Virtual Rehabilitation: XR Design for Senior Users in Immersive Exergame Environments

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***Abstract*—The global ageing population presents significant challenges, with healthcare systems strained to meet the needs of an increasingly elderly demographic. Societies face issues related to healthcare costs, caregiving, and maintaining quality of life for seniors. This paper investigates the impact of a prototype Virtual Reality (VR) exergame application designed for musculoskeletal exercise and rehabilitation of senior users. The system employs an omnidirectional treadmill that combines VR with physical activity, offering immersive experiences while engaging in therapeutic exercises. This application provides an opportunity to senior users, to stay active whilst in the comfort of their home. The application has been evaluated by ten users providing encouraging results. The paper concludes with the presentation of the results and a future plan to further explore the immersive nature of VR and its impact on enhancing motivation and promoting better overall well-being for the senior population.**

Keywords—Exergames, Virtual Reality, Accessibility, User Experience, Senior users, Rehabilitation

I. INTRODUCTION

The ageing population worldwide is increasing rapidly, with far-reaching implications as it is globally expected to reach 2 billion by the year 2050 [1]. This demographic shift has sparked concerns about the health status and well-being of older individuals as well as the impact on societies with already stretched medical capacity and infrastructure. The latter issue presents further challenges associated with the social and psychological aspects of ageing [2].

Recognizing the multifaceted concerns linked to an ageing population, researchers and healthcare professionals are actively exploring strategies to address the health-related challenges faced by the elderly. Among these strategies, exercise has emerged as a pivotal and effective intervention for promoting the health and well-being of older individuals [3, 4]. The positive impact of exercise on various facets of ageing encompasses physical, cognitive, and psychological domains.

Previous studies have consistently demonstrated that engaging in regular exercise can significantly contribute to improving physical functions in the elderly [3,4]. This includes enhancements in muscular strength, cardiovascular fitness, and overall mobility. Beyond its physical benefits, exercise has proven to be instrumental in enhancing cognitive functions among the elderly. Cognitive decline is a prevalent concern in ageing populations [5]. Physical activity can support seniors' cognitive health which in turn can enhance their psychological well-being [6].

Furthermore, the benefits of exercise for the elderly extend beyond the physical realm, encompassing social aspects as well. Group-based or community-oriented exercise programs can foster social interaction and a sense of camaraderie among older individuals [7]. This social dimension is particularly pertinent in addressing the challenges of isolation and loneliness that are prevalent in ageing populations.

To support and motivate elder users to exercise, virtual applications such as XR exergames have been explored by various studies [8-11]. The results of such real and virtual hybrid systems have been promising. However, the use of full-body interaction and immersion for rehabilitation purposes is a research area that presents limited work potentially due to the complexity of the systems involved and the design challenges to cater for vulnerable population groups.

This work investigates the design of accessible and enjoyable VR exergame applications that provide the appropriate level of ease of use for senior users. In particular, the paper describes the development of an Extended Reality (XR) walking exergame application that aims to support the gradual regaining of walking capability for senior citizens who have suffered musculoskeletal injuries, stroke and major operations that affected their mobility.

The proposed system was evaluated, by ten senior users, aiming to identify the user experience (UX) and safety as perceived by the users. In turn, the paper discusses the results of the evaluation and concludes with a future plan for additional features' development based on the users' subjective feedback.

II. Ageing Population & Exercising

The physical limitations that appear gradually in the ageing population have a significant impact on their daily lives and the overall society fabric. As life expectancy rises and birth rates decline, societies face issues related to healthcare costs, caregiving, and maintaining quality of life for seniors.

Introducing exercising either as a prevention method or as a rehabilitation process, could alleviate or significantly delay issues related to musculoskeletal (i.e. sarcopenia and arthritis) or cardiovascular and diabetes diseases [3,4].

In addition, regular physical activity has been linked to positive effects on mental health, including reductions in symptoms of anxiety and depression. The mood-enhancing properties of exercise can contribute to an improved overall quality of life for older individuals, fostering resilience and emotional well-being in the face of the challenges associated with ageing [12].

