertion level through a user’s average heart rate and found a significant heart rate increase.

However, the current study has limitations, including the portability of the application, a small sample size, space constraints, and challenges in acquiring consistent heart rate data in real-time. In future work, we plan to evaluate target heart rates based on ACSM recommendations[192] by dynamically adjusting the exercise difficulty to match the user’s heart rate in real-time. Additionally, it would be interesting to incorporate more challenging tasks and rewards into the application to enhance users’ motivation and engagement. Hiking could present a greater challenge for older adults due to physical balance and fitness considerations. Future studies should ideally include a larger sample size and older adult participants to validate and expand upon these findings. The high scores for fidelity and immersion address our first research question, demonstrating that our SAR application effectively simulates virtual Levada. Similarly, our SAR-based virtual Levada stimulation significantly increased the participant's heart rate and exertion level, addressing our second research question. Our results suggest that the virtual Levada can induce adequate levels of physical activity.

5.2 Feasibility, Validity and Reliability of a VR-Based Cable Car Simulation for Balance Assessment using the Nintendo Wii Balance Board in Young Adults

This chapter evaluated the feasibility, validity and usability of a VR-based Cable Car Simulation (CCS) for balance assessment with a sample of healthy young adults [193]. The results were compared with the WBB-based posturography tool, which was validated by [142]. The study comprised two primary components. First, we evaluated the user experience by measuring the user's sense of presence in the virtual environment and the system's usability. Second, we examined the feasibility of the simulation to assess the user's postural balance by monitoring the COP in various configurations of the virtual environment.

5.2.1 Introduction

The number of people in Portugal aged 65 or above was 2,262,325 in 2019, with an ageing index of 161.3, and it is estimated to be 355.3 by 2060. The ageing population presents a significant challenge to public health, contributing to a growing incidence of chronic diseases and associated health issues. This demographic shift is closely linked to the prevalence of conditions such as reduced mobility, prolonged hospitalisations, elevated morbidity rates, and an increased incidence of falls [194]. One in three people aged 65 or above falls each year, and it has been reported that 50% fall more than once [195]. Moreover, falls are the leading cause of death in older adults [6]. Falls have a substantial impact on the quality of life of older people [196] because injuries that occur during falls cause disability, functional independence, and institutionalisation and also affect their psychological, physical, and socioeconomic status [197].

5.2.2 Method

5.2.2.1 The participants

A convenience sample of 23 participants (10 females, ages: M=29.9 SD =5.0) participated in this study recruited at the Regional Agency for the Development of Research, Technology and Innovation (ARDITI). Participants were undergraduate and graduate students and research assistants who had no physical disabilities and were able to understand and speak English. All participants provided written informed consent and

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[3] The content of this chapter has been published in the proceedings of the IEEE 12th International Conference on Serious Games and Applications for Health [176].

received no compensation for their participation. Two participants were removed because of an error in the projector's display settings.

5.2.2.2 Wii Balance Board-based Posturography Tool

The Nintendo Wii Balance Board (WBB) based posturography tool [142] was used as a reference to our CCS to assess balance, including the modified Clinical Test of Sensory Interaction on Balance (mCTSIB) [122], the Limits of Stability (LOS) test [142], and the Rhythmic Weight Shift (RWS) test [142]. The posturography tool was validated with 144 healthy adults and 53 stroke patients and presented excellent psychometric metrics and sensitivity for assessing balance. The freeware application requires Bluetooth, a personal computer and no internet connection. The mCTSIB measures the mean speed and maximum excursion of COP in the medial-lateral and anterior-posterior axes for 30 s in 4 conditions, eyes open and closed over a plane surface, and eyes open and closed over foam, in an upright standing posture. The LOS and RWS measure the maximum controlled COP excursion in 8 directions and directional control of participants' COP, respectively. In RWS, participants must synchronize their COP object rhythmically with the moving reference in the medial-lateral and anterior-posterior axes. We only used mCTSIB to evaluate static balance. In this study, we used that tool as a reference to validate our balance assessment with our CCS.

5.2.2.2.1 Implementation

The Nintendo WBB was used to assess the balance of the participants by measuring their COP. WBB, a Japanese-manufactured gaming platform (Nintendo Co. Ltd, Kyoto, Japan), is widely used for research purposes such as balance assessment by neuro-otologists and neurologists [132]. For more details, see chapter 4.6.

Based on the posturography tool described above (chapter 5.2.2.2), the algorithms for implementing the mCTSIB, LOS and RWS tests were re-implemented in Unity 3D to assess balance. The balance assessment tests comprise a 3D environment that includes an avatar, direction arrows and ball objects, which were designed and developed in the Blender creation suite (Blender Foundation, Amsterdam, Netherlands) and Unity 3D. Our implementation requires Bluetooth, a personal computer and no internet connection. The following sections describe the implementation of the balance algorithms.

5.2.2.2.2 Modified Clinical Test of Sensory Interaction in Balance (MCTSIB)

The mCTSIB measures the mean speed and maximum excursion of COP in the medial-lateral and anterior-posterior axes for 30 s in 4 conditions, eyes open and closed over a plane surface, and eyes open and closed over foam, in an upright standing posture. It is based on the Romberg’s test [122] [142] :

- Romberg’s test with eyes open on a plane surface
- Romberg’s test eyes closed on a plane surface
- Romberg´s test eyes open on foam
- Romberg’s test eyes closed on the foam

Tests may be conducted up to three times to minimize data collection errors, allowing for data retention or exclusion after each trial. During the mCTSIB test, no feedback on changes in the COP is provided. Equation 5.1 and Equation 5.2 present the total COP distance and the mean speed, respectively.

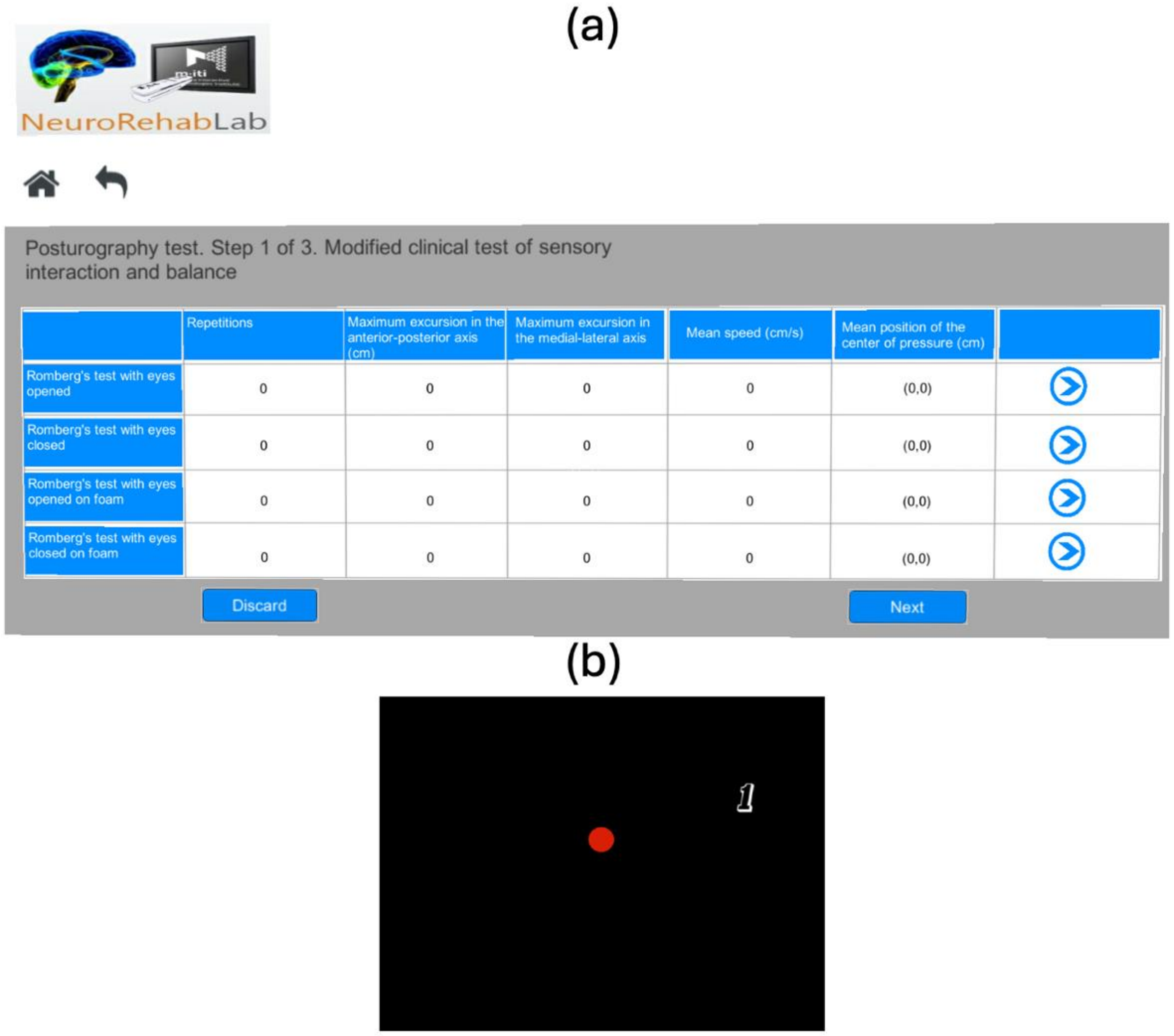
$$d = \sum_{i=0}^{n} d1 + d2 + ... + dn \qquad 5.1$$

$$meanSpeed_{cm/s} = d/30 \qquad 5.2$$

Results are reported in the following output parameters:

- Maximum excursion of COP in the anteroposterior axis (cm)
- Maximum excursion of COP in the mediolateral axis (cm)
- Average speed (cm/s): Equation 2
- COPs alignment: average position of the COPs
- Repetitions: number of times the test is performed within an assessment.

The average of the three repetitions for each test is recorded, and the results are displayed on the application screen after completion (Figure 5.7).



Posturography test. Step 1 of 3. Modified clinical test of sensory interaction and balance

	Repetitions	Maximum excursion in the anterior-posterior axis (cm)	Maximum excursion in the medial-lateral axis	Mean speed (cm/s)	Mean position of the center of pressure (cm)	
Romberg's test with eyes opened	0	0	0	0	(0,0)	➤
Romberg's test with eyes closed	0	0	0	0	(0,0)	➤
Romberg's test with eyes opened on foam	0	0	0	0	(0,0)	➤
Romberg's test with eyes closed on foam	0	0	0	0	(0,0)	➤

Figure 5.6: (a) MCTSIB Results (b) MCTSIB Test

5.2.2.2.3 Limits of Stability (LOS)

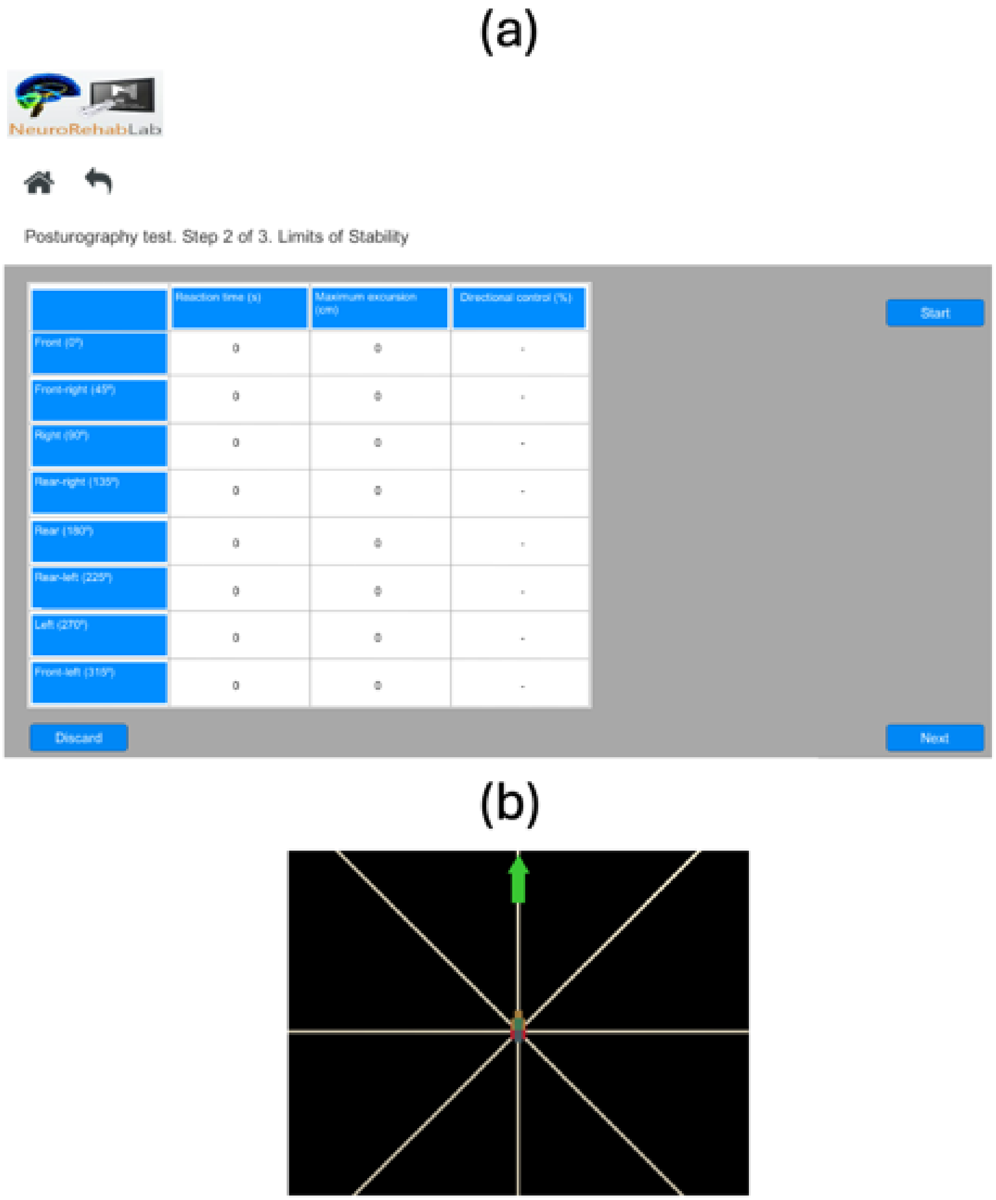
The LOS measures the maximum controlled COP excursion in 8 directions and directional control of participants' COP. The participant is instructed to move the COP in eight directions within the space, as illustrated in (Figure 5.8). The test is comprised of eight tasks of eight seconds each, where the participants are required to move their maximum COP in the indicated direction. After finishing the first task, they are required to move the COP to the origin, and the next task is started in another direction. The avatar represents the COP, and a target object is placed at the end of each directional path, at a distance d, to guide the participant's movement. The participant is free to move in any direction. However, the target object remains in a fixed position and is returned to the center once the participant completes the eight-second task. Equation 5.3 illustrates the directional control percentage during the test.

$$DirectionalControl_{\%} = (Distance_{toTarget}/Distance_{total}) * 100 \qquad 5.3$$

Upon completing the test, results are provided in the following output parameters:

- Reaction time (ms): Time from when the target appears until the user moves in that direction.
- Maximum excursion of COP in each direction (cm).
- MeanSpeed
- Directional Control (%)

The average of the three repetitions for each test is recorded, and the results are displayed on the application screen after test completion (Figure 5.8).



