Physical and Physiological Impact of Custom-Made Virtual Reality Exergames for Older Adults

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Abstract: Aging is associated with decreased physical fitness components, such as strength, power, cardiorespiratory fitness, and balance, resulting in physical limitations on functional activities of daily living. The increasing population of older adults calls for innovative strategies to support functional health, particularly through exercise. This study has two main objectives: (1) to introduce a custom-designed virtual reality (VR) exergame prototype, FitFest, developed to deliver physical activity (PA) sessions for older adults, and (2) to present the results of a pilot study assessing physical and physiological responses during gameplay. Seven older adults (mean age 67.0±3.8 years) participated in 18 user testing sessions involving two VR exergames—Wine Fest and Flower Fest. Each session was monitored for PA intensity and heart rate (HR). The participants spent most of their time in sedentary behavior (56.5±20.4%), followed by light PA (42.1±19.3%), averaging 436.7 steps and a heart rate of 92.1 bpm per session. Although the differences were not statistically significant, Wine Fest led to lower sedentary behavior, higher light PA levels, and more total steps than Flower Fest. The findings suggest that the system can potentially promote light PA among older adults, emerging as a complementary tool to traditional PA sessions.

1 INTRODUCTION

Aging is associated with decreased physical fitness components, such as strength, power, cardiorespiratory fitness, and balance, resulting in physical limitations on functional activities of daily living (Paterson et al., 2007). There is evidence that exercise interventions among older adults can promote gains in functional capacities, enhancing physical health and quality of life.

According to the World Health Organization's physical activity (PA) guidelines, older adults should accumulate at least 150 minutes of moderate-intensity or 75 minutes of vigorous activity per week, emphasizing aerobic capacity (WHO, 2020). Additionally, performing muscle-strengthening and balance activities might be crucial to prevent falls, which has been described as a common and serious concern among this population (Nascimento et al., 2022). Approximately one-third of individuals aged 65 years or older living in community settings experience at least one fall yearly, and one-half fall more than once (Inouye et al., 2009). Although falls often occur due to multiple factors, previous research has related falls to poor balance and strength abilities and gait disorders (Clemson et al., 2010). For instance, among 619 older adults aged 69.5 years, gait speed and body balance presented an inverse relationship with falls, and in turn, falls negatively impact health-related quality of life (Nascimento et al., 2022).

There is a significant body of research advocating the benefits of PA in reducing the risk of several age-related morbidities and all-cause mortality (Paterson et al., 2007). PA programs were associated with reducing the risk of fall-related injuries by 32% to 40%, delaying the loss of physical function and mobility (Dipietro et al., 2019). Additionally,

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according to a systematic review and meta-analysis of longitudinal cohort studies, higher levels of PA were related to an increase of 39% in the odds of healthy aging (Daskalopoulou et al., 2017).

The continuous increase of the older adult population worldwide demands the urgency to provide ways to maintain and improve functional health during aging. Due to the exponential development of technology, exergames have emerged as exercise platforms among several populations, including older adults (Ismail et al., 2022). Exergames are interactive digital tools that combine exercise and video games. Previous research on using exergames to improve physical fitness components among older adults reported beneficial effects on balance, strength, and aerobic capacity (Agmon et al., 2011). Moreover, exergames have also been characterized by the ability to provide mental stimulation, which is crucial to combat age-related cognitive declines (Deary et al., 2009). In a recent systematic review and meta-analysis of randomized control trials to assess the effects of virtual reality (VR) exergames on older adults' cognition and depression, the findings suggested VR exergames usage as beneficial for overall cognitive function and memory (Yen & Chiu, 2021).

Although a significant body of research has emerged on exergame usage among older adults in recent years, most studies were conducted using commercial games and commercial video game consoles such as Nintendo Wii (Agmon et al., 2011; Kirk et al., 2013) and Xbox (with Kinect) (Yang et al., 2020). Overall, commercial game designing might not be appropriate to all populations, the systems lack precision in motion detection and fail to provide a sequential and logical gameplay targeting multicomponent physical fitness components. On the other hand, commercial games are typically based on repetitive movements and scenarios, leading to boredom or reduced motivation over time. Additionally, balance stands out among physical fitness components when promoting exergames interventions in older adults (Agmon et al., 2011; Clemson et al., 2010; Yang et al., 2020), probably because of its relationship with falls. However, it is worth noting that strength and aerobic capacity are also two crucial components that must be worked on within the older adult population (WHO, 2020). Therefore, the purpose of this study is twofold: (1) to present a VR custom-made exergame prototype (FitFest) designed to provide an entire PA session to older adults, and (2) to evaluate the acute physical and physiological responses elicited while playing FitFest.