Given the projected demographic trends and the increasing prevalence of an ageing society, the promotion of exercise as a fundamental component of elderly care and well-being becomes paramount. However, effective implementation of exercise interventions requires careful consideration of the unique needs and preferences of older individuals. Tailoring exercise programs to accommodate varying fitness levels, health conditions, and personal preferences is crucial to ensuring the accessibility and sustainability of such interventions. The following section describes the development of an XR walking application for post-operation rehabilitation of senior citizens with the use of an omnidirectional treadmill.

III. Creative Technologies and Exergames

Emerging technologies such as Virtual, Augmented and Mixed Reality (VR, AR, MR) could offer a unique perspective on the rehabilitation process of senior citizens.

Traditional exercises can become monotonous, making it challenging for older individuals to stay motivated. The introduction of gamification further enhances the enjoyability factor of the exercises through exergames, which combine VR technology with physical exercise or other complex activities that can be daunting or demotivating [13, 14]. This increased enjoyment can serve as a powerful motivator for maintaining a consistent exercise routine [15].

In particular, XR exergames encourage users to engage in physical activity, promoting cardiovascular health, muscle strength, and flexibility. Such experiences could be further enriched with other activities that could enhance an individual's cognitive stimulation, motivation, mental health, pain management, and even social interaction amongst others [16,17].

The combination of physical and virtual worlds provides a unique platform for developers of medical domain applications to introduce various cognitive challenges, such as problem-solving tasks, memory games, and spatial awareness activities. Engaging in these exercises can help maintain cognitive function and potentially slow down cognitive decline in older individuals.

Some VR exergames involve activities that challenge balance and coordination. This can be particularly beneficial for older individuals who may be at risk of falls or experience a decline in these skills. Improved balance and coordination contribute to better mobility and reduce the risk of accidents. However, this should be developed appropriately otherwise might pose additional dangers for the elder users. The proposed system described below has opted for a secure omnidirectional treadmill that stabilizes the user and prevents any potential fall or injury.

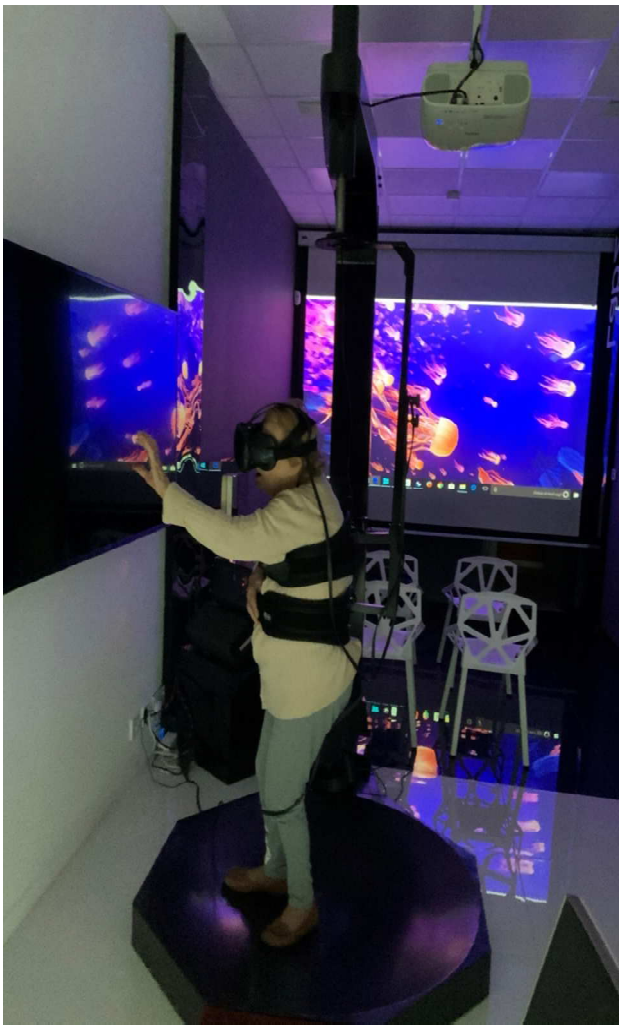

Fig1. Familiarisation stage: VR environment and Omnidirectional treadmill

In the case of rehabilitation after an injury or post-operation, XR applications can provide a distraction and a positive focus, helping to manage pain perception. This could also be useful for older individuals dealing with chronic pain conditions. The immersive nature of VR places can create an environment that takes the mind off discomfort during exercise.

