Virtual Rehabilitation for Patients with Osteoporosis: Translating Physiotherapy Exercises into Exergames

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Abstract

Osteoporosis affects over 200 million people worldwide; osteoporotic fractures occur every three seconds. Physical therapy is a non-pharmaceutical approach to improving; muscle strength, balance and flexibility, thereby reducing the risk of falls and fractures. However, engagement in physical therapy can be challenging due to factors including accessibility, cost, fear and/or boredom. Virtual rehabilitation, incorporating extended reality, and exergames, has emerged as a promising solution to enhance and address engagement issues with traditional physical therapy. In this paper, the authors propose a set of five safe and clinically approved physical exercises targeting older adults with osteoporosis. Underpinned by guidelines derived from a systematic review on virtual rehabilitation and compliant with HSE care guidelines and the concept of 'good' movement, these exercises were reproduced in AR as exergames using the Microsoft Hololens 2 head-mounted display and the Azure Kinect camera. Through the integration of expert knowledge and technology, this research contributes to the development of adapted virtual rehabilitation interventions for patients with osteoporosis.

Keywords: Augmented reality, Rehabilitation, Osteoporosis, Exergames, Physical therapy.

1. Introduction

Today, more than 200 million people suffer from osteoporosis [Sözen, 2017]. One in three post-menopausal women and one in five men over the age of 50 years old are at risk of an osteoporotic fracture during their lifetime. These fractures can result in substantial morbidity, mortality and financial costs [McCabe, 2020; Sözen, 2017]. Given the significant societal and personal burden imposed by osteoporosis, novel approaches which improve quality of life and reduce healthcare costs for people with osteoporosis deserve further investigation [Sözen, 2017].

Physical therapy is an important non-pharmaceutical intervention which improves strength, balance and flexibility, helping to manage pain and reduce the risk of falls and fractures [Dionyssiotis, 2014]. However active engagement with physical therapy can be problematic due to environmental (accessibility, cost, time), physical (risk of falling, difficulty in movement, co-morbidities) and mental factors (fear, boredom or motivation) [Obuko, 2018]. Visual assessments of movement quality by physiotherapists can be accurate and reliable for rating various movements, such as gait [Whatman, 2012], but the quality of these assessments depends on the knowledge, skill and experience of the physiotherapist [Whatman, 2012]. This is one reason virtual rehabilitation is gaining popularity as an alternative or complementary solution to physical therapy [Amanda, 2014].

Virtual rehabilitation refers to any rehabilitation or recovery process which includes the use of a virtual technology (e.g., Virtual reality (VR), Augmented reality (AR), or other digital technologies). Virtual rehabilitation is used to enhance traditional rehabilitation and improve cognitive and/or physical skills [Peng, 2011]. Whilst VR immerses the user in a fully virtual environment, AR overlays digital information onto the real world [Bouchard, 2014]. Exergames are a type of video game or multimedia interaction which requires the player to physically move in order to play [Oh, 2010]. Studies show that exergames can improve physical (balance, strength, fall risk) and cognitive (fear, motivation, memory) function in older adults [Amanda, 2014]. Feedback during exergame participation is key to effective virtual training, similar to physical therapy where the therapist guides and supports the patient's movement, posture and participation [Alnajjar, 2019].

Feedback is typically categorised as visual, auditory, and haptic [Lee, 2017], while provision of timely and useful feedback ensures patients are effectively supported [Doyle, 2011]. We didn't find exergames designed specifically for osteoporosis patients in a systematic literature review. In this paper, we present the integration of an extensive systematic literature review and communication with health and social care experts (i.e., Physiotherapists (PTs), Occupational Therapists (OTs) and Rheumatologists) to design of novel exergames for patients with osteoporosis, with the aim of reducing their risk of fall and fracture.

Note: This paper only presents the design decisions prior to exergame development and testing.