2 METHODS

2.1 Game Development

2.1.1 Game Concept

FitFest consists of two exergames, composed of five mini games each, that integrate sociocultural narratives to create an engaging and enjoyable exercise experience for older adults. The prototype was developed through a multidisciplinary collaboration involving researchers in engineering, sports science, design and storytelling. Input from the target population was also incorporated through qualitative analysis to ensure the games addressed their preferences and needs (Freitas et al., 2024).

The custom-made exergames were designed to simulate a complete exercise session, approximately 45 minutes, following a structured sequence of warm-up, main exercise phase, and cool-down. Exercise selection was guided by established recommendations for physical fitness training in older adults (focusing on balance, cardiorespiratory fitness, strength, and agility training) (Bushman & Medicine, 2017). Additionally, recognizing the progressive cognitive decline associated with aging (Deary et al., 2009), the game design included cognitive challenges to stimulate memory and problem-solving skills—such as catching specific items and solving puzzles. The FitFest differs significantly from existing VR games by including cognitive stimuli, cultural narrative, and physical movements, aiming to foster the recommended physical fitness guidelines for the older population.

Reflecting the cultural values emphasized by the target group (Freitas et al., 2024), each exergame is based on a traditional festivity from Madeira Island:

(1) Wine Fest – Inspired by Portugal's rich winemaking tradition, this game simulates grape harvesting, sorting, transportation, and winemaking. Game illustration can be found in Figure 1.

(2) Flower Fest – Modeled after Madeira Island's renowned Flower Festival, this game involves creating floral arrangements and participating in a traditional dance and parade celebration. Game illustration can be found in Figure 2.

Based on the design characteristics, the Wine Fest was expected to promote more cardiorespiratory fitness based on the winemaking scenario, which involved approximately 10 minutes of "stepping grapes" movements. On the other hand, the Flower Fest included a traditional dance scenario, with an estimated duration of 10 minutes, fostering agility and coordination alongside cardiorespiratory fitness.

Figure 1: Illustration of the Wine Fest scenarios.

Figure 2: Illustration of the Flower Fest scenarios.

To meet different individual profiles that could be found among the target population, the exergames include three difficulty levels: (1) elementary, (2) standard, and (3) advanced, where the speed of the actions, the amplitude of the movements, and the amount of cognitive stimulus vary. The difficulty level provides a game experience that is more appropriate to the individuals' capacities and needs.

To ensure that FitFest stood out from conventional exergames, storytelling was integrated to create a meaningful connection between the players and the character's journey. Players follow the story of a 65-year-old resident seeking to rediscover their youth and break free from monotonous routines by exploring new experiences.

Finally, to guarantee clear instructions during the game, a mandatory tutorial before each scenario was included, following previous literature recommendations in designing exergames for older adults (Barg-Walkow et al., 2017). During the tutorial, the players start by watching a short gameplay video and a person doing the required gestures. They then must replicate the movements needed to play, in a controlled setting, ensuring the movements were understood and the correct posture was maintained.

2.1.2 Hardware

Based on insights from the qualitative analysis (Freitas et al., 2024) regarding older adults' preferences and concerns related to technology use, a wall-projection system was selected for the FitFest experience. This setup helps mitigate common issues associated with headset-based VR systems, such as safety concerns, balance difficulties, motion sickness, and potential anxiety. To accurately track participants' movements, three HTC Vive trackers—positioned at the ankles and waist—along with two handheld controllers, were used. This configuration enabled precise tracking of key body joints while providing a spacious 2-meter-wide gameplay area, supporting both comfort and freedom of movement. The gameplay setup is presented in Figure 3.

Figure 3: FitFest gameplay set-up.

2.1.3 Software

The exergames were developed using the Unity 2022 game engine, employing a 2.5D design that combines 2D elements with 3D environments. This approach

Table 1: Summary of the characteristics of each scenario.