Finally, the addition of multiplayer experiences allows older individuals to connect with friends, family, or even other users online. Social interaction is crucial for mental well-being, and XR applications can provide a sense of community, reducing feelings of isolation.

IV. XR Application Design and Implementation

The use of the aforementioned technologies offers a promising solution in utilising technological advancements to address the physical and mental health needs of older adults.

The proposed system was designed to attract the attention of the user with the level of photorealism presented in the immersive VR environment developed to resemble an easy walk in the park.

The buildings included in the scene were utilised as anchoring points for measuring purposes both for the user and the application. The user could visibly perceive the distance achieved from a building at the early stages of rehabilitation and gradually perform longer walks, potentially around or inside the building.

At later stages of rehabilitation or walking exercises the user could explore the space between the buildings or wander in the Scottish countryside. The latter was designed as a seamless infinite plane that was randomly expanding offering the opportunity to the user to walk or run significant distances.

The gamification aspect appears through different tasks that need to be completed and collect points in relation to the number of steps and speed of completion. These tasks involve either simple activities such as walking on specific routes or distance, or treasure hunting. This game activity requires the user to find specific objects within the buildings or in the park area.

The combination of the VR environment with physical activity and monitoring of the user's performance offers immersive experiences while engaging in therapeutic exercises. By simulating various environments and activities, users can improve mobility, strength, and balance in a safe and enjoyable manner.

This application allows elder users to stay active and independent, reducing the risk of falls and other age-related health complications. Moreover, the interactive nature of XR can enhance motivation and adherence to exercise routines, promoting better overall well-being. Additionally, healthcare professionals can remotely monitor progress and tailor interventions to individual needs, ensuring optimal outcomes [13, 18].

A. Software Requirements

1) Unreal Engine: The application has been developed primarily with the use of Unreal engine which offered a major advantage related to the photorealistic 3D visualisation of the virtual environments.

2) Gait Analysis software: A prototype application was also embedded in the process to trace the user's motion and produce analytical information on gait analysis [13,18].

3) Positioning Software: Proprietary software was provided by the omnidirectional treadmill company for the translation of the user's position in the virtual world and for tracking the gait and pace of the user's walking and running pattern.

4) Photogrammetry Software: Agisoft software was utilised for the translation of the photogrammetry data to a point cloud for each of the structures entailed in the final VR environment.

5) Visualisation software: A number of software packages such as Maya, Substance and Photoshop amongst others were used to produce the final, photorealistic 3D models.

B. Hardware Requirements

The complete hardware system was comprised of multiple types of equipment such as the omnidirectional treadmill, sensors, VR Head-Mounted Display and custom personal computer (PC) that was running the application.

1) Omnidirectional treadmill: The treadmill has been utilised as the main structure that could enable the user to walk or run in any direction whilst being stabilised and secure at the same spot. The omnidirectional treadmill was a custom design developed to support rehabilitation exercises. A multi-point secure harness supports the user through any physical movement, and in an emergency, it could lift the full weight of the user, up to 150 kg. The equipment offered a comfortable yet safe space to exercise whilst all the cables for the VR Headset were fed from a metal structure above the user's head rendering them invisible. The particular treadmills allow better movement in any direction imitating real-world motions that could be translated into a realistic movement in the virtual environment [19].

2) Drone: The VR environment replicates photo-realistically an existing area near Edinburgh. All the surrounding buildings' details and terrain were recorded through aerial photogrammetry with the use of a drone (DJI Inspire 1A). The final result presented photorealistic 3D models with high-resolution textures.