2. Method

In the process of translating approved physical therapy exercises into a set of five exergames for patients diagnosed with osteoporosis, we based our technology choices and game design considerations on:

- Guidelines resulting from a prior systematic review on virtual rehabilitation.
- Input from health and social care experts to ensure that the exergames are suitable and do not put patients at risk of fall or injury and are compliant with HSE care guidelines.
- Further collaboration with a chartered PT regarding 'good movement' and feedback.

Following the PRISMA guidelines our systematic literature review included 23 articles for final analysis from 130 at initial selection. The key results and advice of health and social care experts underpin:

- The choice of adapted, safe, and clinically approved training exercises.
- The definition of overall 'good' movement and its implication for people with osteoporosis,
- Instruction and feedback between patients and physiotherapists during training sessions.

In this paper solely we present considerations and justifications in the design process of our exergames.

3. Design Process and Decision Justification

3.1 Designing an adapted set of exergames for people with osteoporosis.

In our study a final set of five physical training exercises were agreed by a chartered PT, an OT and two Rheumatologists at Galway University Hospital. These exercises target older adults with osteoporosis and comply with HSE care guidelines [Brosna, 2020]. Their aim is to improve physical outcomes such as; muscle strength, flexibility, and balance, for those diagnosed with osteoporosis by Dual-energy X-ray Absorptiometry (DXA) criteria (T-score $\leq$-2.5) per International Society for Clinical Densitometry (ISCD) modifications (postmenopausal women and men aged 50 years and older). These exercises are represented in Table 1, in addition to an associated instructional narrative as provided by the PT to his patients.

Exercise	**Instructions from the PT**
Sit to stand (with a chair)	Context: A chair is placed against a wall. The person sits in the chair. "*Sit on the chair. Interlace your fingers and reach forward with your arms. With your feet slightly apart and your hips at the edge of the chair seat, lift your hips up from the seat to stand. Slowly return to sitting.*"
Squat (with a chair) comprises squat on a chair	Context for the squat on a chair: The person stands on front of the chair. "*Perform a squat by initiating the motion of pushing the hips back and then following this, by bending the knees. Keep your back straight and touch the wall lightly with your buttocks without resting on the wall. Come back up, keeping your back straight at all times.*"

and partial squat	Context for a partial squat: A chair is placed in the middle of the room. The person stands behind the chair with their hands on it. "*Hold the chair in front of you with your hands. Perform a squat by initiating the motion. Push the hips back and then follow this by bending the knees. Keep your back straight and touch the wall lightly with your buttocks without resting on it. Come back up, keeping your back straight at all times.*"
Opposite arm and leg lift (with a chair)	Context: A chair is placed anywhere in the room. The person sits in the chair. "*Sit with your back in a neutral position (slightly arched); your chin must be tucked in. Slightly tighten your abdominals, lumbar muscles and pelvic floor muscles, then lift one arm and the opposite leg without allowing the trunk or pelvis to move or rotate.*"
Arm raises (with or without a chair)	Context for arms raises with a chair: A chair is placed against a wall. Ensure that there are no obstacles to either side of the chair. The person sits in the chair. "*Sit-up straight and lift both arms thumb up at the same time, keeping the thumbs up. Lift to shoulder's height."*
	Context for arms raises without a chair: The person stands with more than an arm's length of space to their left and right. A chair is placed on front of them in the event that they may feel unsteady. "*Stand up and lift both arms thumb up at the same time. Lift to shoulder height. Ensure to maintain thumbs up.*"
Step up comprises Step up and Sidestep up	Context for step up: The person is standing. "*Stand up and take a step with one leg. Then bring the leg back to the starting position. Be careful of putting the foot entirely on the step.*"
	Context for sidestep up: The person is standing. "*Stand up and take a sidestep with one leg. Then bring the leg back to the starting position. Keep your pelvis levelled (making sure you do not hip hang).*"

Table 1: Set of exercises with associated instruction.