Posturography test. Step 2 of 3. Limits of Stability

	Reaction time (s)	Maximum excursion (cm)	Directional control (%)
Front (0°)	0	0	-
Front-right (45°)	0	0	-
Right (90°)	0	0	-
Rear-right (135°)	0	0	-
Rear (180°)	0	0	-
Rear-left (225°)	0	0	-
Left (270°)	0	0	-
Front-left (315°)	0	0	-

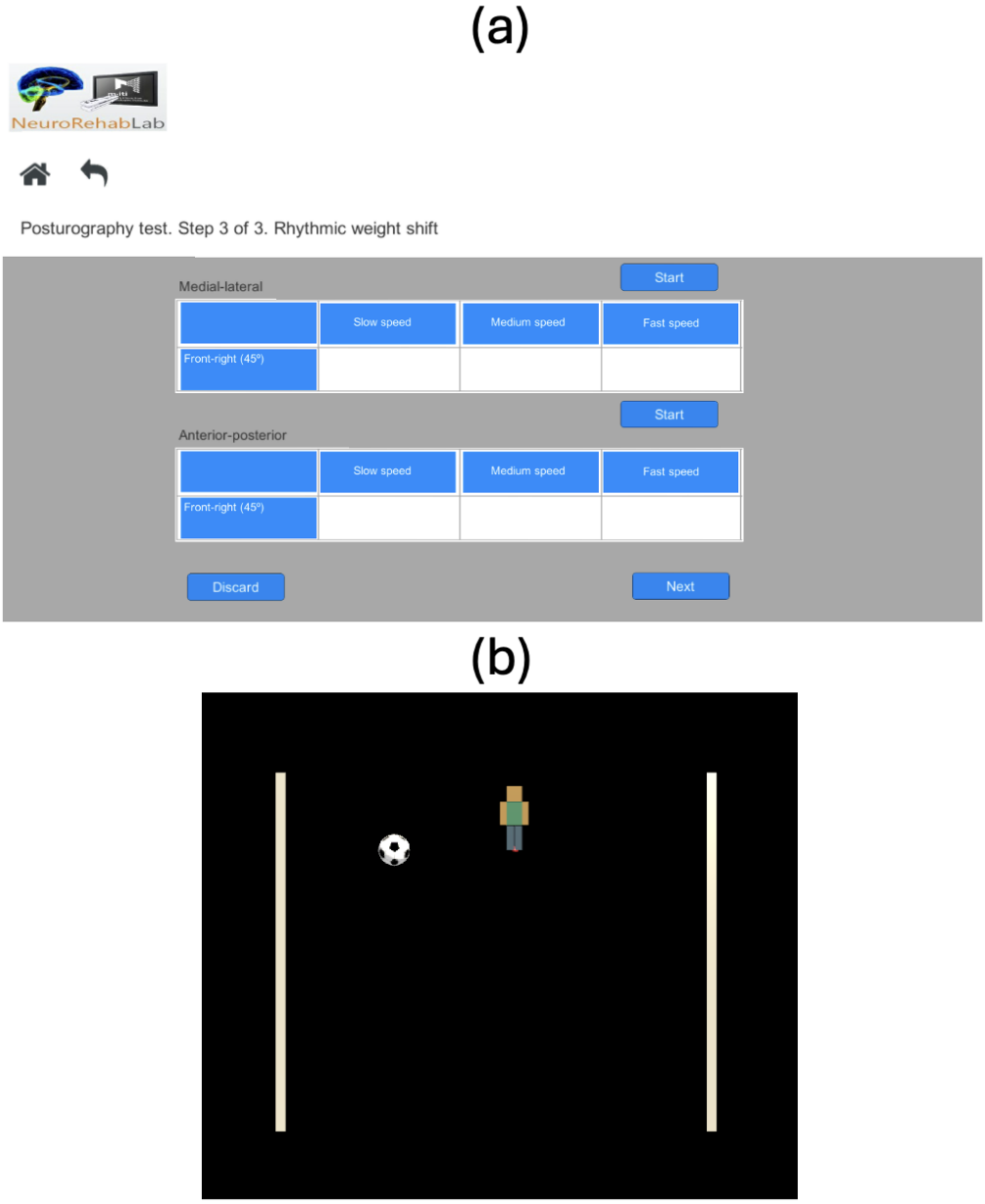
Figure 5.7: (a) LOS Results (b) LOS Test

5.2.2.2.4 Rhythmic Weight Change (RWS).

In RWS, participants are required to synchronize their COP object rhythmically with the moving target along both the medial-lateral and anterior-posterior axes, as illustrated in (Figure 5.9). Unlike the LOS, the COP must fully reach the moving target. The target shifts along the maximal stability directions—anteroposterior and mediolateral—at three distinct speeds (3s, 2s, 1s). Upon completion of the mediolateral test, the target re-centers before initiating the anterior-posterior test. Upon completing the tests (mediolateral and anteroposterior), the results are provided in the following output parameters:

- Average speed (cm/s)
- Directional Control (%)

At the end of the test, the results are displayed on the application screen.



Posturography test. Step 3 of 3. Rhythmic weight shift

Medial-lateral

	Slow speed	Medium speed	Fast speed
Front-right (45º)			

Anterior-posterior

	Slow speed	Medium speed	Fast speed
Front-right (45º)			

Figure 5.8: (a) RWS Results (b) RWS Test

5.2.2.3 Virtual Cable Car Simulator (CCS)

We used the NeuroRehabLab's KAVE system [175][170] to create a virtual environment (For more details, see chapter 4.7). For the development of our simulation, the virtual Cable Car Simulator (CCS) was created in Unity 3D and the Blender creation suite (Blender Foundation, Amsterdam, Netherlands) to create a simulation experience of approximately five minutes, which includes computer-generated 3D objects such as mountains, trees, grass, cable car poles, wires, and station, etc. (Figure 5.10 (a,b,c)). The MCTSIB test (Chapter 5.2.2.2.2) was adapted and implemented within the CCS.

The WBB was connected to the application, and the participant's COP was recorded at 30 Hz during the experiment. The CCS was designed with five turning angles (0, 45, 90, -45, -90) and 4-speed limits (3m/s, 5m/s, 7m/s, 9m/s). After completing the first lap, the cable car auto-restarts at a higher speed. The CCS measures the displacements of the COP for each combination of displacement speed and turning angle, which will then be used to assess the static balance.

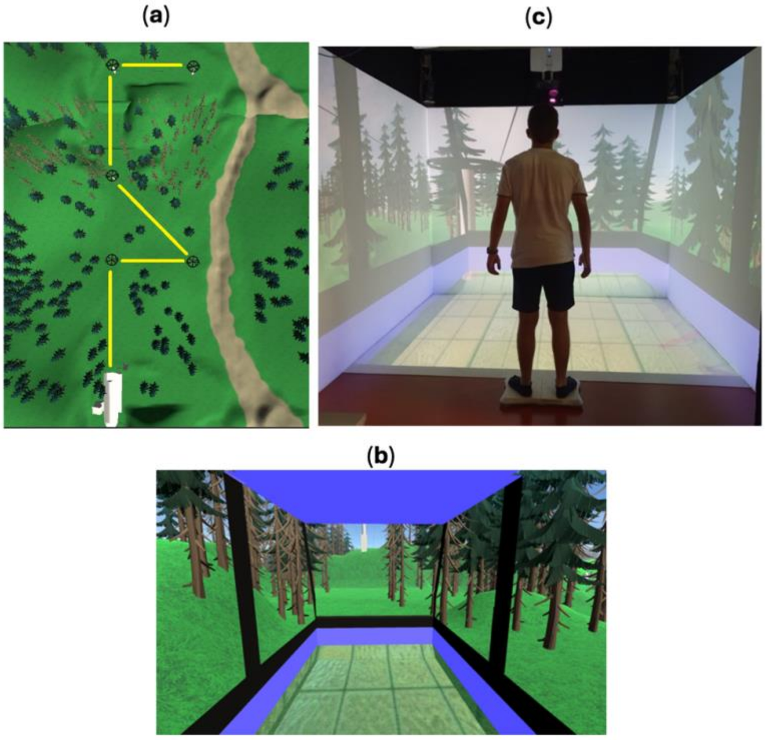


Figure 5.9: (a) Cable Car track (b)Cable Car Inside View (c) Cable Car Cave Setup

5.2.2.4 Procedure

Informed consent was provided, and the protocol for the study was explained. A two-minute test trial was provided to understand the application and objectives. To assess the balance in the VR CCS, participants were asked to stand on the balance board in an upright standing posture and not move their bodies and hands for approximately five minutes. They were only allowed to move their heads to experience the environment. After the simulation experience, a two-minute rest was provided. The participants were asked to stand again on the WBB without the CCS and performed the mCTSIB test from [142]. After the experiment, WSPQ [180] and System Usability Scale SUS [188] questionnaires were provided. WSPQ consists of 24 items, rated on a 7-point scale, and deals with Involvement, Immersion, Visual Fidelity, Interface Quality, and Sound. Haptic feedback and sound were not considered for the VR simulation.

5.2.2.5 Statistical Analysis

We calculated the mean (M) and standard deviation (SD) for the presence and SUS questionnaires. There were two independent variables, Angles and Speed, with five and four levels, respectively. Consequently, we conducted a repeated-measures ANOVA and performed Mauchly's test to assess the equality of variances among conditions. If Mauchly's test yielded a significant result, it would indicate unequal variances of differences, thus violating the assumption of sphericity, requiring the application of corrections (Greenhouse–Geisser, Huynh–Feldt) to obtain a valid F-ratio. Posturography metrics, including the maximum excursion of the COP in the anterior-posterior and medial-lateral axes and mean speed, were computed for all combinations of Speed and angle levels. After repeated ANOVA, post hoc tests were conducted using Estimated Marginal Means (EM Means) and standard contrasts. The significance threshold was set at 5% ($\alpha = 0.05$). Data analysis was performed using IBM SPSS Statistics version 26 (IBM, New York, USA).

5.2.3 Results

We assessed user experience by immersing users in an ecologically valid KAVE-based VR simulation of a Cable Car. The users reported a high sense of presence, as indicated by a mean score of M = 82.7 (SD = 15.1) on the WSPQ. Table 5.3 displays the subitems of the WSPQ, including Realism, Possibility to Act, Quality of Interface, and Possibility to Examine, with their respective means and standard deviations. The high scores for these sub-items suggest a strong perception of presence, reflecting a realistic, user-friendly, and reliable VR environment. Regarding the system's usability, the total mean score on the SUS was M = 72.8 (SD = 17.6). Comparing our study to existing research, the average SUS score typically falls between 68 and 70.5. Our study's SUS score of 72.8 indicates good system usability.

Table 5.2: Witmer and Singer's Presence Questionnaire Scores [Mean (SD)]

SubItems	**WSPQ**	
	Items	**Scores**
Total score	All except 20,21,22	82.7 (15.1)
Realism	3,4,5,6,7,10,13	29.8 (7.1)
Possibility to Act	1,2 8,9	14.0 (5.1)
Quality of Interface	14a, 17a, 18a	17.0(2.9)
Possibility to Examine	11,12,19	12.4 (4.0)
Self Evaluatio Performance	15,16	9.9(2.5)

[a] Reversed Items

Three parameters from the mCTSIB were monitored: the maximum excursion of COP in the medial-lateral, anterior-posterior and mean speed. For the simulation, there were two factors, i.e., Angle and CCS speed, with five and four levels, respectively. All three parameters from the mCTSIB were recorded for each angle and cable car speed during the experiment. The CCS and COP analysis by the posturography test rendered very consistent results (Table 5.4). A correlation analysis shows that the mean velocity of the COP of the CCS at higher speeds and with rotational angles provided strong and significant correlations with the same metric of the mCTSIB test. The mean speed for nearly all combinations of Angles (0, 45, 90, -45, -90) and Speeds (3m/s, 4m/s, 5m/s, 6m/s) of the Cable Car was found to be significantly correlated ($p < 0.05$) with the modified mCTSIB when conducted with eyes open. However, no significant correlations were observed between the maximum excursion of COP in the medial-lateral or anterior-posterior axis in the CCS and the maximum excursion of COP of the mCTSIB test.

Table 5.3: Correlation of mean velocity between Romberg eyes open and Cable Car Simulation's angles and speed limits. Abbreviations: Angle (A), Meter Per Second (MPS).

Romberg_Eyes_Open		
Angles and Speeds	**Correlation Coefficient**	**Sig. (2-tailed)**
A0 deg and 3MPS	.775**	<0.001
A45 deg and 3MPS	.768**	<0.001
A90 deg and 3MPS	.661**	<0.001
A-45 deg and 3MPS	.826**	<0.001
A-90 deg and 3MPS	.729**	<0.001
A0 deg and 4MPS	.497*	<0.001
A45 deg and 4MPS	.576**	<0.001
A90 deg and 4MPS	.580**	0.003
A-45 deg and 4MPS	.738**	<0.001
A-90 deg and 4MPS	.418*	0.042
A0 deg and 5MPS	.686**	<0.001
A45 deg and 5MPS	.480*	<0.001
A90 deg and 5MPS	.676**	<0.001
A-45 deg and 5MPS	.796**	<0.001
A-90 deg and 5MPS	.681**	<0.001
A0 deg and 6MPS	0,371	0.074
A45 deg and 6MPS	.778**	<0.001
A90 deg and 6MPS	.612**	<0.001
A-45 deg and 6MPS	.569**	<0.001
A-90 deg and 6MPS	.782**	<0.001
Mean of 3MPS	.824**	<0.001
Mean of 4MPS	.683**	<0.001
Mean of 5MPS	.686**	<0.001
Mean of 6MPS	.695**	<0.001
Mean of A0 deg	.674**	<0.001
Mean of A45 deg	.713**	<0.001
Mean of A90 deg	.779**	<0.001
Mean of A-45 deg	.807**	<0.001
Mean of A-90 deg	0.67**	<0.001

Additionally, we performed repeated ANOVA for each mCTSIB parameter. Mauchly's test was non-significant, $p > 0.05$, indicating that the condition of sphericity was met. Therefore, there was a significant difference ($p = 0.03$) among the speeds of the CCS in the maximum excursion of the COP in the anterior-posterior axis. The contrasts were conducted between pairs of CCS speed levels using F-tests to assess the variation. Notably, Level 4 (Cable Car Speed) exhibited a significantly greater COP distance than Level 1 in the anterior-posterior axis ($p < .05$). This observation aligns with the fact that Level 4 had a speed three times higher than that of Level 1. However, no significant differences ($p > .05$) were found between the other Cable Car Speed pairs (Level 2 vs. Level 4, Level 3 vs. Level 4). Additionally, examining the effect size, we observed a substantial effect (η2 = 4.621) between Level 1 and Level 4.

5.2.4 Discussion

Balance tasks are task-specific, and traditional assessments are not designed according to the specific postural demands of real-world tasks; as such, they lack ecological validity, and findings may not transfer [143] [144] [145]. Therefore, customised balance tools are required for more effective balance and postural evaluation. We assessed the feasibility of our ecologically valid VR-based CCS for balance assessment by measuring COP and compared it with validated WBB assessments. Although our simulation may not accurately reproduce all aspects of the real Cable Car in VR, such as movement or vibrations, we attempted to simulate the impact of variations in the CCS directions (angles) and speed limits.

For the subjective evaluation of the simulation, we measured the participant's sense of presence and usability of the application using WSPQ and SUS. The presence M = 82.7 (SD = 15.1 and SUS scores M = 72.8 (SD = 17.6) were reported to be good, however, slightly lower than our previous work with the same KAVE system. Nevertheless, the results are comparable with the literature. For example, Gonçalves et al. [183] evaluated the feasibility of the VR-Bus ride by evaluating the balance and postural control. The authors reported a high presence score of 93.94 (19.13) for the 19-item questionnaires. Wood et al. developed a VR-based application using a WII balance board to evaluate the richer interaction modalities. The authors used HMD and desktop screens to compare the presence and motivation and reported higher immersion scores of 6.4/10 than the desktop screen of 4.4/10 [199]. Another study used a large-screens-based VR environment for the balance assessment and reported that the subjects' reaction was delayed and overrated compared to the real situation [80]. We also need to consider the following differences from the literature. Our participants could not act in the simulation except by standing upright. Therefore, the scores for the 'Possibility to Act' and 'Possibility to Examine' were necessarily lower. The high score for the Immersion and Quality of Interface suggests the high presence and usability of the application.

The CCS was designed with four different speed limits and five manoeuvring angles to create optical flow in both horizontal and vertical directions. The postural control was assessed by measuring COP. From the results, we found that the participants had significant excursion of COP in only the anterior-posterior axis with a cable car speed limit of 6m/s. This indicates that the higher the speed, the more induced change in the COP. Gonçalves et al. reported increased COP in the medial-lateral axis with the change in the speed of a simulated Bus. The metrics COP and mean speed from the validated WBB tool [142] were compared with our simulation results, and we found multiple correlations in mean speed.

5.2.5 Conclusion

The literature highlighted limitations of the WBB's hardware-designed consistency and signal loss. This VR simulation is based on no physical movements, which may create less impact on their postural control. The simulation tool may be improved by increasing the speed limits, directional angles, and environment, such as adding more depth to the cable car track. The simulation experience had no sound effects, and some participants suggested adding it for future studies.

To conclude, the study assessed the feasibility and ecological validity of the VR simulation for balance assessment in young adults. The change in COP showed strong correlations with validated tests, supporting its feasibility for balance assessment.

6 Profiling and Risk Assessment: Feasibility of A Virtual Reality-Based Simulation Tool for Assessing the Risk of Falls in Older Adults

This chapter aimed to validate our ecologically valid, custom immersive VR-based CCS platform and SFTs, based on validated protocols, to assess physical fitness and static balance in older adults [200]. The use of simulated functional activities in VR may enhance the validity of balance and fitness assessments, with the specific goal of identifying users at high risk of falls. The VR environment [201] was found to have high usability and a strong perception of presence.

6.1 Introduction

Older adults with difficulties in daily life activities are particularly vulnerable to falls, leading to injuries, disabilities, poor quality of life, mortality, and financial dependency. Addressing these risk factors through interventions like physical exercise, home modifications, and medical management can help reduce the incidence and impact of falls among older adults [7].

Physical exercise has been identified as one of the best solutions to reduce the risks of falls. Some exercises that can minimize the risks of falls are body stretch, strength and balance training, tai chi, and treadmill workouts [11]. Cognitive impairments, including low memory, self-control and response, are also linked with falls among older people [12][11]. Thus, cognitive-motor interference (CMI) challenges the ability of older adults to execute tasks effectively, such as walking and speaking simultaneously [13] [14], putting them at higher risk of falls and experiencing difficulties executing those cognitive tasks [15] [16].

Several organizations, such as the Joint American and British Geriatric Society (ABGS), the British Geriatric Society (BGS) [17] and the National Institute of Clinical Excellence (NICE) UK, have introduced a set of guidelines to assess and reduce the risk of falls [18]. It is also recommended that older adults incorporate moderate-to-high-intensity balance training into their multi-tier exercise program [19]. One study conducted home-based training sessions, which were successful for both

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[4] The content of this chapter has been published in the Applied Sciences journal and belongs to Special Issue Human Activity Recognition (HAR) in Healthcare, 2nd Edition [185].

men and women. It helped to reduce the risk of falls and associated injuries by about 35–45%. These sessions included multiple exercises, such as walking, muscle strength training, and balance training, which were recommended by health professionals and trained nurses at home. However, the need for health professionals to administer the training sessions is a known limitation [20].