Wine Fest			
Scenario	Targeted component	Gameplay movements	Time (m)
1	Balance, agility, strength, and cardiorespiratory	Grape harvesting and storage	8
2	Balance and agility	Grape storage and selection	6
3	Strength	Grape transportation	8
4	Cardiorespiratory	Winemaking	10
5	Problem-solving and working memory	Puzzle solving	6
Flower Fest			
Scenario	Targeted component	Gameplay movements	Time (m)
1	Balance, agility, strength, and cardiorespiratory	Flower picking and storage	8
2	Balance, agility, and strength	Creating flower arrangements	6
3	Balance, agility, and cardiorespiratory	Parade	8
4	Balance, agility, and cardiorespiratory	Traditional dance	10
5	Problem-solving and working memory	Puzzle solving	6

allowed for efficient development while preserving visual appeal and providing depth that enhances gameplay across various scenarios/mini games. The design emphasizes intuitiveness and affordance to naturally elicit the appropriate gestures from players. Details on each scenario can be consulted in Table 1.

2.2 User Tests

A series of user tests was conducted to evaluate the physical and physiological effects of the FitFest exergames, focusing on PA intensity and heart rate (HR) metrics. Additionally, participants' ratings of perceived exertion were assessed. The sessions took place at a local community center for four weeks. Participants performed one exergame session per week, using Wine Fest and Flower Fest as alternates. The exergames sessions sequence was equal for all participants, and the sessions were supervised by two members of the research team to ensure safety and protocol adherence.

Prior to testing, participants' height and body mass were measured using a portable stadiometer (SECA 213, Hamburg, Germany; accuracy: ± 0.1 cm) and a portable scale (SECA 760, Hamburg, Germany; accuracy: ± 0.1 kg), respectively. During gameplay, participants wore an accelerometer to assess PA intensity and an HR sensor to monitor heart rate and heart rate variability. After completing each game scenario, participants rated their perceived exertion using a 10-point scale using the game interface.

2.2.1 Participants

The study involved a convenience sample of seven older adults (2 males) aged 67.0 ± 3.8 years, who collectively completed 18 user testing sessions. Although the experimental design considered one session per week for each participant, compliance was not achieved by all who participated. Two participants completed the four sessions scheduled, two participants completed a total of three sessions, one participant completed two sessions, and two participants completed only one session. Participants were selected based on the following inclusion criteria: (a) age 65 years or older; (b) absence of physical or cognitive impairments; and (c) no medical contraindications to physical exercise. All participants were engaged in activities developed at a local community center where the study took place. The procedures implemented were approved by the Ethics Committee of the University of Madeira (Nº111/CEUMA/2024) to ensure adherence to data protection regulations. Participation was entirely voluntary, and informed consent was obtained from all participants prior to the study. Data collection adhered to the principles of the Declaration of Helsinki and complied with all relevant ethical guidelines and regulations.

2.2.2 Physical Activity

Physical activity (PA) intensity was measured using the ActiGraph GT3X+ accelerometer, which participants wore on their right hip throughout the entire session. The device was initialized with a sampling frequency of 30 Hz. Raw data from the GT3X+ were converted into 10-second epochs for analysis. Activity classification—including time spent in sedentary behavior, light, moderate, moderate-to-vigorous, and vigorous activity—was determined using ActiLife software (version 6; ActiGraph, Pensacola, FL, USA), based on validated cutoff points established in prior research with older adult populations (Bammann et al., 2021; Barnett et al., 2016). The number of steps taken during the session was also recorded. The accelerometer was programmed individually for each participant prior to their session, with data collection beginning at the start of the exergame.

2.2.3 Heart Rate

During the exergame sessions, participants wore a Polar H10 sensor to monitor heart rate (HR). The device was secured to the chest using the manufacturer-provided strap, ensuring optimal skin contact. This placement allowed the sensor's electrodes to capture accurate, real-time HR data throughout the session.

2.2.4 Rate of Perceived Exertion

The rate of perceived exertion (RPE) scale (Robertson, 2004) was incorporated into the exergame after each scenario conclusion. Using the 10-point scale (1 – extremely easy, 10 – extremely hard), participants had to move to the right or left side to indicate the number that would better correspond to their effort. After selecting the number that best represented their perceived effort, participants raised one hand above their head to confirm their choice. Since each exergame consists of five scenarios, this process was repeated five times during the session.