3.2 Technology choice and exergame design

Based on the results from our systematic literature review, we were able to determine guidelines and criteria for the technology choice and the exergame design. The comparison of four types of devices (Head-mounted display (HMD), body tracking camera, balance board and specific device) in this review and their evaluation through criteria such as: immersion, effectiveness in training, global body tracking, engagement, comfort, and interaction, guided us in selecting the Microsoft Hololens 2 HMD and the Azure Kinect body tracking camera. The exergame design took into account both the limitations arising from the target audience's vulnerability (related to osteoporosis) and the guidelines provided by existing literature and HSE. As such, design considerations included:

- The design of positive game features [Vanden, 2021; Blomqvist, 2021] i.e., positive, colourful, non-aggressive content (see Figure 1 for the prototype of each game) and immersive sounds.
- The possibility for content personalization [Andreikanich, 2019] through adapting the game to the needs of the player (e.g., type of virtual objects, level of difficulty etc.).
- Movement variability adaption based on the physical ability of the patient (see Section 3.3)
- The provision of positive and easy to understand instruction and feedback [Vanden, 2021].

Detail on the exergames is provided in Table 2, with the conceptual exergames' designs presented in Figure 1. During a training session, patients will participate in each of the five exergames. They will be able to choose whether they want to follow the pre-determined 'scenario' or select the exergames in any order. The 'Sit to stand' game is the only exergame presented in third person view to ensure a continuity of immersion, support interaction and mitigate against the risk of boredom during training.

Physical exercises	**Conceptual exergames description**	**Camera position**	**Starting position**
Sit to stand	Third person platform game. The participant moves a character from one platform to the next (up and down) by standing down and sitting. Main goal: To progress on the path.	In front	Seated on a chair. Position: Facing the virtual platform.

Squat	First person game. The participant is required to squat to avoid the cloud coming in front of his/her eyes. Main goal: avoid the virtual object (e.g., cloud).	On the side	Seated on a chair. Position: Facing the virtual object.
Opposite arm and leg lift	First person game. The participant is required to lift the correct body part (right/left arm/leg) to hit the ball coming in front of their eyes. Main goal: Hit the virtual object (e.g., ball).	In front	Seated on a chair. Position: Facing the virtual object.
Arm raises	First person game. The participant must raise his/her arms to help the (virtual) bird to fly in front of their eyes. Main goal: Move the virtual object (e.g., bird).	In front	Seated on a chair. Position: Facing the virtual object.
Step up	First person game. The participant must step over a virtual obstacle coming on the floor in front of them. Main goal: Avoid the virtual object (e.g., rock).	In front	Standing. Position: Facing the virtual object.

Table 2: Conceptual exergame description.

Figure 1: Prototype of each exergame (from left to right: opposite arm leg lift, arm raises, squat, step up, sit to stand)

3.3 ‘Good’ movement in physiotherapy and in games

Notwithstanding the accruing positive cognitive and physical benefits of exercise, it is not atypical that participants can use improper techniques when performing exercises e.g., they are executed too fast, too intensely and/or with an incorrect position [ACSM, 2021]. A lack of adherence to correct posture, intensity and breathing can result in injuries [ACSM, 2021]. Consequently, whilst an ‘appropriate pace’ is critical, it might differ for each patient, as proper pace and alignment depend not only on the exercise but also on the ability of the patient. This is of particular importance in the context of frail patients. Through discussion with the chartered PT, ‘good’ movement is defined as exercise movement made with appropriate pace and alignment and which are suitable to the patient in question. Movement variability refers to the nonlinearity in movements which can occur over multiple repetitions [Harbourne, 2009]. In the context of physical therapy, it is important that a PT shouldn’t and won’t expect the patient in a training session, to repeat the movement in the exact same manner each time [Harbourne, 2009]. It is important to consider this concept of movement variability when designing both physical and virtual training as movement variability directly influences both the learning of the movement and the movement’s accessibility. To cater to movement variability, the human body is divided into biomechanical points which can be checked for alignment to ensure that the exercise is correctly executed. Biomechanics is the science of the movement of the human body [Raiola, 2020]. Table 3 presents the biomechanical points to be checked to ensure correct alignment to the five selected exercises used in our study (based on advice from the PT).