To summarise, the literature highlights how common commercial exergames fall short in addressing the needs of older adults. The relevance of adequate, objective, and automated user profiling is essential for the effective personalisation of an exergame intervention designed for older adults.

6.2 Related Work

The fall risk classification can be defined as a single or group of assessments performed to evaluate the risk of falls to individuals and to provide feedback if follow-up assessments or training are required. The standard methods are followed based on the individual's level of risk of falls to customize or implement assessments and interventions [202]. Some common fall risk classification methods include self-reported questionnaires, physical exercise tests, and posturography procedures. These methods have some limitations, advantages, and drawbacks. For example, the Stay Independent Brochure is a valid and reliable instrument for the risk assessment of falls [21]. However, it can only be used for certain populations and takes long to complete. The literature also highlights other physical functional tests, such as the timed-up-and-go (TUG) test and the Berg balance scale or walking speed, as profiling tools [202]. However, these mobility tests require trained healthcare professionals to evaluate the risk of falls in healthy community-dwelling older adults [22]. Computer-based posturography is another way to assess the individual's balance and quantify body sway. The posturographic parameters can be acquired for static and dynamic balance conditions, providing valuable information on postural controls [23]. Multivariate logistic regression may not be feasible to obtain the optimal fall risk classification as the posturographic parameters are highly correlated and may be non-linear. Therefore, utilizing artificial intelligence (AI)-based methods such as machine learning may solve the complexity of the data set [203]. AI-based methods may still require trained professionals, but the goal of AI-based methods may increase the autonomy of those professionals and help to solve the complexity of the data set generated during the tests. Posturographic parameters and AI-based methods have been used in several studies for multiple types of older adult populations belonging to different groups or organizations [204][205][206][207][208], such as osteoporotic [209], parkinsonism [210], and multiple sclerosis [211]. Posturography systems comprise multiple hardware components such as force platforms [207][210][211], pressure platforms [206], inertial sensors [206][212], or depth cameras [208] to acquire posturographic data. The common machine learning algorithms are mostly used in studies of random forests, decision trees, neural networks, support vector machines (SVMs), and k-nearest neighbors [206][207] [211]. The receiver's operating characteristic (ROC) analysis [206] shows that these algorithms can reach an accuracy between 80 and 99.9% [207][209][211][213] or an area under the curve (AUC) between 85 and 88%.

Some studies evaluated the efficacy of wearable sensor-based functional assessments for predicting the risk of falls. The machine learning models were implemented to classify participants as fallers (Fs) and non-fallers (NFs) based on the features of the sensor data. The following criteria were used to classify participants as Fs and NFs: quantitative evaluation of the standard function procedure (e.g., Berg Balance Scale (BBS) and Tinetti Gait and Balance Scale), self-reported fall incidents, and hospitalization history [142][214][188]. Wearable sensor-based tools have been developed recently and are available commercially to assess the risk of falls in older adults.

It has been considered that older people have low motivation for traditional physical exercise programs [215][216]. However, combining immersive VR (IVR) and physical exercise could be a suitable training program for older people's physical needs and requirements [216]. The literature is scarce on VR simulations to assess the risk of falls. However, most of the studies used VR-based exergames through interventions to reduce the risk of falls. Exergames are game-based physical training performed in a virtual environment and have been shown to improve physical fitness [217] and as a treatment option for multiple types of conditions [218][219]. VR is an ideal platform for cognitive-motor interference because it offers physical exercise, joy, and cognitive functions in one platform, increasing the intervention's ecological validity, safety, and acceptance.

The literature highlighted commercial VR-based exergames for multiple physical activities, such as balance and strength training for older adults. Thus, the efficacy and feasibility of VR technology have been acknowledged to minimize the risks of falls [40–42]. Habibnezhad et al. [220] created a VR simulator to evaluate the risk of falls for construction workers. The VR system comprised three trackers, a VR headset, and a virtual environment. The inverse kinematic method was used for the body–joint simulations to create the virtual leg movements. The study showed that the VR simulator performed better than the traditional VR systems to asses upper-limb stability during gait movements [220]. Another study investigated the effect of multiple VR-based visual stimuli on postural control while standing in an upright posture. The participants' postural stability was quantified by measuring the COP in a VR environment. The authors created the virtual simulation of the rotary optokinetic drum and observed that visual stimuli invoked by the rotary optokinetic drum may enhance the instability more than the stance with the eyes closed [221]. Yeh et al. examined the impact of delayed visual feedback and cognitive performance on postural control in healthy young and older adult populations. The participants were asked to position their COP (upright posture with eyes open) in a fixed target as precisely as possible with the visual and delayed-visual feedback of their COP position. They also performed arithmetic tasks (cognitive dual tasks). An increase in postural sway was observed in older adults with delayed visual feedback, which indicates that older adults rely more on vision to control their posture [222]. One study assessed the validity and reliability of the data from a WBB against a force platform (FP) in older adults with type 2 diabetes mellitus. The regression model showed that the WBB was able to describe most of the changes in COP sway of the force platform between 42 and 72% for all test cases. The authors suggest that WBB is a valid and reliable tool for quantifying the COP excursion [223].

Another study created a VR-based tool to assess the risks of falls. An HMD was used along with motion sensors to record kinematic data during the tests. The results indicated that the participants who were at high risk of falls took a longer execution time for interventions and a number of steps [224]. Garcia introduced a VR tool to assess the risk of falls in older adults. The author implemented the choice stepping reaction time task (CSRT) and used an HTC Vive headset (VR headset), suggesting that the highly immersive VR tool can concentrate more on cognitive and motor tasks instead of the technology being used [225]. Similarly, an Oculus Rift headset was used in another study to assess dynamic balance through head mobility. A virtual park scene was created where participants had to ask to save their heads from approaching the balls. The objective of the task was to stimulate the vestibular function to quantify head movements and assess dynamic balance. The results indicated significant between-group differences in head paths, head accelerations, and peak frequencies. However, no significant differences were found in the postural sway parameters [226]. Another study used non-immersive VR and treadmill training to improve cognition and body movements and identified fewer incidents of falls when compared to treadmill training without VR [227]. Some studies showed the efficiency of novel tech-based intervention programs in improving balance [175][133] and locomotion in older adults [227] [228].

Aspects such as the visual representation of the user's body in a virtual environment affect the perception of spatial presence and may decrease the presence level if the user's virtual body is not represented in the VR environment [229]. Augmented reality (AR) can offer a higher sense of presence and realism than VR. Applications for motor rehabilitation are an excellent example of the benefits of using AR [230]. It allows users to interact with real-world objects by implementing an adapted virtual environment, which is more ecologically valid, accessible, and feasible for older adults [227]. The following sections of this chapter describe the methods and the results of our study.

6.3 Method

6.3.1 The participants

Following a repeated measures samples design, We tried to recruit as many participants as possible from the older adult population and managed to recruit only 25 participants (19 females, ages: M = 71.2 SD = 7.8) from a local senior gymnasium in Funchal, Portugal, by invitation of the sports science professionals who work at this gymnasium. However, it is regarded as an adequate sample size for the purposes of validation studies [231]. The balance assessments were performed at the University of Madeira, Laboratory of Pedagogy and Optimisation of Sports Performance. The participants were healthy Portuguese older adults who were provided with informed written consent before the study and received no compensation for their participation. Six participants were removed because they lost their heart rate data due to connectivity issues of the chest band sensors to the system application. Following the Declaration of Helsinki, the procedures were implemented and supervised by experienced, trained staff and approved by the Faculty of Human Kinetics Ethics Committee, CEIFMH Nº3/2023.

6.3.2 Apparatus

6.3.2.1 Hardware

We implemented the KAVE system [175][170] to create a virtual environment (For more details, see chapter 4.1.4.1.1. The Nintendo WBB was used to assess the balance of the participants by measuring their COP. WBB, a Japanese-manufactured gaming platform (Nintendo Co. Ltd, Kyoto, Japan), is widely used for research purposes such as balance assessment by neuro-otologists and neurologists [132]. For more details, see chapter 4.6.

The heart rate was measured using a chest band, Polar H10 (Polar Electro Oy, Kempele, Finland), for cardiorespiratory endurance. The Polar H10 connects with Acti-Graph’s WGT3X-BT accelerometer (Actigraph Corporation, Pensacola, FL, USA) to measure the intensity (magnitude vector) and the motion of the physical exercise. The accelerometer data (metrics) were processed by an ActiLife6 computer application (version 6.13.4, ActiGraph, Cary, NC, USA).

6.3.2.2 Software

Our VR-based CCS, created in Unity 3D (unity3d.com), was used to simulate a realistic and more ecologically valid environment (Figure 6.1(a)) (Figure 6.1(b)) and examine the static balance in older adults. See chapter 5.2.2.3 for more details.

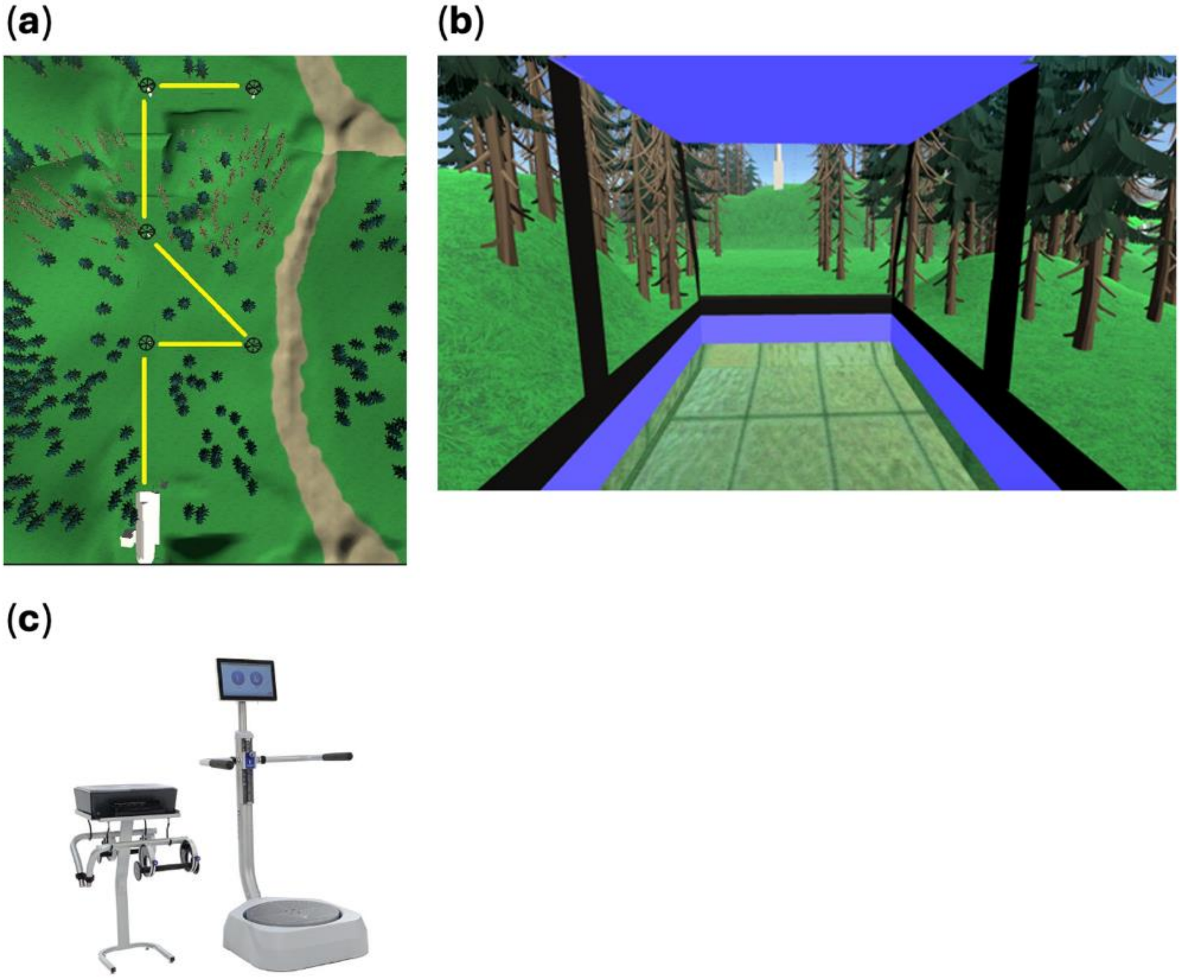

Figure 6.1: Software Setup (a) Cable Car Track Top View; (b) Cable Car Inside View; (c) Biodex Balance System (BBS).

Additionally, a VR-based SFT application previously created in our lab [233] assessed cardiorespiratory endurance and lower body strength. The virtual Levada tracks comprise computer-generated 3D objects such as trees, mountains, tunnels, and irrigation canals, designed and developed in Unity3D Engine and Blender software (Blender Foundation, Amsterdam, The Netherlands). It simulates virtual hiking based on in-place stepping. Based on the assessments from the SFTs [127], our 2MST and 30-s chair sit-stand (30SST) exercises were implemented (See chapter 5.1).

As a means of comparison and validation of the system, we used a Biodex Balance System (BBS) SD (biodexrehab.com) as a reference (Figure 8.1(c)). It offers both static and dynamic balance assessment and the risk of falls. The advantages of BBS are the development of muscle tone, balance and agility improvement and treatment for various pathologies. It is highly user-friendly, has a touch screen, and a step-by-step guide for executing static and dynamic balance training and protocols. The BBS can only be operated or serviced by qualified, trained personnel. However, subjects may require minimal supervision. The BBS is quick and efficient in profiling older adults for the risk of falls and has been extensively validated in this population [219].

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6.3.3 Questionnaires

The 7-point Likert scale questionnaire was used to evaluate the participant's cyber-sickness. Similarly, the system usability scale SUS [173] questionnaire was employed to measure the system's usability. The ITC-Sense of Presence Inventory (ITC-SOPI) [201] is a 5-item Likert scale (Strongly Disagree, Disagree, Neither Agree nor Disagree, Agree, and Strongly Agree) questionnaire used to assess a participant's level of presence in an immersive virtual or a displayed environment, and it comprises four components: Spatial Presence, Engagement, Naturalness, and Negative Effects.

6.3.4 Procedure

The participants were randomly assigned to one group, and informed consent was provided before the study. The study protocol and the two-minute demo session were given at the start of the study. The participants performed the static balance assessment tests on the BBS platform for 15–20 min.

Before each testing session, the equipment was adjusted according to the participant’s height. Participants underwent a single training session to ensure they understood the protocol and to mitigate learning effects during subsequent testing phases. A 60-s rest interval separated the testing sessions. Participants performed the protocol in a unilateral stance while barefoot for bilateral comparison. The assessment measured the overall stability index (OSI), the anteroposterior stability index (APSI), and the lateromedial stability index (LMSI). Each index was assessed under four levels of stability, ranging from level 4 (most stable) to level 1 (most unstable). Lower scores on these indexes indicate better balance, reflecting less deviation from the horizontal position [58]. They were provided a 10-minute break after finishing BBS assessments.

Subsequently, participants performed the 2MST (Figure 6.2(a)) and 30SST in the KAVE-based VR environment (Figure 6.2(b)). During the tests, they were asked to wear a Polar H10 chest band and an Actigraph device to monitor heart rate (minimum and maximum) and physical activity. A 10-minute rest was provided after finishing the fitness tests. Participants were asked to stand on the WII balance board in an upright standing position for approximately five minutes during the CCS (Figure 6.2(c)). They were instructed not to move their body while standing on the balance board. However, they were allowed to move their head and eyes. The cybersickness, system usability scale [188] and ITC-SOPI [201] questionnaires were provided afterward.

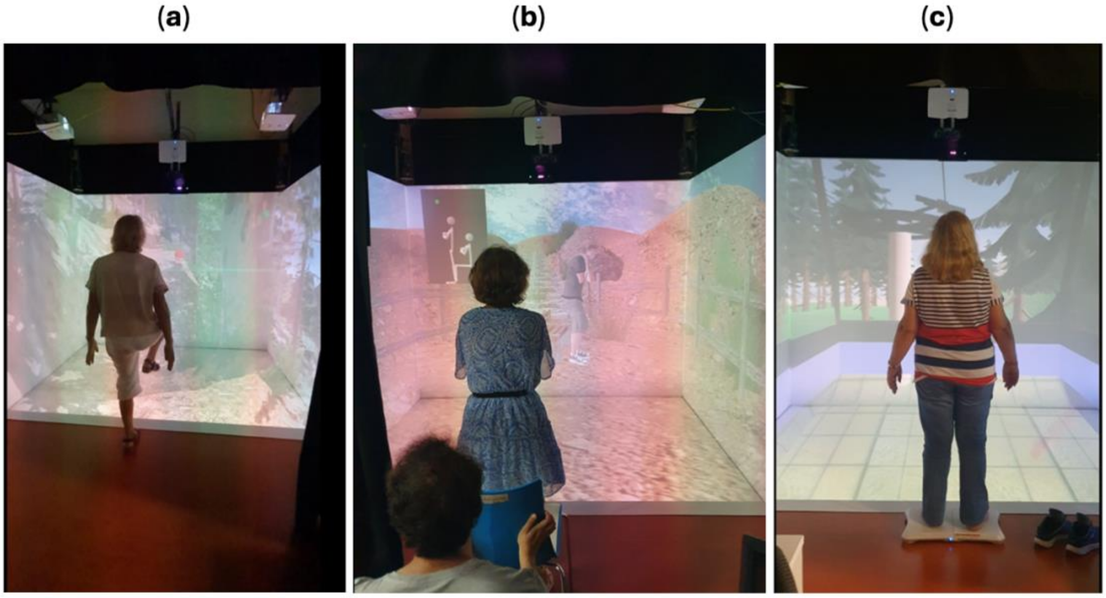

Figure 6.2: The KAVE-based VR Simulations Include (a) a Two-minute Step Test; (b) a 30-second Sit-Stand; (c) Cable Car Simulation Balance Assessment.