2.3 Statistical Analysis

Descriptive statistics are presented as mean ± standard deviation and were used to analyze physical activity (PA) intensity and heart rate (HR) during the FitFest exergames. To compare differences between the Wine Fest and Flower Fest games in terms of PA intensity, HR, and RPE, the Mann-Whitney U test was applied. Statistical analyses and graphical presentations were performed using IBM SPSS Statistics 29.0 (SPSS Inc., Chicago, IL, USA) and GraphPad Prism version 10 (GraphPad Software, San Diego, CA, USA). The threshold for statistical significance was set at $p < 0.05$.

3 RESULTS

Due to inconsistencies in the data collection process (accelerometer malfunction), two user testing sessions were excluded from the analysis of physical activity (PA) intensity and heart rate (HR). As a result, 16 sessions were included in the final analysis—11 for Wine Fest and 5 for Flower Fest.

Table 2 presents the descriptive statistics for PA intensity and HR across all analyzed sessions. Overall, the FitFest exergames were primarily characterized by sedentary behavior (56.5 ± 20.4%), followed by light-intensity activity (42.1 ± 19.3%). On average, participants completed approximately 436.7 steps per session, with a HR of 92.1 bpm.

Table 2: Descriptive statistics for PA intensity and HR while playing the FitFest exergames.

Variable	FitFest Overall	Wine Fest	Flower Fest
	M ± SD	M ± SD	M ± SD
Sedentary behavior (%)	56.5 ± 20.4	53.6 ± 22.1	62.9 ± 16.2
Light PA (%)	42.1 ± 19.3	44.7 ± 20.4	38.4 ± 17.0
Moderate PA (%)	1.4 ± 2.4	1.7 ± 2.8	0.6 ± 0.8
Moderate-to-vigorous PA (%)	1.4 ± 2.4	1.8 ± 2.8	0.8 ± 0.9
Total steps (n)	436.7 ± 308.7	502.9 ± 345.4	291.0 ± 143.1
Steps/minute (n)	10.8 ± 7.9	12.8 ± 8.7	6.5 ± 3.4
Average HR(bpm)	92.1 ± 14.5	92.1 ± 16.6	92.2 ± 9.7
Minimum HR (bpm)	115.0 ± 25.3	115.2 ± 29.7	114.4 ± 13.5
Maximum HR (bpm)	71.8 ± 12.0	71.6 ± 11.7	72.0 ± 14.2
M ± SD (mean ± standard deviation) PA (physical activity), HR (heart rate)			

Figures 4, 5, and 6 present the comparison between the two exergames in terms of physical activity (PA) intensity, step count, and heart rate (HR) measurements. Wine Fest elicited lower levels of sedentary behavior (53.6 ± 22.1% vs. 62.8 ± 16.2%), higher levels of light-intensity PA (44.7 ± 20.4% vs. 36.4 ± 17.0%), and a greater average number of steps (503.0 ± 345.4 vs. 291.0 ± 143.1) compared to Flower Fest. However, these differences did not reach statistical significance. HR values were similar across both exergames, with an average of 92.1 bpm.

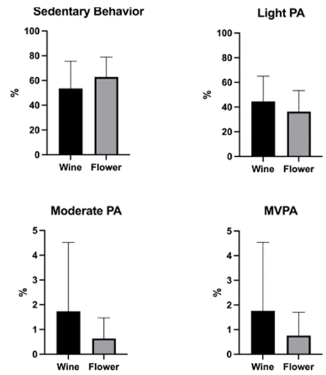

Figure 4: Comparison between exergames regarding PA intensity.

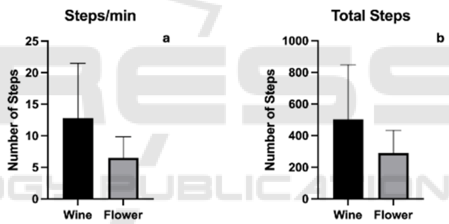

Figure 5: Comparison between exergames regarding the number of steps.

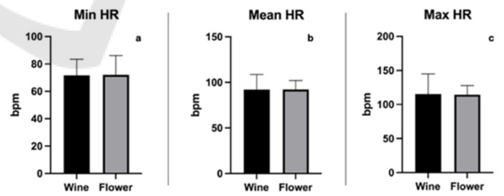

Figure 6: Comparison between exergames regarding heart rate.

The analysis of perceived exertion (RPE), as shown in Figure 7, revealed higher exertion levels during scenarios 3 and 4, which primarily involved tasks targeting strength and cardiorespiratory fitness. In contrast, scenario 2—focused on agility and coordination—was perceived as less physically demanding by participants.