Exercise	**Biomechanical point to check for alignment**
Sit to stand	Spine - hip, Shoulder - hip (for osteoporotic patient)
Squat	Spine - hip, Shoulder - hip (for osteoporotic patient)
Arm raises	Elbow to wrist, No bent elbow

Opposite arm and leg lift	Shoulder-elbow-knee
Step up	Knee angle - hip, No need for a strictly exact movement

Table 3: Biomechanical points to check for alignment for each exergame.

The biomechanical points in Table 3 can be directly translated to the Azure Kinect, as the Azure Kinect body tracking SDK can track a participant's skeletal representation using 31 joints (Figure 2).

Index	Joint name	Index	Joint name
0	Pelvis	20	Ankle Left
1	Spine Naval	21	Foot Left
2	Spine Chest	22	Hip Right
3	Neck	23	Knee Right
4	Clavicle Left	24	Ankle Right
5	Shoulder Left	25	Foot Right
6	Elbow Left	26	Head
7	Wrist Left	27	Nose
8	Hand Left	28	Eye Left
9	Hand tip Left	29	Ear Left
10	Thumb Left	30	Eye Right
11	Clavicle Right	31	Ear Right
12	Shoulder Right		
13	Elbow Right		
14	Wrist Right		
15	Hand Right		
16	Hand tip Right		
17	Thumb Right		
18	Hip Left		
19	Knee Left		

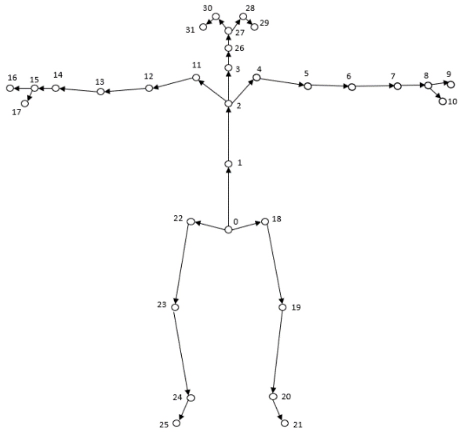

Figure 2: Body joints with Azure Kinect body tracking

In this research, correct alignment within each exergame will be measured by calculating the angle between the equivalent joint/biomechanical points. Care will be taken in leaving an appropriate threshold based on;

- Movement variability.
- Error and/or approximation (human and/or Azure Kinect).
- Ability of each participant - as not every patient might not be in the same physical condition.

Note: The PT will assess the patients in advance of using the exergames, in order to identify individual thresholds. The exergames will then be modified on the basis of this evaluation.

3.4. Implementation of PT's feedback in the Exergames

Feedback provides information and guidance to players, thereby impacting their learning, motivation and engagement [Boyer-Thurgood, 2017; Gautier, 2022; Johnson, 2022]. Feedback can be delivered through different modalities, including auditory, visual and haptic [Boyer-Thurgood, 2017; Gautier, 2022; Demain, 2012; Menelas, 2017]. The type of modality is dependent on the game's context and aim. As an example, auditory feedback may be more effective than visual feedback in highly visual games, as it will keep players' visual processing system from being overloaded [Gautier, 2022]. Feedback features (e.g., modality, duration, type etc.) are important as they respond to players' actions and provide information on their performance. Within the context of physical therapy, feedback from the PT is one of the key elements of effective physiotherapy. Indeed, [De Souza, 1990] highlighted the importance of the PT in providing a supportive and advisory role. Feedback from a PT to a patient during a training session can be divided into; direct feedback (i.e., verbal comments/advice on current movement, and physical re-positioning) and indirect feedback (i.e., instruction which is not directly related to the movement e.g., 'be careful that the chair is against the wall' and other safety cues). Focussing on the set of five exercises presented previously, Table 4 outlines direct and indirect in-person feedback given by a chartered PT during a training session. Table 4 also highlights how this in-person feedback can be translated to in-exergame feedback.