6.3.5 Statistical Analysis

Participant The means (M) and standard deviation (SD) were computed for SUS, ITC-SOPI questionnaires, the number of steps, magnitude vector, and heart rate, respectively.

The independent variables from the CCS were track Angle and Speed, with five and four levels, respectively. The dependent variables were the maximum excursion of the COP in the anterior-posterior (AP) and medial-lateral (ML) directions and mean velocity, which was calculated for all combinations of speed and angle variations. The metrics from BBS include EOMeanScore, ECMeanScore, Composite Mean Score; Stability Overall, Stability Anterior–Posterior; Media–Lateral; Percentage of Time in Zone A, B and C; Percentage of Time in Quadrant 1, 2, 3 and 4; Stability Index Front–Back and Left–Right. The participants were classified as high-risk and low-risk falls based on the BBS's feature Composite–Mean score.

The linear discriminant analysis and the LeaveOneOut cross-validation method in MatlabR2023b (Mathworks Inc., Natick, MA, USA) were used to estimate the classifiers' accuracy, precision, and recall. Therefore, a repeated-measures ANOVA was performed with Greenhouse–Geisser, Huynh–Feldt corrections applied to obtain a valid F-ratio when appropriate.

The statistical analysis was performed using IBM SPSS Statistics version 26 (IBM, New York, NY, USA).

6.4 Results

The participants reported high scores in the ITC-SOPI for all the components: Spatial Presence (Mean: 2.8; SD: 0.69), Engagement (Mean: 3.28; SD: 0.88), Naturalness (Mean: 3.67; SD: 0.84), and Negative Effects (Mean: 1.55; SD: 0.83). Examining the results, participants were highly engaged and perceived an ecologically highly valid VR environment. However, the spatial presence was slightly low. It was also observed that participants' responses were low for the component of the negative effect of the environment (Figure 6.3), which is a positive result.

The mean score on the SUS was M = 73.8 (SD = 12.0) for the system's usability. This indicates a good usability score (>68) [60].

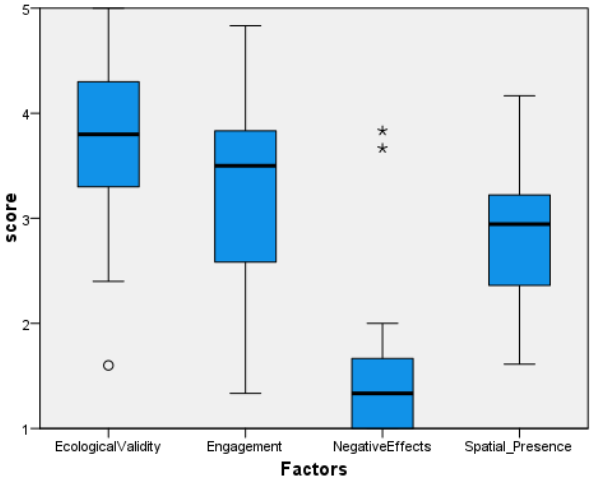

Figure 6.3: Box Plot Indicating the Results of the ITC-SOPI Questionnaire. The asterisks and circles are the far-out and far outliers, respectively.

Table 6.1 shows the results from the repeated ANOVA, which was executed on all the 2MST, 30SCST, and CCS parameters. We found significant differences ($p < 0.05$) in three of the CCS speeds and track angles in the anterior-posterior axis (speed = 5, angle = −90; speed = 7, angle = 90; speed = 7, angle = −90). This indicates that, as predicted by our data with healthy participants (See chapter 5.2), the different CCS parameters can induce measurable behavioral differences also in older adults.

Table 6.1: Anova results for the Maximum excursion of COP in anterior-posterior axis for cable car speed and trajectory angles. Abbreviations: Angle (A), Meter Per Second (MPS).

Cable car speed and trajectory angles	F	Sig.
A-90 deg and 5MPS	4.461	0.050
A90 and 7MPS	7.11	0.016
A-90 deg and 7MPS	5.10	0.037

The maximum excursion of COP in the AP direction for all combinations of Angles (0, 45, 90, −45, −90) and Speeds (3 m/s, 5 m/s, 7 m/s, 9 m/s) was correlated with nearly all metrics of BBS metrics such as EOMeanScore, ECMeanScore, and Composite Mean, etc. (Table 6.2). However, no significant correlations were observed between the BBS metrics and the maximum excursion of COP in medial-lateral directions. The mean angles are the parameters where angles were ignored, speed limits were selected, and vice versa. The COP mean velocity for almost all combinations of Angles (0, 45, 90, −45, −90) and speed limits (3 m/s, 4 m/s, 5 m/s, 6 m/s) of the CCS was observed to be significantly correlated with the parameters of BBS. Again, these findings indicate that the CCS is effective at inducing behavioral responses and that the COP metrics of the CCS are consistent with those of the BBS.

Table 6.2: Correlation between the CCS's COP in anterior-posterior direction for all angles and speed limits and BBS parameters (Pearson Correlation, Sig. (2-tailed)). Abbreviations: Percentage Time (PT), Abbreviations: Angle (A), Meter Per Second (MPS).

Pearson Correlation Sig. (2-Tailed) N = 19	**Stability Overall**	**Stability AntPost**	**Stability Media Lateral**	**PTnZoneA**	**PTinQuad1**	**PTinQuad2**	**PTinQuad4**	**Stability IndexFB**	**Stability IndexLR**
Mean of A0 deg	0.559 0.013	0.519 0.023	0.631 0.004	−0.499 0.030	−0.494 0.031	0.64 <0.01	−0.469 0.043	0.520 0.023	0.630 0.004
Mean of A45 deg						0.57 0.01			
Mean of A90 deg						0.47 0.04			
Mean of A-45 deg						0.48 0.03	−0.46 0.04		
Mean of A-90 deg					−0.517 0.023	0.522 0.022			
Mean of 3MPS						0.486 0.035	−0.50 0.029		
Mean of 5MPS					−0.470 0.042	0.566 0.011			
Mean of 7MPS					−0.495 0.031				
Mean of 9MPS			0.459 0.048		−0.486 0.035	0.570 0.011			0.458 0.049
max heart rate							−0.566 0.011		

A Discriminant Analysis (DA) was performed to assess the sensitivity of the KAVE simulations to profile and classify participants as high-risk-falls or low-risk-falls based on the assessment conducted by the BBS. The participants classified in the higher 50 percentile predicted Composite Mean score (11 points) were referred to as high-risk falls, and those below were in low risk falls. Several DA models, such as linear, pseu-dolinear, diaglinear, pseudoquadratic, diagquadratic, and support vector machine (SVM), were built along with the leave-one-out cross-validation method to evaluate the performance of the models (accuracy, recall, precision, and F-score). The selected input features for the classifier included CCS speeds and turning angles, their average responses, 2MST, 30SST, and HR. A DA with each feature was performed to establish the prediction power of each feature modality; additionally, a posterior stepwise regression approach was used to perform the feature selection.

Discrimination accuracies differ substantially, with the best classification for HR at 55%, CCS at 72%, 2MST and 30SCST at 72%, and 100% for the combined features through a stepwise regression (Table 6.3). The selected features were the maximum excursion of the COP for high speeds at high turning angles for both AP and ML, the mean of the speeds (average of four cable car speeds limits at each trajectory angle for the maximum excursion of COP) at 45-degree turning angles for both AP and ML, the mean of the angles (average of four trajectory angles at each cable cars speed limit for the maximum excursion of COP) at high speeds in the AP direction, and the COP at high speeds for no rotation. The mean of the speeds

Table 6.3: Classification results for the Maximum excursion of COP in the anterior-posterior axis for cable car speed.

LOO Cross-Validation	**CCS**	**Mean of Turns**	**Mean Speeds**	**2MST & 30SCST**	**HR**	**Step-Wise Feature Selection**
DA Model	Pseudolinear	Linear	Diagquadratic	SVM	Diagquadratic	Linear
Accuracy	0.72	0.66	0.66	0.72	0.55	1
Recall	0.72	0.66	0.66	0.72	0.55	1
Precision	0.72	0.66	0.66	0.75	0.55	1
F-score	0.72	0.66	0.66	0.73	0.55	1

6.5 Discussion

The main goal of our study was to assess the feasibility of using a KAVE-based VR platform combining simulations of Levadas and a cable car to perform a balanced assessment and profiling of the older adult population for high risk of falls and the related user experience. Overall, the participants reported high presence scores in the ITC-SOPI questionnaire, suggesting the validity of the ecological functional simulation and good usability scores with the SUS.

The participants' level of familiarity with VR technology may impact the assessment. We did not record the participant's VR familiarity experience; however, VR simulation sickness was monitored. The simulation sickness was classified into three categories: None, Moderate, and High. A total of 79% of participants reported no VR simulation sickness, and the rest experienced only a moderate level, indicating low simulation sickness overall.

To evaluate the feasibility and sensitivity of the system as a profiling method capable of detecting users with a high risk of falls, we used the BBS as a gold-standard reference for balance assessment and predicting the risk of falls. In addition, two senior fitness tests (2MST and 30SST) were also implemented together with the CCS. The CCS COP data show that CCS trajectory angles and speeds impacted the participant's balance in AP and ML directions. Significant differences in COP metrics were observed for the higher speeds (5 m/s and 7 m/s) and turning angles (90 and −90). In addition, numerous features from the CCS were correlated with BBS features, which supports the validity of our CCS to induce behavioral responses and for balance assessment.

The performance of DA models was evaluated to classify participants as high-risk and low-risk falls. We achieved excellent results from the classification using a step-wise feature selection. A linear DA on the selected features rendered a classification accuracy of 100%, indicating that our VR simulation of ecological and functional activities is precise in identifying the risk of falls in older adults. This also suggests that immersive VR environments can be used to implement standard procedures for fitness and balance assessments, proposing alternatives to traditional and expensive laboratory setups and creating custom environments based on functional activities with higher ecological validity. The classical functional tests (e.g., timed-up-and-go) are considered objective assessment tools without using certain equipment to acquire reliable data. These tests are not accurate in detecting minute changes because of the ceiling effect [117]. In contrast, the force platforms are commonly used for the balance assessment. However, they are time-consuming, require a laboratory setup, and cannot be used in clinical environments [117] [232].

Previous research reported 86% accuracy with a WBB-based exergame to assess the physical independence of the participants. A 30-s sit-stand test was used as a reference to compare the results [233]. Seo et al. developed a balance ability diagnosis system for older adults for balance assessment using a WII balance board [234]. The stability index (SI) algorithm was implemented, and the center of pressure parameter was used to predict the stability index of the balance system (Biodex SD). High accuracy was observed for the SI algorithm, and the linear regression model confirmed that the R-values ranged between 0.943 and 0.983. Similarly, another study evaluated the effect of virtual reality exercises on balance and falls in older adults [235]. The instruments used in this study included a demographic questionnaire, the Berg Balance Scale, the Timed Up and Go test, the Falling Efficacy Scale, and the Xbox Kinect 360 for VR exercises. The results showed that VR exercises may improve balance and reduce fear of falling among older adults.

A systematic review was performed to assess the reliability and validity of the WBB. The authors confirmed the reliability of the WBB; however, they also reported the impact factors such as reference criteria, intervention duration, parameters, data acquisition platform, and sample size [140]. In one study, VR HMD and force platforms were compared to evaluate the balance of older adults. The participants at high risk of falls changed their body posture in the anterior-posterior direction significantly compared to the control group. The results showed that the VR HMD is portable with minimal VR simulation sickness, inexpensive, and provides visual perturbation compared to the traditional mechanical platforms for measuring the multiple sensory aspects of the balance [236].

6.6 Limitations

Our simulations use a KAVE-based VR environment, which requires an adequate laboratory setup. Hence, a mobile-based VR implementation could make this system more portable and facilitate its acceptance and widespread use. Our VR implementation of the SFTs uses a Kinect sensor and sometimes does not detect gesture signals. It also requires players not to wear black clothes to facilitate the tracking. In addition, Kinect has latency issues that, although they do not affect the measurements per se, can affect the user experience.

Further, Microsoft does not provide software development kit (SDK) updates. Hence, an alternative system would be ideal for improved motion detection and interaction. Although the CCS resembles an actual cable car and its environment, it does not have a realistic motion. The CCS could be improved by changing the environment, tracks, and rotation speeds, implementing only those found to induce statistically significant behavioral responses.

Nintendo has halted its production of the WBB and does not provide support any more. Some other limitations of the WBB include hardware-designed consistency and signal loss. The literature has also highlighted the limitations of the WBB, such as poor reliability and quality, and it has not been suggested that the clinical platforms be replaced completely [140].

This study was conducted on healthy older adults. However, participants with multiple pathologies could affect the balance and risk-of-fall tests. Therefore, a larger sample of older adults with different pathologies should be considered in future studies for high classification accuracy.

6.7 Conclusions

To conclude, in this study, we showed that our KAVE-based VR platform can assess the risk of falls for older adults with very high accuracy and reliability, relying on COP data. Our system comprises multiple simulations, such as a Virtual Levada and a cable car simulation, to offer low VR simulation sickness, high immersion, and usability. The Virtual Levada implemented VR-based senior fitness tests such as a 30-s sit−stand and two-minute step test. The Nintendo WBB may be used as an alternative and cost-effective tool for balance assessments and risk of falls in the older adult population.

7 Feasibility of Closed-loop Physiologically Adaptive VR Environments for Fitness

In this chapter we introduce a SAR application for fitness training for cardiorespiratory responses based on electrophysiology of the users [237]. The adaptation of physiological signals was implemented in a stepping-in-place VR simulation (Virtual Levada) to control the intensity of the physical activity of the participants. The adaptation rules were created on the closed loop based on the participant's HR, using the BLEngine tool [147], which is designed to keep the participant in the target heart rate zone.

7.1 Introduction

Physical inactivity has been recognized as the fourth leading cause of death worldwide [25]. A sedentary lifestyle is considered the sole risk factor for cardiovascular diseases, which account for approximately 30% of global mortality. Thus, promoting an increase in physical activity among people of all ages will help in reducing the risk of cardiovascular diseases [185]. A novel way to increase physical activity is to use exergames to exercise and promote health and well-being [238]. Exergames are digital games that require the usage of the whole body to control a game, increasing the physical activity level and potentially improving the physical fitness components, such as endurance, strength, balance and flexibility [187]. According to the American College of Sports and Medicine (ACSM), exergaming can be described as a healthy and beneficial form of exercising by engaging and challenging the participants to play [239]. Several studies have shown that exergames can enhance enjoyment and intrinsic motivation compared to traditional exercises and efficiently promote physical and mental health [240] [241].

Although not strictly a computer game, the system used in this chapter is a VR simulation of a pleasant real-life experience [228]. In recent years, VR technologies have progressed much, and many VR systems have been introduced. The usage of VR technology is trending because it provides a

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[5] The content of this chapter has been published in the proceedings of the 15th International Joint Conference on Biomedical Engineering Systems and Technologies [239].

high level of immersion, the extent to which the VR system delivers sensations from the real world to the virtual world [168][169]. In particular, systems such as Cave Automatic Virtual Environments have been reported effective in immersing and engaging participants during VR experiences [170].

VR-based applications are being used for athletic training, fitness training, and high-intensity interval training, as the full-body interaction and highly immersive experience are the main advantages of using VR technology for cardiorespiratory training [32]. Recent studies have established that VR applications can increase enjoyment, motivation and engagement, contrary to traditional exercises, such as cycling and running. Garcia et al. [242] investigated the feasibility and efficacy of a Kinect-based stepping exergame and reported participant improvements in stepping, standing balance, gait speed, and mobility. Ioannou et al. [109] introduced the concept of virtual performance augmentation (VPA), which refers to running and jumping in place. The authors reported that VPA could induce moderate to high physical activity levels, increasing intrinsic motivation, general physical activity motivation, and perceived competence and flow.

Although these VR applications have shown the potential to improve cardiorespiratory training, training intensity is often lower than what is expected to be the fitness recommendations [239]. Thus, to maintain the player’s training intensity, one possibility is to monitor the user and adapt the VR application response. This adaptation allows changing the training load required to achieve the desired exertion levels [185]. Here, a closed-loop control approach was implemented using the biocybernetic-loop-engine (BLEngine) [147] to monitor the heart rate (HR) and adapt a virtual hike experience to control the intensity of the exercise performed by the participants. We aimed to address our third research question:

RQ3. Are personalised and adaptive SAR-CAVE-mediated applications feasible for fitness?

7.1.1 Participants

Participants were recruited through a convenience sample of volunteer university students and staff, with no compensation provided for their participation. Twenty-two healthy adults (12 females and 10 males) volunteered to participate in this study. Two participants were excluded from the study: a male participant due to a technical error and a female participant who decided to withdraw due to virtual reality sickness. The sample considered for the analysis was composed of the remaining 20 participants (ages: M=29,25 SD =25,03). The demographic information of the participants is described in (Table 7.1).

Table 7.1: Sample statistics.