3) Custom PC: Although the 3D models were optimised it was still difficult to operate through wireless VR Headsets. As such, it was deemed essential to power the application from a custom PC with a powerful graphics card to support the complex 3D environment models.

4) VR Headset: The visual immersion was provided by a HTC Vive Pro VR Headset. The reason for using the particular equipment was the ability to perform at a high Frames Per Second (FPS) rate due to the connectivity to the desktop computer described above. In this way, the user could explore and exercise in a highly photorealistic environment. The complete system was designed to be portable to facilitate home-based exercise, eliminating the need to travel to a rehabilitation centre, gym or exercise class. This convenience is especially beneficial for older individuals who may face mobility challenges or prefer the privacy of home-based workouts.

V. Evaluation

To identify the user's experience and acceptance of such a system in contrast to their experience with the traditional rehabilitation methods.

1) Evaluation Process: The evaluation process entailed a Pre-test questionnaire, a familiarisation round (5 minutes), a 10-

Fig 2. Participant walking in the VR environment with the use of the Omnidirectional treadmill.

minute walking exercise (the main experiment) and the post-test questionnaire.

The pre-test questionnaire gathered the demographic users' information, their prior experience with XR and the typical steps' score required for their daily rehabilitation treatment.

The familiarisation round provided ample time for the participants to explore the controls and VR immersion in a different environment.

2) *Experiment Rationale:* This experiment focused primarily on the steps required and achieved daily by each participant using the typical methods of walking in short proximity in a dedicated space or at home.

Maintaining a simple task was essential at this stage as the project aims to identify how users perceive the use of XR applications.

Being mindful of the plethora of exercises and requirements of different rehabilitation cases it is a future plan to gradually enrich the initial application with additional more complex and specialised exercises.

3) *Participants:* Ten participants, 65-88 years old, (6 female, 4 male) volunteered to evaluate the proposed XR application. All the participants had minimal computer and technology literacy. This created a homogenous group and reduced potential bias, concerning the application scenario of the proposed prototype system.

VI. Results and Discussion

The feedback provided in the post-questionnaire section of the evaluation offered valuable insight into the user's experiences, concerns and future requirements for future system iterations. The post-questionnaire statements are presented in Table I below.

TABLE I. Post Questionnaire Results

No	*Statements*
Q1	The VR application is easy to use.
Q2	The VR application is easy to navigate and control.
Q3	I find the VR environment a calm place to exercise.
Q4(-)	I find the VR environment uncomfortably immersive.
Q5	I would like to experience other VR places as well.
Q6	It is easy to perform the exercises on the Omnidirectional Treadmill.
Q7 (-)	I feel uncomfortable using the Omnidirectional Treadmill.
Q8	I feel safe using the Omnidirectional Treadmill.
Q9	I feel more motivated to engage in rehabilitation exercises using the VR application compared to traditional methods.
Q10	I would like to meet, socialize and exercise virtually with other people in the VR environment.

A final (Q11) statement/question was an open question aiming to attract additional comments or feedback that the users would like to provide about their experience. Some of the users' comments

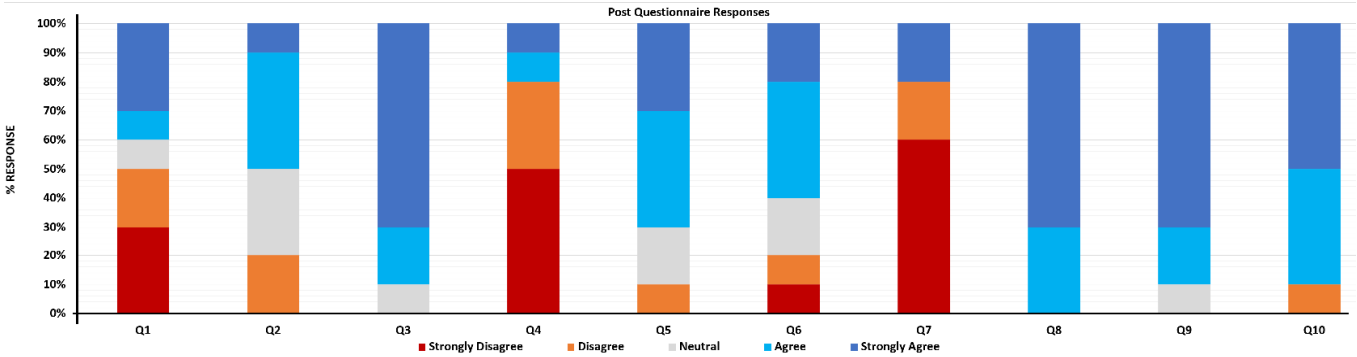

Fig 3. Post-Questionnaire responses of the senior users evalaution.