	General	Sit-to-Stand	Squat	Arm raises	Opposite Arm and Leg Lift	Step up
Example of in-person feedback	**Direct**: "Breathe", **Indirect**: "Keep eye contact with the PT", "Ensure a safe space around you during training"	**Direct:** "Align your forehead to your knee", "Sit up straight" **Indirect:** "Use a chair against a wall to prevent it from slipping"	**Direct**: "Keep your back straight"	**Direct**: "Squeeze your shoulder and keep your tummy/stomach back", "Extend your elbow" If seated, "Sit up straight"	**Direct**: "Sit up straight"	**Direct**: "Take your time", **Indirect**: "Check your foot position while stepping", "Do you have need of other supports?"
Example of in-game feedback	**Direct:** "Breathe", "Don't hesitate to take a break if necessary", **Indirect:** "One more…", "You are doing well", etc.	**Direct:** "Remember to sit up straight", **Indirect:** "Be careful that your chair is placed with the back against a wall"	**Direct:** "Remember to keep your back straight"	**Direct:** "Remember to sit up straight", "Remember to stand straight"	**Direct:** "Remember to sit up straight", **Indirect:** "Well done, now repeat it with the right/left leg/arm"	**Indirect**: "Take your time to step over the rock"

Table 4: Feedback from the PT to the patients.

Visual feedback in the exergames will be provided by:

- Displaying a score to indicate performance (e.g., number of repetitions performed) and success (e.g., number of correctly performed repetitions).
- Providing feedback on the current posture (e.g., 'Maintain the pose for two more seconds') and/or participation in the game (e.g., 'Keep your arms raised to allow the bird to fly higher').
- Providing real-time visual reaction to the action on the screen (e.g., in the arm raise exercise, the bird may fly in reaction to the player's movement. In the sit to stand exercise, the virtual character moves from one block to the next).

Meanwhile, audio feedback using music, and sounds will enhance the player's experience and provide additional cues and/or feedback related to the activity or game being played.

4. Conclusions

Worldwide, osteoporosis is a significant challenge for more than 200 million people. Existing research shows that virtual rehabilitation and exergames present promising opportunities to enhance traditional physical therapy by increasing motivation and enjoyment. By translating physical therapy into exergames to be played using an Hololens 2 HMD and Azure Kinect, this research focuses on the design of an adapted physical training programme for older adults with osteoporosis. To ensure the suitability of the exergames, we integrated HSE care guidelines and the expertise of health and social care experts (i.e., PTs, OTs and Rheumatologists). Underpinned by their recommendations, a set of five safe exercises was selected to improve players' balance, muscle strength and flexibility. These physical exercises were then mapped onto a series of conceptual exergames. A systematic literature review on virtual rehabilitation provided guidelines regarding the choice of the technology and the design of the exergames, within the context of usability, comfort, and personalization. Based on this review and technology evaluation via criteria such as; immersion, effectiveness in training, global body tracking, engagement, comfort and interaction, the Microsoft Hololens 2 HMD and Azure Kinect body tracking camera were selected. Meanwhile, ongoing interactions with a chartered PT supported the definition of 'good' movement i.e. movement made with a proper alignment at a proper pace. This definition will help us to define correct movement in the exergame environment. Moreover, the calculation of the angle between the equivalent joint/biomechanical points for each exercise will help to ensure correct alignment.

In this paper, we also discussed the importance of feedback in supporting patients in their training. We propose to use both visual and audio feedback in the exergames. Written exergame feedback will be based on direct feedback given by a PT during a physical training session. In future work, we plan to investigate the impact of a training programme where patients with osteoporosis engage with the exergames, for twice weekly 20-minutes sessions over a period of six weeks.

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