(N=20)	Mean	STD	Min	Max
Age	29,25	25,03	23,00	44,00
Height (cm)	168,95	9,06	159,00	191,00
Weight (kg)	64,35	14,16	47,00	102,00
BMI (kg/m2)	22,26	2,60	17,91	27,96

7.1.2 Experimental Setup

7.1.2.1 Hardware

We used the NeuroRehabLab's KAVE system [175] to create a virtual environment; see chapter 4.7 for more details. A photoplethysmography (PPG) sensor was used to measure the heart rate (HR) at rest during the pre-assessment procedure (chapter 2.3.2) with a wearable device, the Biosignalsplux (PLUX - Wireless Biosignals, Lisboa). Finally, the HR at rest was computed with the Opensignals software (PLUX-Wireless Biosignals, Lisboa) [116]. To measure the HR of the participants during the experiment, the HR chest band Polar H10 (Polar Electro Oy, Kempele, Finland) was placed on the participants. The Polar H10 was paired with the Acti Graph's WGT3X-BT accelerometer (Actigraph Corporation, Pensacola, FL, USA) to measure physical activity during the experiment. The metrics for physical activity were computed using the ActiLife6 software (version 6.13.4, ActiGraph, Cary, NC, USA) to process the accelerometer data.

7.1.2.2 Software

The environment simulated a Levada hiking track and was developed by [228] (Figure 7.1). The Levada track included computer-generated 3D objects, such as trees, mountains, tunnels and irrigation canals, created with Unity3D Engine and Blender creation suite (Blender Foundation, Amsterdam, Netherlands). Then, an adaptation of the procedure in [44] was implemented in the VR Levada environment to determine a target height at which the knee of the participant had to be raised during stepping-in-place to progress in the VR Levada hiking track. The initial height was calculated by the Kinect as the middle point between the hip and the knee so that it adjusts to people of different heights. The height of the hip and the knee were set, respectively, as the boundaries of maximum and minimum required heights during the adaptation.

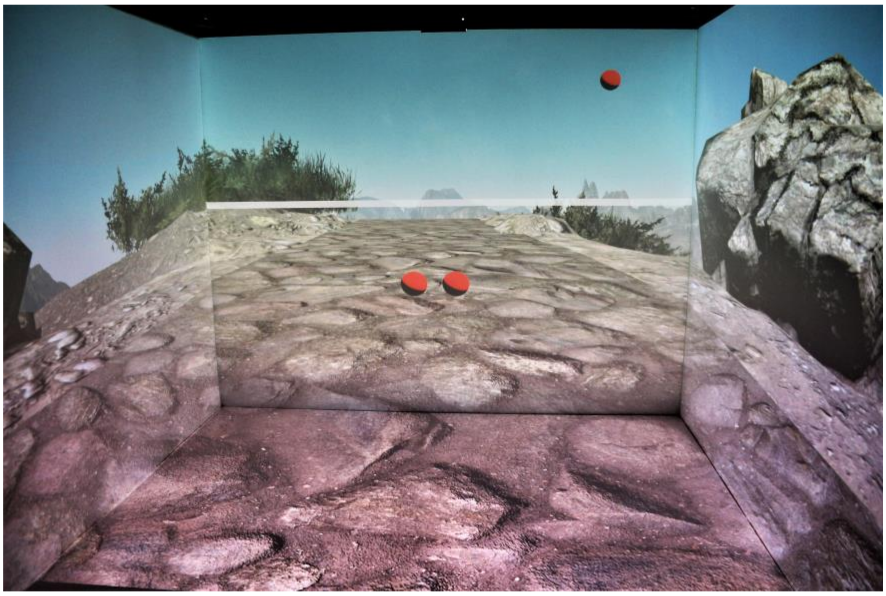


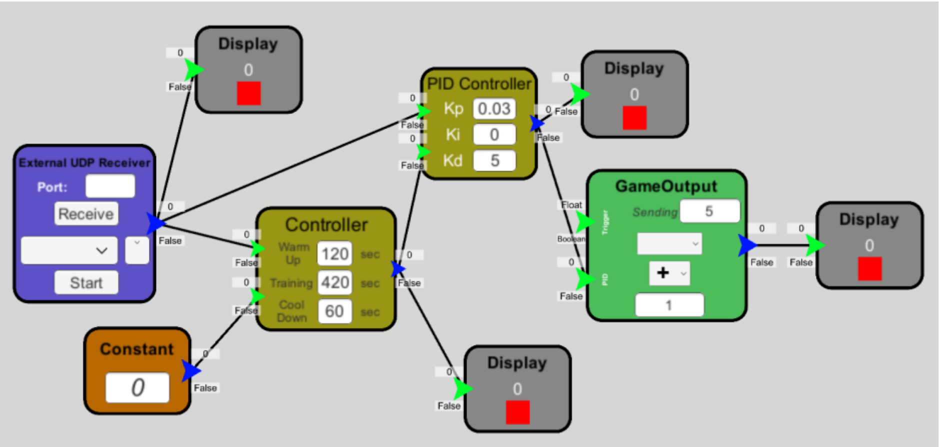
Figure 7.1: Example of our VR Levada hiking track. The red dots represent the knees of the participant. The white line represents the target height at which the knee had to be raised.

The main goal of the adaptive control of HR was to drive participants to reach the heart rate zone, moderate to vigorous intensity (57% - 63%), as mentioned in chapter 2.3.3, and keep them inside that zone during the whole training phase. The cardiorespiratory fitness adaptation based on the HR was performed using an updated version of the Biocybernetic Loop Engine (BLEngine) [238]. The BLEngine received the real-time HR data from the Polar H10 chest band using UDP communication.

Then a proportional-integral-derivative controller (PID controller) was implemented to adapt the height to which the participants had to raise their knees while stepping in place. Then, the target height was adapted every

5 seconds, according to the instantaneous HR (HR5sec). For the warm-up phase, a linear regression was calculated to drive the participant's HR, between the initial HR of the participant and the target HR, to gradually increase the intensity of the exercise so that after 2 minutes, the participant reached the intended HR zone. The PID controller followed Equation 7.1, with Kp = 0:03 as the proportional constant and Kd = 5 as the derivative constant. These HR adaptive rules implemented on the BLE software are shown in (Figure 7.2).

$$PID = K_{\mathrm{p}} * (HR_{\mathrm{target}} - HR_{5\mathrm{sec}}) + K_{\mathrm{d}} * \left(\frac{Error_{\mathrm{current}} - Error_{\mathrm{previous}}}{\Delta t} \right) \tag{7.1}$$



Warm Up 120 sec
Training 420 sec
Cool Down 60 sec

Kp 0.03
Ki 0
Kd 5

Sending 5
+
1

Figure 7.2: Adaptive HR rules used on the BLE software.

7.2 Experimental Procedure

7.2.1 Pre-Assessment

All participants performed a pre-assessment session on a different day, before the experiment. In this session, the HR of the rest of each participant was measured to calculate their experimental target HR. The participants also performed the 3-minute YMCA Step Test [187] to assess their physical fitness.

7.2.2 HR Computation

Participants were asked to sit and relax in a chair in a quiet room for 5 minutes without moving or speaking. Then, the HR was computed using a PPG sensor with the biosignalsplux wearable device. The PPG sensor was placed on the index finger of the left hand. The HR of the rest of the participants was calculated as the average HR of the 5 minutes using the Opensignals software, as mentioned in Chapter 2.2.1.

The target HR for the experiment was calculated using the Karvonen formula [243]. After computing the heart rate at rest, the maximum HR (HRmax) was calculated using Equation 7.2. Then, the heart rate reserve (HRR), which is the difference between the maximum heart rate and the heart rate at rest, was calculated using Equation 7.3. Finally, the target HR was calculated using Equation 7.4, with a target exercise intensity of moderate to vigorous (approximately 60% of the HRR), according to [239].

$$HRmax = 220 * Age \tag{7.2}$$

$$HRR = HRmax * HRrest \tag{7.3}$$

$$TargetHR = (\%intensity * HRR) + HRrest \tag{7.4}$$

7.2.3 3-min YMCA Step Test

The 3-minute YMCA Step Test [187] was used to assess the cardiorespiratory fitness of the participants. To perform this test, a 30 cm step, a digital chronometer and a metronome were used. First, the test procedure was explained to the participants by demonstrating the cadence stepping. The metronome was set to 96 beats per minute, with 4 clicks representing one step cycle: 1st beat - first foot up, 2nd beat – second foot up, 3rd beat - first foot down, 4th beat – second foot down. The duration of this test was 3 minutes. After completing the test, participants immediately sat down, and the average HR for 1 min was assessed using the same sensor as in Chapter 2.3.2.

7.2.4 Physical Exertion Metrics

The data acquisition for the physiological signals was performed with a custom-made log file implemented on the BLEngine to record all the HR-related signals, and then all the HR metrics were computed using Python. For the accelerometer signals, the ActiLife6 software provided all the required metrics. Concerning the HR-related metrics, the following metrics were computed: Average HR, Percentage of Time in the Target HR Zone, considering 100% as being the 10 min condition, and the root mean square error (RMSE) between the HR and the target HR.
In terms of the accelerometer metrics, the METS, vector magnitude, MVPA, and Percentage in Sedentary and Light exercises were computed using the Actilife6 software.

Finally, a digital version of the OMNI Rated Perceived Exertion (RPE) scale (Borg, 1998) was used to assess the perception of exertion from the participants after both conditions, in a 0 to 10 scale (0 – Extremely Easy, 10 - Extremely Hard).

7.2.5 User Experience

To assess the user experience, the sickness and dizziness experienced by the participants during the VR experience, a short brief questionnaire was answered with a 5-point Likert Scale (1-none, 5-A lot). Also, the WSPQ was used to assess the sense of presence. It includes 24 items addressing Involvement, Immersion, Visual Fidelity, Interface Quality, and Sound, rated on a 7- 7-point Likert scale. Consistent with other studies, items 20-22 related to sound were excluded. Items 23-24 related to haptics were not applicable to this study [244].

The Intrinsic Motivation Inventory (IMI) was used to assess intrinsic motivation. It is a multidimensional measurement questionnaire, which is comprised of seven sub-scales and used for several studies, including exercising and sports. The questionnaire contains the following sub-scales on a 7-point Likert scale: Interest/Enjoyment, which is considered to be the main self-report measure for this questionnaire (7 items), and Pressure/Tension, which is considered to be a negative predictor of intrinsic motivation (5 items) [245] [246].

The System Usability Scale (SUS), created by [188], was implemented to assess the application’s usability. SUS comprises ten items and allows a quick evaluation of the usability of a wide variety of products and services, including hardware and software.

7.2.6 Protocol

This study is divided into two components: the study of the adaptive control of HR and the study of the user experience in the virtual environment. Participants were provided with informed consent prior to the pre-assessment session. After the pre-assessment session, a within-subjects experimental design was used, in which participants performed the three following conditions on consecutive days with an approximate time interval of 24 hours: Adaptive VR Levada experiment (Experimental condition for VR adaptive control of HR and user experience), Non-Adaptive VR Levada experiment (Control condition for adaptive control of HR) and Adaptive Non-VR experiment (Control condition for the user experience).

For each experiment, participants were asked to wear the Polar HR chest band and the ActiGraph accelerometer placed on the hip. The experiment consisted of stepping in the same place at the pace of 125 beats per minute set by a metronome, with 2 clicks representing a step cycle, as the participants had to raise their knees to a target height to progress in the hiking track. Each experiment had a total duration of 10 min: a 2-minute warm-up to drive the participants to the target HR zone, a 7-minute training in the target HR zone, and a 1-minute cool-down. This timeline is shown in (Figure 7.3).

At the end of each experiment, participants answered a sickness/dizziness questionnaire and classified the perceived exertion using the Rated Perceived Exertion Scale (RPE scale) [247]. For the test and control conditions of the user experience, participants answered the WSPQ [177], the Slater-Usoh-Steed Questionnaire [248] and the Intrinsic Motivation Inventory (IMI) [246] [245].

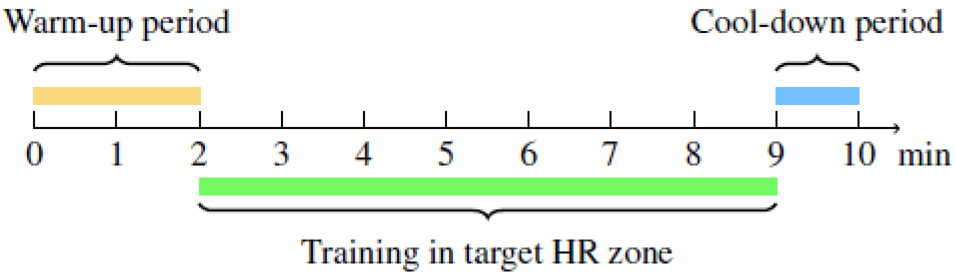


Figure 7.3: Timeline of each experiment.

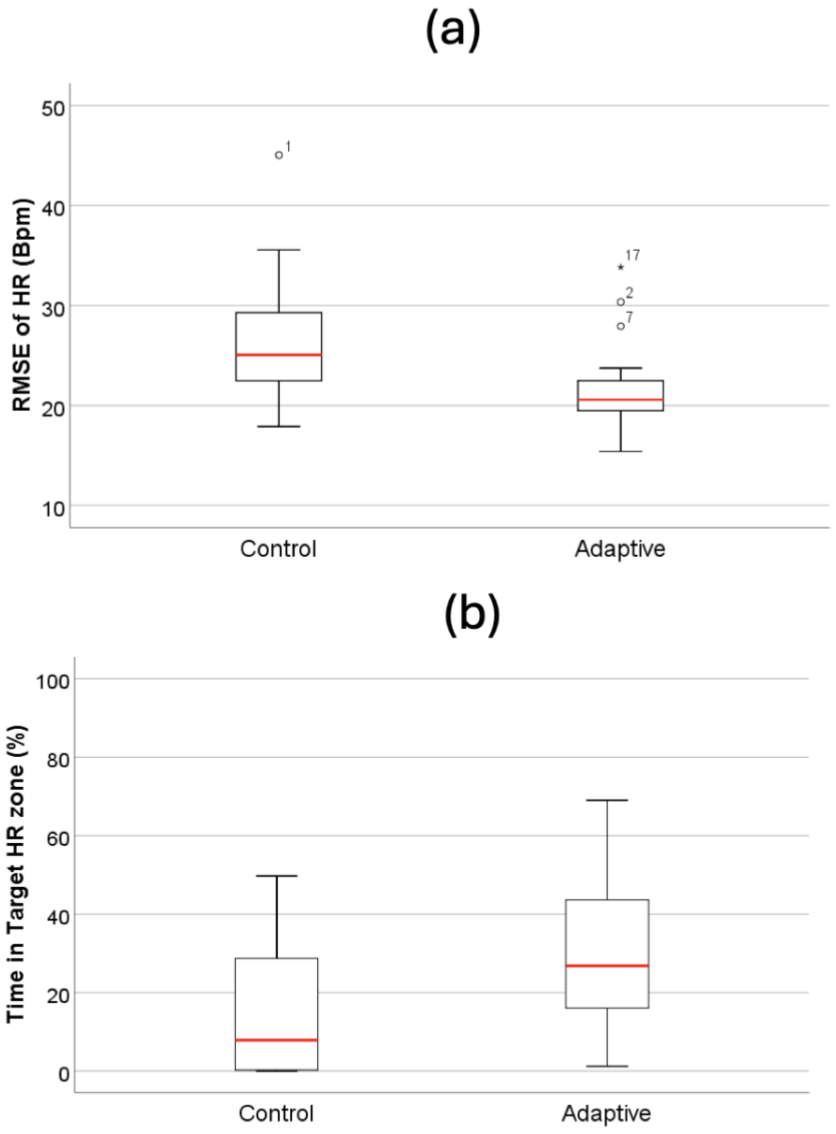
7.3 Statistical Analysis

For the physiological signals statistical analysis, the Kolmogorov-Smirnov normality test was used to assess the normality of the data. Since the data was not normally distributed, non-parametric statistical tests were used. The Wilcoxon matched-pair signed ranks test was used to compare conditions. Regarding the statistical analysis for the questionnaires, all the data from the questionnaires are ordinal (Likert Scale). Thus, non-parametric tests were used to assess the significance of the results. The Wilcoxon matched-pairs signed-rank test was also performed for the questionnaires. All the statistical analysis was performed in SPSS Statistics version 26.

7.4 Results

7.4.1 Adaptive Control of HR

Training in a specific heart rate zone has benefits and helps improve cardiorespiratory performance, according to the ACSM guidelines [239]. To measure the efficacy of the procedure implemented to drive and maintain the participants in the target heart zone, the metrics related to HR were analyzed. When performing the statistical comparison, we found no significant difference in the average HR between the Non-Adaptive VR (Mdn=142.02, Range=70.82) and the Adaptive VR condition (Mdn=138.90, Range=48.12). In terms of the difference between the HR and the target HR, the RMSE revealed lower values in the Adaptive VR condition (Mdn=20.57, Range=18.46) compared to the Non-Adaptive VR condition (Mdn=25.08, Range=27.14). This result was significantly different, T=173, $p<0.05$, r=0.57 (Figure 7.4(a)). Finally, the Adaptive VR condition had a significantly higher percentage of time (T=32.00, $p<0.01$, r=0.61) in the target HR zone (Mdn=26.83, Range=67.83) compared to the Non-Adaptive VR condition (Mdn=7.83, Range=49.67) (Figure 7.4(b)).



7.4: (a)Boxplot of the RMSE for the Non-Adaptive VR Levada and Adaptive VR Levada conditions (b) Boxplot of the Time in the target HR zone in percentage for the Non-Adaptive VR Levada and Adaptive VR Levada conditions.