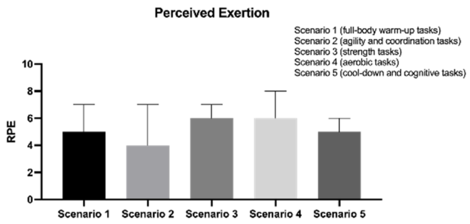

Figure 7: Rate of perceived exertion results for each scenario.

4 DISCUSSION

This study examined the physical and physiological responses of a custom-made VR exergame system, FitFest, among older adults. The overall analysis indicated that gameplay was primarily characterized by sedentary behavior, followed by light-intensity PA. Among the two exergames, Wine Fest promoted slightly higher PA intensity and a greater number of steps than Flower Fest, though these differences were not statistically significant.

According to ACSM guidelines, moderate-intensity PA is recommended for achieving substantial health benefits in older adults, particularly in cardiorespiratory fitness (Bushman & Medicine, 2017). However, FitFest did not elicit moderate-to-vigorous PA levels. One explanation is that gameplay included tutorial segments and interactive rating tasks using the Borg scale between scenarios, which contributed to reduced active time. While these features were designed to enhance clarity and provide recovery, they also limited continuous exertion. Nevertheless, literature supports that even light-intensity activities can offer health benefits (Chodzko-Zajko et al., 2009).

The mean heart rate (HR) recorded during FitFest gameplay aligns with light PA, corresponding to approximately 60% of the age-predicted maximal HR (153 bpm using 220 – age) (Fletcher et al., 2013). Although this formula may underestimate true maximal HR in older adults (Tanaka et al., 2001), it remains widely accepted for clinical applications. According to the literature, light PA is significantly and positively related to physical health and well-being in older populations (Buman et al., 2010). Compared to previous studies using Kinect-based balance-focused exergames (80–87 bpm) (Ogawa et al., 2019) and Nintendo Wii Sports (94 ± 10 bpm) (Kirk et al., 2013), FitFest HR values are within a similar range, reflecting its multicomponent design encompassing strength, balance, agility, and aerobic tasks.

Perceived exertion ratings (RPE) revealed that strength and aerobic scenarios were considered the most demanding, consistent with current PA guidelines (Chodzko-Zajko et al., 2009). Interestingly, a cool-down scenario focused solely on cognitive tasks was also perceived as moderately intense. This may relate to the cognitive challenge posed, as older adults commonly experience age-related cognitive decline (Deary et al., 2009). Prior research suggests that lower self-efficacy may increase perceived exertion in older adults during cognitively demanding tasks (Hu et al., 2007). Therefore, cognitive components of exergames should be tailored to avoid inducing frustration or discouragement.

This exploratory study presents several limitations. First, the small sample size and uneven distribution of sessions between the participants limit generalizability. All the participants were recruited from a local community center, where the study took place, and there is a need to increase the sample size and the number of sessions for future validation of the FitFest. Second, the short-term nature of the testing does not allow for assessment of long-term benefits or sustained engagement. Third, all participants played at the same difficulty level to ensure standard procedures during testing, which may not reflect individual physical or cognitive capacities. Personalized assessments and adaptive difficulty scaling are recommended for future implementations since they might promote gameplay scenarios more appropriate to the individuals' characteristics and enhance challenge. Future research can explore users' HR responses to adapt the difficulty level during gameplay. Additionally, the inclusion of tutorials and inter-scenario tasks (which corresponded to an estimated total time of 6 minutes), while necessary for clarity, may have affected overall activity intensity and increased time spent in sedentary behavior. Lastly, the lack of a control group limits the interpretation of the FitFest effects, which should be tackled in future longitudinal studies.

Despite these limitations, this study provides valuable insights into the potential of FitFest, a custom-made multicomponent VR exergame, to promote light-intensity PA among older adults. While it may not be a substitute for moderate-to-vigorous PA interventions, FitFest can be a complementary tool to traditional exercise programs implemented in community centers to increase activity levels and engagement. Besides, by including cognitive stimulus, FitFest aligns physical and cognitive tasks, which are crucial among older populations. Future developments should focus on individualization and increased intensity based on real-time adapted difficulty. Also, reducing passive time by including shorter tutorials and seamless scenario transitions to maximize benefits should be considered.

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