The analysis of the evaluation results is presented in Figure 3. In particular, Q1 had mixed responses where the ease of use of the application scored almost equally between agree (40%) and disagree groups (%50). This could potentially reflect that some of the users are not familiar with such technology and rather apprehensive of the seemingly complex hardware surrounding them.

The Q2 presented a more positive outcome as 50% of the participants felt that it was easy to navigate and control the application whilst 30% were neutral in their response. These participants responded to the open-ended question (Q11) that probably thought further familiarisation would feel more capable of controlling and navigating through the application. Q3 returned 90% of positive results signifying that the open space in the park with traditional buildings in the Scottish countryside was indeed a calming environment for the users.

The negative questions introduced on the questionnaire (Q4 and Q7) highlighted a strong positive outcome in support of the proposed XR application. Q4, in particular, highlighted that the high-resolution immersive environment was welcomed and did not create any visual or auditory discomfort.

Similarly, Q7 offered a reassuring outcome of 80% disagreeing with the statement. The use of the omnidirectional treadmill combined with the VR environment was a comfortable experience that they would like to repeat. However, some users (20%) felt that the support vertical structure that was holding the harness and their weight was very rigid and straight. This was creating discomfort as some users had spinal deteriorations. This issue could be further explored with the use of more flexible materials for the support of the harness that could follow a larger variation of body postures.

This might be attributed to the fact that Q8 returned 100% positive responses emphasizing the feeling of safety provided by the omnidirectional treadmill structure. The robust metal column and the multipoint safety harness were significant support physically and psychologically for the users who felt secure and free to walk without the fear of falling.

Q5 acquired also positive answers, 70%, supporting the idea of developing multiple real-life environments to improve the variety of exercise places and potentially adding a touristic or educational element in the process.

Q6 followed the positive pattern of responses. Equally to Q7 and Q8, the particular statement presented a positive (60%) user perception concerning the ease of use of the omnidirectional treadmill. The 20% of neutral and negative responses were from the older users of the group who felt unsure about how to step into and operate the treadmill. Potentially this could be resolved with a different design of treadmill floor that could be flat and closer to the ground.

The motivation of the users to exercise more as they explore the virtual environment was presented by the 90% positive responses of Q9. Finally, the 90% positive replies on Q10 reinforced an initial hypothesis during the development of the prototype related to the added value of such a system offering a virtual place for socialising or exercising with friends and family. This could further expand as a common meeting place from the comfort of their home especially if they have limited mobility or overcoming difficult periods to socialise such as the recent pandemic.

8 Conclusions

This paper explored the impact of the XR application focusing on exergames for rehabilitation. The paper presented the design rationale and development of an XR application. The evaluation of the system by ten senior users offered encouraging results. These highlighted that the combinatory approach of physical and virtual activities within an immersive and photorealistic VR environment offers an enticing and motivating approach to elder users to improve their physical well-being.

The system and evaluation limitations were primarily related to the hardware used, which lacked the flexibility to adapt fully to users' physical characteristics and movement constraints. These limitations were reflected in the negative aspects highlighted by users' feedback and post-test interviews Furthermore, the availability of elder users requiring such rehabilitation is also a limiting factor as they cannot be transported easily to the evaluation space, affecting the granularity of the evaluation results.

Their suggestions will form a plan for future actions and development to improve further the accessibility and adaptability of the XR application. Stemming from these evaluation outcomes the consequent experiments will require larger participants' numbers to improve the granularity of the results.

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