Figure 7.6 depicts the time evolution and relationship between participants' HR and their target HR over the 10 minutes of the experiment. HR data in Figure 7.6(a) (black line), shows that the Adaptive VR Levada condition spends more time inside the target HR zone (red band) compared to the Non-Adaptive VR Levada Figure 7.6(b). Also, the variability of the data (shaded area) is smaller than that of the non-adaptive condition.

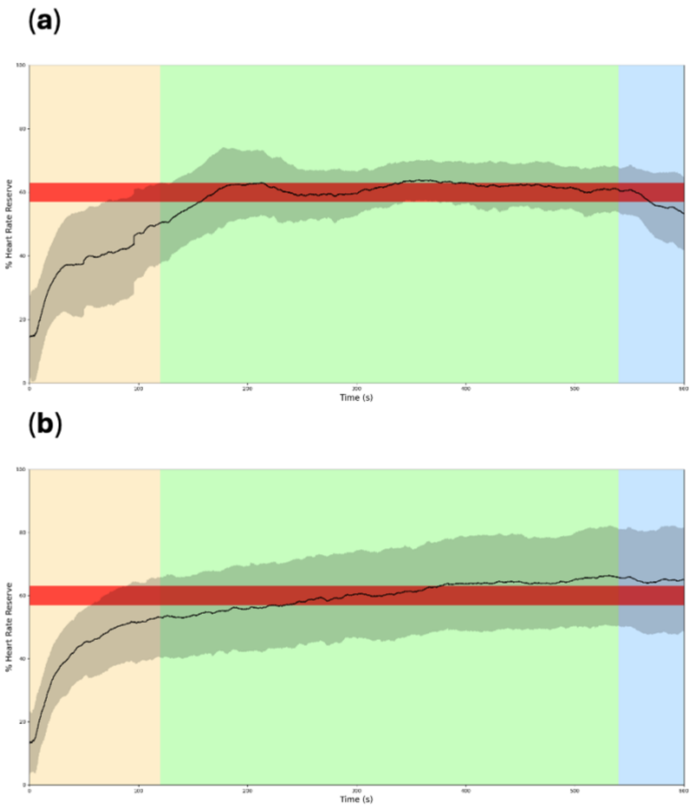


Figure 7.5: (a) Adaptive VR Levada (b) Non-Adaptive VR Levada Average HR of all participants throughout the whole experiment for the Adaptive and Non-Adaptive VR conditions. Black line - Average HR, Black Shadow – Average Standard Deviation, Red Band - Target HR zone, Yellow Band - Warm-up Phase, Green Band - Training Phase, Blue Band - Cool-down Phase.

The classification of the cardiorespiratory fitness of our participants is shown in Table 7.2.

Table 7.2: 3-min YMCA Step Test Classification.

	Males (n=9)	**Females (n=11)**
Excellent	2	4
Good	1	0
Above Average	0	0
Average	2	1
Below Average	2	3
Poor	0	3
Very Poor	2	0

7.4.2 Physical Exertion

Concerning the accelerometer metrics extracted, in the Adaptive VR Levada condition, the METS values were lower (Mdn=1.02, Range=1.59) than the

Non-Adaptive VR Levada condition (Mdn=1.05, Range=2.33). In terms of the Percentage of time spent in Sedentary and Light exercise, in the Non-Adaptive VR Levada condition, the participants spent more time in Sedentary exercise (Mdn=34.17, Range=85.83) compared to the Adaptive VR Levada (Mdn=29.00, Range=95.50). Consequently, the time spent in Light exercise was higher for the Adaptive VR Levada condition (Mdn=70.50, Range=95.00) than in the Non-Adaptive VR Levada (Mdn=59.67, Range=84.33). For the MVPA, the Non-Adaptive VR Levada condition values were higher (Mdn=0.05, Range=4.27) than the Adaptive VR Levada values (Mdn=0, Range=4.92). Finally, the magnitude vector values for the Adaptive VR Levada were higher (Mdn=27168.5, Range=36849.8) than the Non-Adaptive VR Levada condition values (Mdn=20891.1, Range=33329.1). Despite these positive results, no statistically significant differences were found for any metrics computed between the Non-Adaptive VR Levada and Adaptive VR Levada conditions.

The results for the perceived exertion (RPE Scale) reported by the participants revealed that the Adaptive VR Levada condition showed lower values of perceived exertion (Mdn=4.00, Range=8.00) compared to the Non-Adaptive VR Levada condition (Mdn=5.00, Range=6.00) (Fig.7.7). However, this difference revealed not statistically significant (p =0.089).

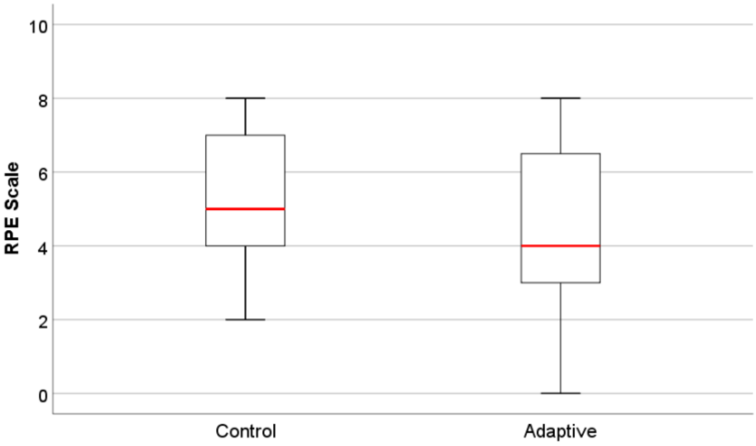


Figure 7.6: Boxplot of the Rated Perceived Exertion (RPE)

7.4.3 User Experience

No statistical difference was found between the Adaptive Non-VR and Adaptive VR Levada condition regarding the sickness and dizziness short 5-point questionnaire. Participants reported slightly higher level of dizziness

(Mdn=2.00, Range=3.00) on the Adaptive VR Levada condition compared to the Adaptive Non-VR condition (Mdn=1.00, Range=3.00). For the sickness question, the results reported were the same on both conditions (Mdn=1.00, Range=2.00).

Presence was measured with WSPQ. The total mean score for the sum of all sub-scales was M=93.1(16.1), which indicates a presence level of 70%, similar to the result reported by [228] and higher than the result reported by [170] (Table 7.3). The mean rating score of involvement suggested that the user was engaged with the experiment, while the immersion score shows that the user perceived the environment realistically. The visual fidelity and interface quality scores represented clarity, perception depth and user-friendly application. The mean rating score of the sound also indicated the realistic sound coming from the application environment.

Table 7.3: Mean Rating Score for each sub-scale of the.

Sub-Scale	**Mean Rating Score (SD)**
Involvement	4.78 (0.95)
Immersion	5.23 (0.79)
Visual Fidelity	4.3 (1.6)
Interface Quality	5.3 (1.1)
Sound	4.7 (1.5)

Regarding the results obtained between the Adaptive Non-VR and the Adaptive VR Levada conditions for the IMI questionnaire (Table 7.4), no significant differences were found for either Pressure/Tension or Interest/Enjoyment.

Table 7.4: Intrinsic Motivation Inventory Results

Sub-Scale	**VR Mean(SD)**	**NON-VR(SD)**	**p-value**
Interest/Enjoyment	4.62 (1.37)	4.42 (1.19)	0.37
Pressure/Tension	2.65 (0.99)	2.71 (1.26)	0.87

7.5 Discussion

Most studies related to exercising with adaptive control of HR are based on cycle ergometers or exergames [185][249][238]. This study assessed the feasibility of performing an adaptive control of cardiorespiratory training based on the participant’s HR while performing a stepping activity in a virtual Reality hiking simulation. The results obtained from our study showed that the algorithm implemented was able to drive the participants to reach the target heart zone within approximately the first 2-3 minutes of the exercise. Then, the participants in the Adaptive VR Levada exerted more than 20% of the total duration of the experiment (10-min), in the target heart rate zone, compared to the Non-Adaptive VR Levada condition, while having a median RMSE of 20 beats per minute between the heart rate and the target heart rate. Both of these results agree with the results obtained [238] in which the time that the participants exerted in the target HR zone was 40% higher in the adaptive condition with an RMSE of 15 beats per minute, considering the entire experiment of 20 minutes.

Regarding the RPE scale, although no significant difference was found between the Non-Adaptive VR Levada and Adaptive VR Levada conditions, participants reported lower values of perceived exertion in the Adaptive VR Levada condition. This indicates that even though participants were training in the target HR zone for more time, their perception of effort was smaller. This suggests that lower levels of fatigue come from training in a more controlled HR regime. These results are also in agreement with the results obtained by [238].

In terms of sense of presence, most of the papers in the literature report treadmills or cycling ergometers, which makes it difficult to compare with our study. In our experiment, the impact of VR on physical exertion and intrinsic motivation during the virtual hiking simulation was investigated in a stepping-in place-based application. From the results obtained, it is possible to observe that this simulation of a virtual hiking activity generated a high sense of presence, approximately 70%, with the sub-scale immersion having the highest mean rating score of m = 5:23 compared to the other sub-scales. Regarding intrinsic motivation, participants reported a higher value for intrinsic motivation in the Adaptive VR condition of approximately 66% compared to 63% in the Adaptive non-VR condition for the sub-scale interest/enjoyment and a lower value of pressure/tension of 38% for Adaptive VR condition and 39% for the Adaptive non-VR condition. Even though no significant effect was found for intrinsic motivation, the results for interest/ enjoyment are in agreement with other studies that reported higher values for sub-scale interest/ enjoyment in augmented reality than in non-augmented reality applications [238].

7.6 Limitations

Although the main goal of this study was achieved successfully, there are some limitations implicit in this study. The effect of VR is specific to the design of our VR Levada experiment and our particular CAVE, so we do not have information on what can happen on other VR delivery technologies or simulations, as well as the effect of adding gamification to the task. This study targeted a training intensity of 60% with a mandatory pace of stepping of 125 beats per minute set by a metronome. To generalize the application of this system to other situations, higher or lower training intensities, with a different pace set by the metronome, should be tested. Also, the single variable adapted during the entire study was the target height at which the participants had to raise their knees. A variable could be added to adjust the pace set by the metronome to combine the adaptation with the target height. Finally, the acquisition of HR was performed on a consumer-grade device, the Polar H10 chest band.

7.7 Conclusion

This study aimed to create a stepping-based VR application simulating the Madeiran hiking tracks, the Levadas, that could adapt to the physiological signals of the participant to provide adequate levels of exercise intensity. Our data indicate that the adaptation rules created on the closed-loop, according to the participant’s HR, using the BLEngine, could drive the participant to the desired target heart rate zone. Thus, successfully adjusting the intensity of training within the target heart rate zone of optimal effectiveness. This adaptation increased the time in which the participants were in the target heart rate zone by 20% compared to a Non-Adaptive VR condition. Thus, closed-loop systems have the potential to perform better for fitness applications than VR-based applications and in safer training conditions. Also, participants perceived lower levels of exertion in the adaptive condition. In conclusion, we highlight the potential of personalised and adaptive VR applications to improve the cardiorespiratory fitness, engagement and motivation of the participants.

8 Conclusion – Main Contributions and Future Work

The literature highlighted the potential benefits of VR exergames to prevent sedentarism in older adults, which may increase fitness, balance and motivation. Therefore, our goal was to assess the fitness, balance and motivation of older adults by designing and implementing standard fitness procedures in VR-based simulation applications. The development of balance tools could reduce the risk of falls and the injuries associated with them. The implementation of VR-based simulations may enhance the ecological validity, which increases the efficacy of the standard fitness procedures.

The thesis is comprised of two main research goals. First, we evaluated the feasibility of two primary VR setups i.e., CAVE and HMD, based on the level of presence and realism they provided during the experiment. A user study validated these setups, revealing that participants experienced a stronger sense of presence in the CAVE-based environment compared to the HMD. This suggests that the CAVE system may be more feasible, as higher presence can lead to better performance and improved training outcomes [181]. We implemented automated fitness tests and balance tools in KAVE-based VR simulations tailored to the older adults' requirements. We validated through several user studies to profile users based on their fitness and balance levels for increasing fitness, reducing sedentarism and risk of falls. Second, we implemented the Biocybernetic Loop Systems (BLS) in our KAVE-based VR simulations for the closed-loop systems to train endurance and balance. The adaptation of physiological signals was implemented in a VR simulation (Virtual Levada) to control the intensity of the physical activity of the participants. The adaptation rules were created on the closed loop based on the participant’s HR, using BLEngine, which kept the participant in the target heart rate zone.

The thesis presented five published papers, which were aligned with our research goals; see Appendix A – Curriculum Vitae: Publications. In this research work, 108 participants in total participated in the studies from the implementation of automated fitness tests and balance tools in VR-based simulation to their validation. The following subsections summarize the contributions made during the research process presented in this thesis.

8.1 Design and Implementation of Standard Fitness Procedures in Simulations to assess Fitness, Balance, and Enhance Motivation in the Older Adults

We evaluated the ecological validity of two main different VR environments (Cave vs HMD) before starting to implement standard fitness procedures in SAR-based simulations. We validated the KAVE [175], an open-source system previously developed at our lab, by implementing it in our virtual pedestrian crossing simulation. The KAVE comprises scripts, objects, and prefabs that use a 140$ Kinect V2 tracking sensor (Microsoft, Redmond, USA) to add a parallax effect and full-body tracking for interaction with virtual objects. It also uses four Hitachi projectors and external speakers for the sound effects. Similarly, an HTC Vive headset (vive.com), was also tested in a pedestrian crossing simulation to make a comparison with the KAVE system. Vive renders stereoscopic textures of 3D models, has lighthouse sensors for tracking the position and rotation of the headset and provides a high refresh rate to reduce lag in rendering graphics. To evaluate the ecological validity of both VR environments, we addressed two research questions:

- Which VR environment is more efficient at training pedestrians?
- Which VR environment induces more presence?

The percentage of collisions (accidents) was monitored when the user performed street-crossing tasks. The participants in the HMD group had a significantly higher percentage of collisions than those who were in the CAVE group. Fewer collisions may suggest an environment that is more suitable for training pedestrians [164]. The level of the user's perception of presence for both VR setups was high and almost the same. The presence was slightly higher in the CAVE condition when compared to the HMD setup but not significantly different.

After the evaluation of the VR setups, we designed and created several KAVE-based simulations that implemented automated senior fitness tests (2-minute step test, 30-second chair-stand test) [61]. We modified the 2-minutes step to be used as a six-minute stepping exercise with three different difficulty levels created by modulating the required stepping height of the knee. We validated the fitness tests by comparing them to their non-VR counterparts and by measuring user’s behavioral and physiological signals (heart rate). Therefore, we asked the following research questions:

- Does a SAR-based simulation provide a high presence and usability?
- Can a stepping exercise in SAR be used to induce adequate physical activity?

The instruments WSPQ and system usability (SUS) scores were reported to be high, which indicates that the Virtual Levada SAR simulation had high immersion. A significant increase in heart rate at each difficulty level of the simulation was observed, which suggests that the stepping exercise induced adequate physical activity.

The balance evaluation was one of the key elements of our research for assessing the risk of falls. Balance tasks are task-specific and traditional assessments are not designed according to the specific postural demands and do not transfer effects to performance to evaluate the balance. Therefore, we designed and created a KAVE-based Cable Car Simulation (CCS) and implemented a modified Clinical Test of Sensory Interaction on Balance (mCTSIB), also known as the Romberg test [142], using a Wii Balance Board (WBB). We evaluated the validity and usability of CCS with 23 young adults and validated it with a Posturography tool [142]. The validity of cable car simulation was assessed by measuring the user's sense of presence in the VR environment and the influence of the simulation on the user's postural control by monitoring the COP in various configurations. Three parameters were monitored during the experiment: Maximum excursion of COP in anterior-posterior and medial-lateral directions and the mean speed. The Cable Car simulation was designed with five turning angles (0, 45, 90, -45, -90) and 4-speed limits (3m/s, 4m/s, 5m/s, 6m/s) to create a maximum impact on the user's postural control. We observed that the participants had significant excursion of COP in only the anterior-posterior axis with a cable car speed limit of 6m/s. This suggest that the higher the speed, the more change would be in the COP. The metrics of COP and mean speed from the WBB tool were compared with the simulation results, and we found a correlation in mean speed [142].

After the initial validation study, we improved the CCS by increasing the speed limits, directional angles, and environment (adding more depth to the cable car tracks), and evaluated the feasibility and sensitivity of the system, combined with the KAVE-based SFTs, as a profiling method capable of detecting users with a high risk of falls. We conducted a study with 25 older adults and validated the CCS with the gold standard Biodex Balance System (BBS) for balance assessment and predicting the risk of falls. The 2MST and 30SST were also implemented together with the CSS. The CCS COP data showed that CCS trajectory angles and speeds impacted the participant's balance in AP and ML directions. Significant differences in COP metrics were observed for the higher speeds (5 m/s and 7 m/s) and turning angles (90 and −90). In addition, numerous features from the CCS were correlated with BBS features, which supports the validity of our CCS to induce behavioral responses and for balance assessment.

The performance of several Discriminant Analysis (DA) methods was evaluated to classify participants as high-risk and low-risk of falls. We achieved excellent results from the classification using stepwise feature selection on a linear DA, in which selected features rendered a classification accuracy of 100%, indicating that our SAR simulation of ecological and functional activities is precise in identifying the risk of falls in older adults. This also suggests that immersive VR environments can be used to implement standard procedures for fitness and balance assessments, proposing alternatives to traditional and expensive laboratory setups and creating custom environments based on functional activities with higher ecological validity.

8.2 Integration of Virtual Simulation with Biocybernetic Loop Systems (BLS) to Close the Loop

VR simulations have been promising to improve cardiorespiratory endurance. However, in most cases, the intensity of the physical activity is not adequate according to the fitness guidelines. One possible solution is adaptive VR simulations where the user's exercise intensity is controlled by adapting the simulation feedback. A closed-loop control method was implemented using the BLEngine [147] to monitor the HR and adapt a Virtual Levada SAR experience to control the intensity of the stepping exercise performed by the participants. We asked the following research questions:

- RQ1: Can an adaptive system successfully manipulate training intensity?
- RQ2: Can an adaptive system effectively keep participants in the desired target HR zone?
- RQ3: How does an adaptive system compare to its non-adaptive counterpart?
- RQ4: What is the impact of VR feedback on perceived exertion levels and motivation?

We evaluated the feasibility and efficacy of the HR-based adaptive SAR simulation by conducting a study with twenty-two healthy adults. The Adaptive VR Levada simulation was able to bring the participants into the target heart zone, approximately the first 2-3 minutes of the exercise, answering the first question (RQ1). Regarding RQ2 and RQ3, the participants in the *Adaptive VR* Levada exerted more than 20% of the total duration of the experiment (10 minutes) in the target heart rate zone, compared to the *Non-Adaptive VR* Levada condition. The perceived exertion level was observed to be lower in the *Adaptive VR* condition, which indicates that the perception of effort was low regardless of whether participants were training in the target HR zone for a long time, addressing the impact of VR feedback on perceived exertion levels (RQ4). This shows that a lower exertion level is associated with training in a highly controlled HR environment.

8.3 Limitations and Future Work

The KAVE-based VR environment has space constraints and requires an adequate laboratory setup. Therefore, CAVE-based simulations are not easily portable, and the system could be redesigned for mobile-based VR systems and facilitate its acceptance and widespread use. The Kinect sensor sometimes does not detect gesture signals. It also requires players not to wear black clothes to facilitate the tracking. In addition, Kinect has latency issues that, although they do not affect the measurements per se, can affect the user experience.

We could not run a longitudinal intervention with the adaptive Levada on the target population. Its long-term impact, ability to reduce falls, or sensibility of the profiling method in other populations, age groups or conditions. Also, limitations of the adaptive system. Only HR could use other information such as WBB or COP or navigation speed.

Further, Microsoft does not provide software development kit (SDK) updates. Hence, an alternative system would be ideal for improved motion detection and interaction, such as inertial sensors [206][212] or depth cameras [208]. Nintendo has halted its production of the WBB and does not provide support anymore. Some other limitations of the WBB include hardware-designed consistency and signal loss. The literature has also highlighted the limitations of the WBB, such as poor reliability and quality, and it has not been suggested that the clinical platforms be replaced completely [140]. The adaptive VR Levada could be configured to incorporate other physiological signals, such as Electroencephalogram (EEG) or eye tracking (ET), for emotion recognition. The VR Levada adaptation may be implemented and controlled using the Cable Car simulation parameters, including COP and speed limits. Future research should focus on longitudinal interventions with the adaptive VR Levada for older adults to enhance physical fitness and reduce the risk of falls. VR-based applications are being developed using multiple physiological signals to classify multimodel emotions [250].

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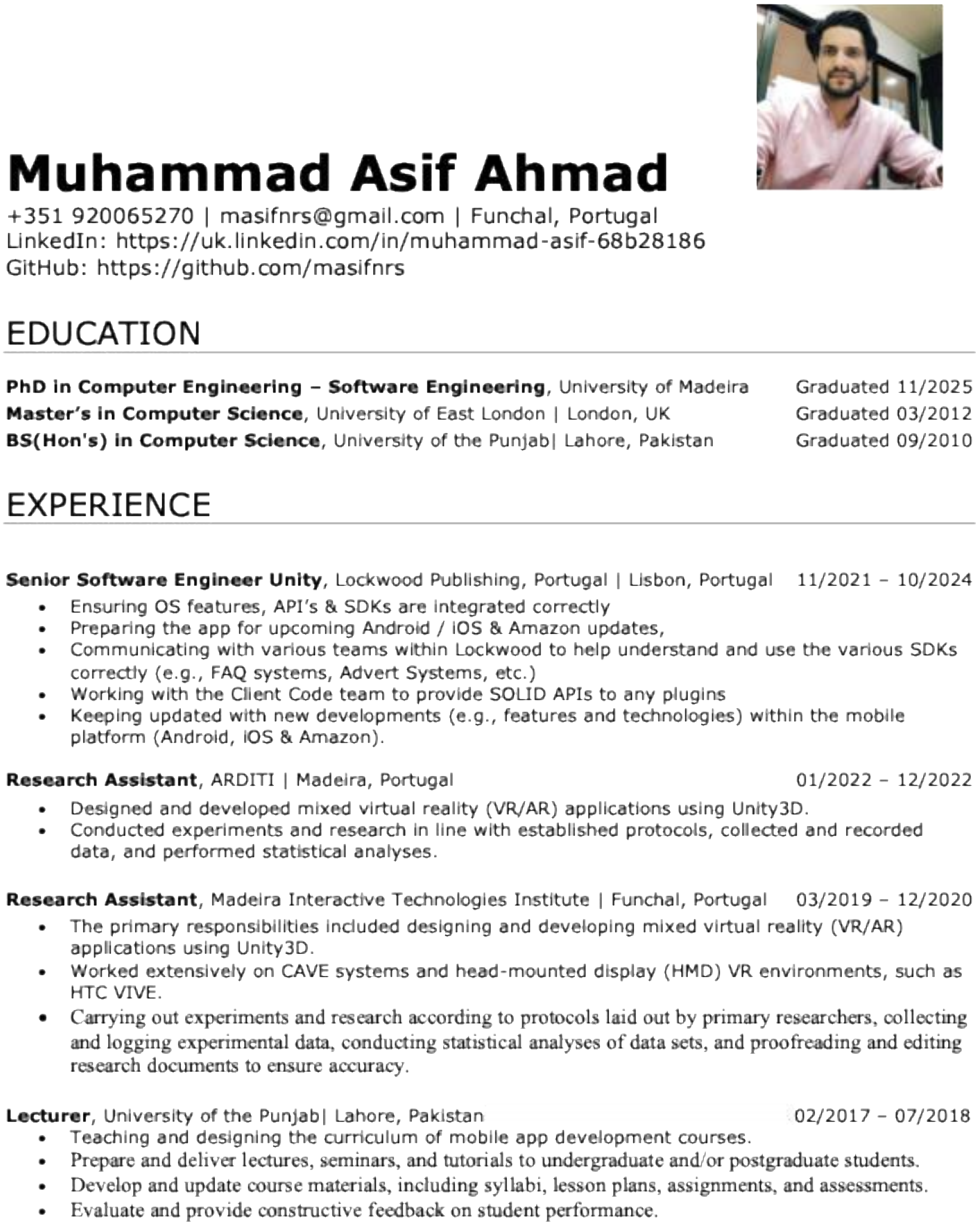
Appendices

Appendix A - Curriculum Vitae



Muhammad Asif Ahmad

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GitHub: https://github.com/masifnrs

EDUCATION

PhD in Computer Engineering – Software Engineering, University of Madeira — Graduated 11/2025
Master's in Computer Science, University of East London | London, UK — Graduated 03/2012
BS(Hon's) in Computer Science, University of the Punjab| Lahore, Pakistan — Graduated 09/2010

EXPERIENCE

Senior Software Engineer Unity, Lockwood Publishing, Portugal | Lisbon, Portugal — 11/2021 – 10/2024

- Ensuring OS features, API's & SDKs are integrated correctly
- Preparing the app for upcoming Android / iOS & Amazon updates,
- Communicating with various teams within Lockwood to help understand and use the various SDKs correctly (e.g., FAQ systems, Advert Systems, etc.)
- Working with the Client Code team to provide SOLID APIs to any plugins
- Keeping updated with new developments (e.g., features and technologies) within the mobile platform (Android, iOS & Amazon).

Research Assistant, ARDITI | Madeira, Portugal — 01/2022 – 12/2022

- Designed and developed mixed virtual reality (VR/AR) applications using Unity3D.
- Conducted experiments and research in line with established protocols, collected and recorded data, and performed statistical analyses.

Research Assistant, Madeira Interactive Technologies Institute | Funchal, Portugal — 03/2019 – 12/2020

- The primary responsibilities included designing and developing mixed virtual reality (VR/AR) applications using Unity3D.
- Worked extensively on CAVE systems and head-mounted display (HMD) VR environments, such as HTC VIVE.
- Carrying out experiments and research according to protocols laid out by primary researchers, collecting and logging experimental data, conducting statistical analyses of data sets, and proofreading and editing research documents to ensure accuracy.

Lecturer, University of the Punjab| Lahore, Pakistan — 02/2017 – 07/2018

- Teaching and designing the curriculum of mobile app development courses.
- Prepare and deliver lectures, seminars, and tutorials to undergraduate and/or postgraduate students.
- Develop and update course materials, including syllabi, lesson plans, assignments, and assessments.
- Evaluate and provide constructive feedback on student performance.

Senior Software Engineer, OZI Technologies | Lahore, Pakistan 09/2014 – 09/2015

- My primary responsibilities included designing and developing mobile games for iOS and Android platforms using Unity 3D.

Lecturer, British Institute of Technology | London, UK 08/2013 – 08/2014

- Teaching and designing the curriculum of computing courses.
- Prepare and deliver lectures, seminars, and tutorials to undergraduate and/or postgraduate students.

Software Developer, Dictate Now | Hertfordshire, UK 10/2012 – 08/2013

- Developing and updating the IOS Dictation app, which records dictations and then uploads them to the server. After uploading, the sectary gets the file from the server and starts writing dictations.
- Developed the same dictation app for the Android platform.
- Developed dictation application in vb.net for desktop machines.
- Developed and updated components of the dictation application for the Blackberry platform.

Software Engineer Embedded Systems, Enmac Technologies | Lahore, Pakistan 01/2010 – 01/2011

- Developed mp4 application in c language.
- Developed Qibla finder application for the device model eq400.

Publications

Ahmad, M.A.; Cameirão, M. Road Crossing Behaviors of Pedestrians in Two Different Virtual Reality Environments; 2021;

Ahmad, M.; Sousa, H.; Quintal, É.; Bermúdez I Badia, S. Efficacy of Augmented Reality-Based Virtual Hiking in Cardiorespiratory Endurance: A Pilot Study: In Proceedings of the Proceedings of the 14th International Joint Conference on Biomedical Engineering Systems and Technologies;

Ahmad, M.A.; Badia, S.B.I. Validity and Reliability of VR-Based Cable Car Simulation for Balance Assessment Using the Nintendo Wii Balance Board. In Proceedings of the 2024 IEEE 12th International Conference on Serious Games and Applications for Health (SeGAH); IEEE: Funchal, Portugal, August 7 2024; pp. 1–7.

Ahmad, M.A.; Gouveia, É.R.; Bermúdez I Badia, S. A Virtual Reality-Based Simulation Tool for Assessing the Risk of Falls in Older Adults. Appl. Sci. 2024, 14, 6251, doi:10.3390/app14146251.

Lima, R.; Asif, M.; Sousa, H.; Bermúdez I Badia, S. Adaptive Control of Cardio-Respiratory Training in a Virtual Reality Hiking Simulation: A Feasibility Study: In Proceedings of the Proceedings of the 15th International Joint Conference on Biomedical Engineering Systems and Technologies; SCITEPRESS - Science and Technology Publications: Online Streaming, --- Select a Country ---, 2022; pp. 91–99.

Masu, R.; Bala, P.; Ahmad, M.A.; Correia, N.; Nisi, V.; Nunes, N.; Romão, T. VR Open Scores: Scores as Inspiration for VR Scenarios; 2020;

SKILLS

- Unity 3D, AR/VR
- Android platform (json, xml, webservices, animation, Google's Material Design)
- RX Android, RX Java, Google Volley, Retrofit, Butter Knife, Sqlite
- IOS Native Development (objective c)
- Object Oriented Programming in Java, Html5, CSS3, JavaScript, C++
- Microsoft SQL Server, Store Procedures,
- R MATLAB, Machine learning, Signal processing
- Webservices/ REST Services development in MS web API, php, java.
- Cocos2dx (2d games development)
- Experience with agile development (Scrum)

REFERENCE

- References will be provided on request.

Appendix B

Presence Instruments

- Witmer & Singer Presence Questionnaire
- The ITC-Sense of Presence Inventory (SOPI)

PRESENCE QUESTIONNAIRE

(Witmer & Singer, Vs. 3.0, Nov. 1994)*
Revised by the UQO Cyberpsychology Lab (2004)

Characterize your experience in the environment, by marking an "X" in the appropriate box of the 7-point scale, in accordance with the question content and descriptive labels. Please consider the entire scale when making your responses, as the intermediate levels may apply. Answer the questions independently in the order that they appear. Do not skip questions or return to a previous question to change your answer.

WITH REGARD TO THE EXPERIENCED ENVIRONMENT

1. How much were you able to control events?

|_______|_______|_______|_______|_______|_______|_______|

NOT AT ALL	SOMEWHAT	COMPLETELY

2. How responsive was the environment to actions that you initiated (or performed)?

|_______|_______|_______|_______|_______|_______|_______|

NOT RESPONSIVE	MODERATELY RESPONSIVE	COMPLETELY RESPONSIVE

3. How natural did your interactions with the environment seem?

|_______|_______|_______|_______|_______|_______|_______|

EXTREMELY ARTIFICIAL	BORDERLINE	COMPLETELY NATURAL

4. How much did the visual aspects of the environment involve you?

|_______|_______|_______|_______|_______|_______|_______|

NOT AT ALL	SOMEWHAT	COMPLETELY

5. How natural was the mechanism which controlled movement through the environment?

|_______|_______|_______|_______|_______|_______|_______|

EXTREMELY ARTIFICIAL	BORDERLINE	COMPLETELY NATURAL

6. How compelling was your sense of objects moving through space?

|_______|_______|_______|_______|_______|_______|_______|

NOT AT ALL	MODERATELY COMPELLING	VERY COMPELLING

7. How much did your experiences in the virtual environment seem consistent with your real world experiences?

|_______|_______|_______|_______|_______|_______|_______|

NOT CONSISTENT	MODERATELY CONSISTENT	VERY CONSISTENT

8. Were you able to anticipate what would happen next in response to the actions that you performed?

|_______|_______|_______|_______|_______|_______|_______|

NOT AT ALL	SOMEWHAT	COMPLETELY

9. How completely were you able to actively survey or search the environment using vision?

|_______|_______|_______|_______|_______|_______|_______|

NOT AT ALL	SOMEWHAT	COMPLETELY

10. How compelling was your sense of moving around inside the virtual environment?

|_______|_______|_______|_______|_______|_______|_______|

NOT COMPELLING	MODERATELY COMPELLING	VERY COMPELLING

11. How closely were you able to examine objects?

|_______|_______|_______|_______|_______|_______|_______|

NOT AT ALL	PRETTY CLOSELY	VERY CLOSELY

12. How well could you examine objects from multiple viewpoints?

|_______|_______|_______|_______|_______|_______|_______|

NOT AT ALL	SOMEWHAT	EXTENSIVELY

13. How involved were you in the virtual environment experience?

|_______|_______|_______|_______|_______|_______|_______|

NOT INVOLVED	MILDLY INVOLVED	COMPLETELY ENGROSSED

14. How much delay did you experience between your actions and expected outcomes?

|_______|_______|_______|_______|_______|_______|_______|

NO DELAYS	MODERATE DELAYS	LONG DELAYS

15. How quickly did you adjust to the virtual environment experience?

|_______|_______|_______|_______|_______|_______|_______|

NOT AT ALL	SLOWLY	LESS THAN ONE MINUTE

16. How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?

|_______|_______|_______|_______|_______|_______|_______|

NOT PROFICIENT	REASONABLY PROFICIENT	VERY PROFICIENT

17. How much did the visual display quality interfere or distract you from performing assigned tasks or required activities?

|_______|_______|_______|_______|_______|_______|_______|

NOT AT ALL	INTERFERED SOMEWHAT	PREVENTED TASK PERFORMANCE

18. How much did the control devices interfere with the performance of assigned tasks or with other activities?

|_______|_______|_______|_______|_______|_______|_______|

NOT AT ALL	INTERFERED SOMEWHAT	INTERFERED GREATLY

19. How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?

|_______|_______|_______|_______|_______|_______|_______|

NOT AT ALL	SOMEWHAT	COMPLETELY

IF THE VIRTUAL ENVIRONMENT INCLUDED SOUNDS:

20. How much did the auditory aspects of the environment involve you?

|_______|_______|_______|_______|_______|_______|_______|
NOT AT ALL SOMEWHAT COMPLETELY

21. How well could you identify sounds?

|_______|_______|_______|_______|_______|_______|_______|
NOT AT ALL SOMEWHAT COMPLETELY

22. How well could you localize sounds?

|_______|_______|_______|_______|_______|_______|_______|
NOT AT ALL SOMEWHAT COMPLETELY

IF THE VIRTUAL ENVIRONMENT INCLUDED HAPTIC (SENSE OF TOUCH):

23. How well could you actively survey or search the virtual environment using touch?

|_______|_______|_______|_______|_______|_______|_______|
NOT AT ALL SOMEWHAT COMPLETELY

24. How well could you move or manipulate objects in the virtual environment?

|_______|_______|_______|_______|_______|_______|_______|
NOT AT ALL SOMEWHAT EXTENSIVELY

Last version : March 2013

*Original version : Witmer, B.G. & Singer. M.J. (1998). Measuring presence in virtual environments: A presence questionnaire. *Presence : Teleoperators and Virtual Environments*, *7*(3), 225-240. Revised factor structure: Witmer, B.J., Jerome, C.J., & Singer, M.J. (2005). The factor structure of the Presence Questionnaire. *Presence, 14*(3) 298-312.

ITC SOPI

Please read the instructions below before continuing

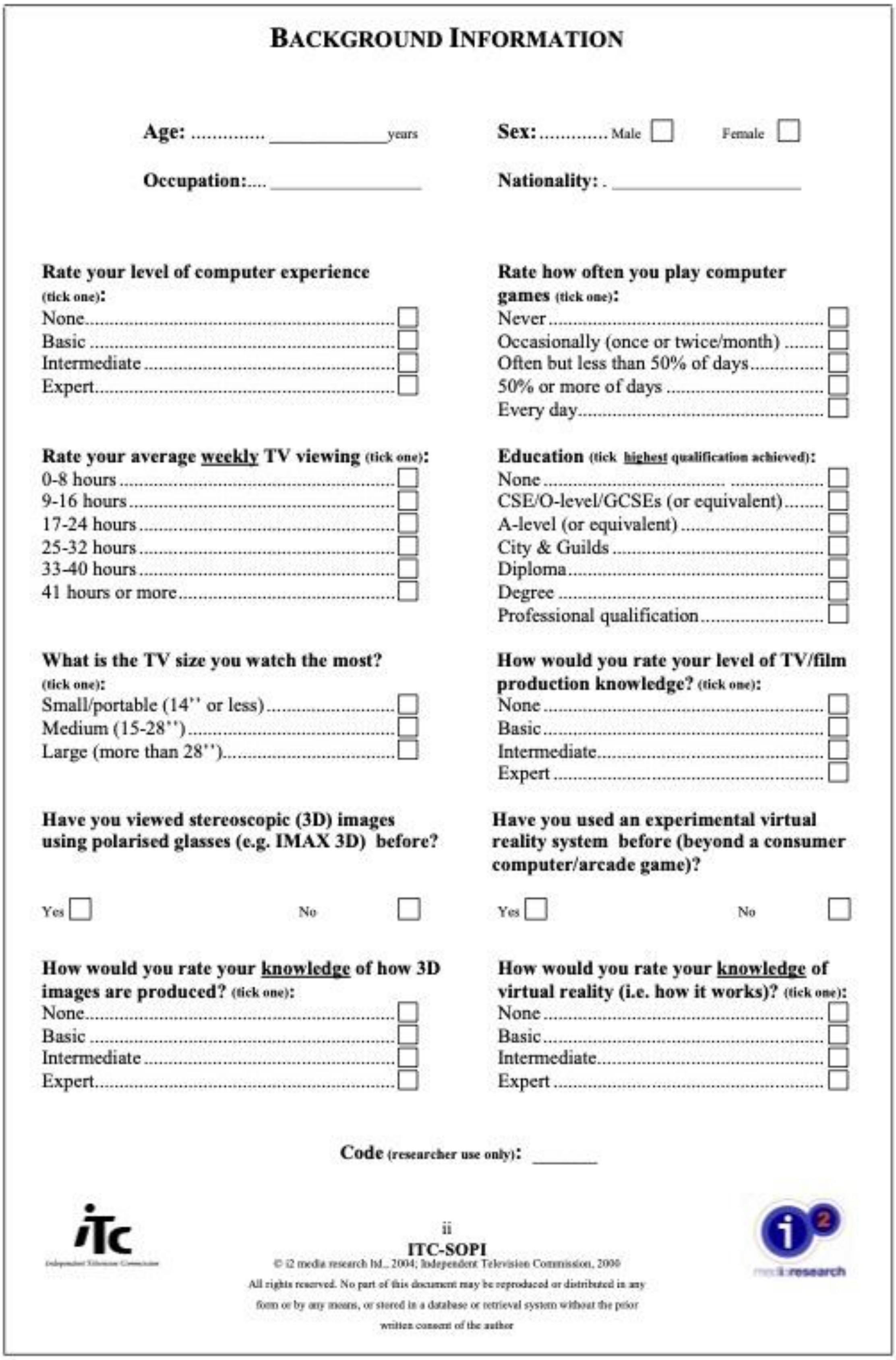
Instructions:

We are interested in finding out what you feel about the experience you have just had in the 'DISPLAYED ENVIRONMENT'. We use the term 'displayed environment' here, and throughout this questionnaire, to refer to the film, video, computer game or virtual world that you have just encountered. Some of the questions refer to the 'CONTENT' of the displayed environment. By this we mean the story, scenes or events, or whatever you could see, hear, or sense happening within the displayed environment. The displayed environment and its content (including representations of people, animals, or cartoons, which we call 'CHARACTERS') are different from the 'REAL WORLD': the world you live in from day-to-day. Please refer back to this page if you are unsure about the meaning of any question.

There are two parts to this questionnaire, PART A and PART B. PART A asks about your thoughts and feelings once the displayed environment was over. PART B refers to your thoughts and feelings while you were experiencing the displayed environment. Please do not spend too much time on any one question. Your first response is usually the best. For each question, choose the answer CLOSEST to your own.

Please remember that there are no right or wrong answers – we are simply interested in YOUR thoughts and feelings about the displayed environment. Please do not discuss the questionnaire with anyone who may also complete it as this may affect your answers or theirs. We should be grateful if you would also complete the 'Background Information' overleaf.

All of your responses will be treated confidentially.



BACKGROUND INFORMATION

Age: .... ____________ years

Sex: .... Male ☐ Female ☐

Occupation:.... ______________

Nationality: . ________________

Rate your level of computer experience (tick one)**:**

- None ☐
- Basic ☐
- Intermediate ☐
- Expert ☐

Rate how often you play computer games (tick one)**:**

- Never ☐
- Occasionally (once or twice/month) ☐
- Often but less than 50% of days ☐
- 50% or more of days ☐
- Every day ☐

Rate your average weekly TV viewing (tick one)**:**

- 0-8 hours ☐
- 9-16 hours ☐
- 17-24 hours ☐
- 25-32 hours ☐
- 33-40 hours ☐
- 41 hours or more ☐

Education (tick highest qualification achieved)**:**

- None ☐
- CSE/O-level/GCSEs (or equivalent) ☐
- A-level (or equivalent) ☐
- City & Guilds ☐
- Diploma ☐
- Degree ☐
- Professional qualification ☐

What is the TV size you watch the most? (tick one)**:**

- Small/portable (14'' or less) ☐
- Medium (15-28'') ☐
- Large (more than 28'') ☐

How would you rate your level of TV/film production knowledge? (tick one)**:**

- None ☐
- Basic ☐
- Intermediate ☐
- Expert ☐

Have you viewed stereoscopic (3D) images using polarised glasses (e.g. IMAX 3D) before?

Yes ☐ No ☐

Have you used an experimental virtual reality system before (beyond a consumer computer/arcade game)?

Yes ☐ No ☐

How would you rate your knowledge of how 3D images are produced? (tick one)**:**

- None ☐
- Basic ☐
- Intermediate ☐
- Expert ☐

How would you rate your knowledge of virtual reality (i.e. how it works)? (tick one)**:**

- None ☐
- Basic ☐
- Intermediate ☐
- Expert ☐

Code (researcher use only)**:** _______

ii

ITC-SOPI

PART A

Please indicate HOW MUCH YOU AGREE OR DISAGREE with each of the following statements by circling just ONE of the numbers using the 5-point scale below.

(Strongly disagree)	**(Disagree)**	**(Neither agree nor disagree)**	**(Agree)**	**(Strongly agree)**
1	**2**	**3**	**4**	**5**

<u>AFTER</u> MY EXPERIENCE OF THE DISPLAYED ENVIRONMENT…

1. I felt sad that my experience was over 1 2 3 4 5

2. I felt disorientated..1 2 3 4 5

3. I had a sense that I had returned from a journey..1 2 3 4 5

4. I would have liked the experience to continue 1 2 3 4 5

5. I vividly remember some parts of the experience.......................................1 2 3 4 5

6. I'd recommend the experience to my friends. 1 2 3 4 5

PART B

Please indicate HOW MUCH YOU AGREE OR DISAGREE with each of the following statements by circling just ONE of the numbers using the 5-point scale below.

(Strongly disagree)	**(Disagree)**	**(Neither agree nor disagree)**	**(Agree)**	**(Strongly agree)**
1	**2**	**3**	**4**	**5**

<u>DURING</u> MY EXPERIENCE OF THE DISPLAYED ENVIRONMENT…

1. I felt myself being 'drawn in'. 1 2 3 4 5

2. I felt involved (in the displayed environment). 1 2 3 4 5

3. I lost track of time..1 2 3 4 5

4. I felt I could interact with the displayed environment...............................1 2 3 4 5

5. The displayed environment seemed natural. 1 2 3 4 5

6. It felt like the content was 'live'. 1 2 3 4 5

7. I felt that the characters and/or objects could almost touch me..................1 2 3 4 5

8. I enjoyed myself. 1 2 3 4 5

9. I felt I was visiting the places in the displayed environment.....................1 2 3 4 5

10. I felt tired. 1 2 3 4 5

(Strongly disagree)	**(Disagree)**	**(Neither agree nor disagree)**	**(Agree)**	**(Strongly agree)**
1	**2**	**3**	**4**	**5**

<u>DURING</u> MY EXPERIENCE OF THE DISPLAYED ENVIRONMENT…

11. The content seemed believable to me..1 2 3 4 5

12. I felt I wasn't *just* watching something. 1 2 3 4 5

13. I had the sensation that I moved in response to parts of the displayed environment 1 2 3 4 5

14. I felt dizzy. 1 2 3 4 5

15. I felt that the displayed environment was part of the real world. 1 2 3 4 5

16. My experience was intense..1 2 3 4 5

17. I paid more attention to the displayed environment than I did to my own thoughts (e.g., personal preoccupations, daydreams etc.). 1 2 3 4 5

18. I had a sense of being in the scenes displayed..1 2 3 4 5

19. I felt that I could move objects (in the displayed environment). 1 2 3 4 5

20. The scenes depicted could really occur in the real world...........................1 2 3 4 5

21. I felt I had eyestrain. 1 2 3 4 5

22. I could almost smell different features of the displayed environment. 1 2 3 4 5

(Strongly disagree)	**(Disagree)**	**(Neither agree nor disagree)**	**(Agree)**	**(Strongly agree)**
1	**2**	**3**	**4**	**5**

<u>DURING</u> MY EXPERIENCE OF THE DISPLAYED ENVIRONMENT…

23. I had the sensation that the characters were aware of me..........................1 2 3 4 5

24. I had a strong sense of sounds coming from different directions within the displayed environment..1 2 3 4 5

25. I felt surrounded by the displayed environment 1 2 3 4 5

26. I felt nauseous. 1 2 3 4 5

27. I had a strong sense that the characters and objects were solid.................1 2 3 4 5

28. I felt I could have reached out and touched things (in the displayed environment)..1 2 3 4 5

29. I sensed that the temperature changed to match the scenes in the displayed environment..1 2 3 4 5

30. I responded emotionally 1 2 3 4 5

31. I felt that *all* my senses were stimulated at the same time..........................1 2 3 4 5

32. The content appealed to me. 1 2 3 4 5

33. I felt able to change the course of events in the displayed environment. ...1 2 3 4 5

(Strongly disagree)	(Disagree)	(Neither agree nor disagree)	(Agree)	(Strongly agree)
1	**2**	**3**	**4**	**5**

<u>DURING</u> MY EXPERIENCE OF THE DISPLAYED ENVIRONMENT…

34. I felt as though I was in the same space as the characters and/or objects...1 2 3 4 5

35. I had the sensation that parts of the displayed environment
(e.g. characters or objects)were responding to me. 1 2 3 4 5

36. It felt realistic to move things in the displayed environment......................1 2 3 4 5

37. I felt I had a headache...1 2 3 4 5

38. I felt as though I was participating in the displayed environment.............1 2 3 4 5

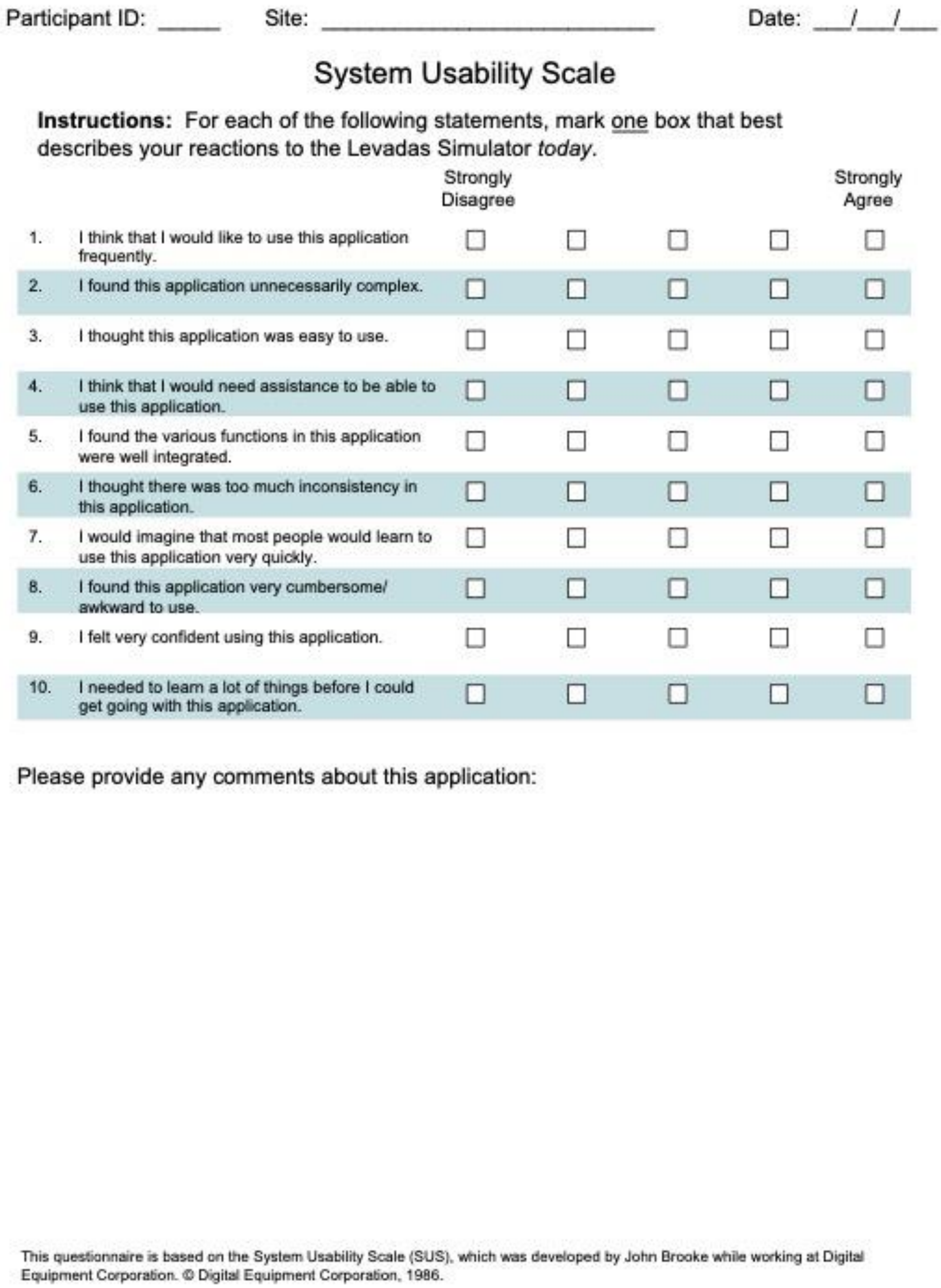
<u>If there is anything else you would like to add, please use the space below:</u>

<u>PLEASE CHECK THAT YOU HAVE ANSWERED ALL THE QUESTIONS</u>

<u>THANK YOU VERY MUCH FOR YOUR TIME AND PARTICIPATION</u>

Appendix C

System Usability Scale



Participant ID: _____ Site: ___________________________ Date: ___/___/___

System Usability Scale

Instructions: For each of the following statements, mark one box that best describes your reactions to the Levadas Simulator *today*.

		Strongly Disagree				Strongly Agree
1.	I think that I would like to use this application frequently.	☐	☐	☐	☐	☐
2.	I found this application unnecessarily complex.	☐	☐	☐	☐	☐
3.	I thought this application was easy to use.	☐	☐	☐	☐	☐
4.	I think that I would need assistance to be able to use this application.	☐	☐	☐	☐	☐
5.	I found the various functions in this application were well integrated.	☐	☐	☐	☐	☐
6.	I thought there was too much inconsistency in this application.	☐	☐	☐	☐	☐
7.	I would imagine that most people would learn to use this application very quickly.	☐	☐	☐	☐	☐
8.	I found this application very cumbersome/ awkward to use.	☐	☐	☐	☐	☐
9.	I felt very confident using this application.	☐	☐	☐	☐	☐
10.	I needed to learn a lot of things before I could get going with this application.	☐	☐	☐	☐	☐

Please provide any comments about this application:

This questionnaire is based on the System Usability Scale (SUS), which was developed by John Brooke while working at Digital Equipment Corporation. © Digital Equipment Corporation, 1986.