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Recov-R: Evaluation of a Home-Based Tailored Exergame System to Reduce Fall risk in Seniors

STEPHEN UZOR, University of Cambridge
LYNNE BAILLIE, Heriot-Watt University

Rehabilitation has proven effective to significantly reduce fall risk in seniors; however, low adherence to home rehabilitation and a lack of feedback on performance and progress indicate that seniors might not receive the amount of therapy necessary to reduce their risk of falling. We present a tailored exergame system for the home (called Recov-R) to motivate seniors to exercise and facilitate effective recovery by promoting optimal quality of movement during exercise. Based on an 8-week field study, with 38 participants, we present results on the use of the Recov-R system, versus standard care, in the home. Our findings suggest that the use of the system can increase adherence to exercise and reduce fall risk by improving outcomes of physical function – mobility and balance. We also highlight opportunities, based on these results, for the design of effective exergame technologies for musculoskeletal rehabilitation in the home.

CCS Concepts: • Human-centered computing → Field studies; Empirical studies in HCI

KEYWORDS
Exergames, Falls, Tailored Games, Rehabilitation, Quality of movement, Home study, Balance and strength therapy

1 INTRODUCTION

Approximately 33% of adults over the age of 65, and half of those aged 80+, fall at least once a year [Gillespie et al. 2012; Tinetti et al. 1994]. In minor cases, a fall may not lead to any serious injuries; injurious falls on the other hand may lead to fractures in the wrist or, in more serious cases, the hip. Both injurious and non-injurious falls may result in disability, loss of independence and confidence, and a fear of falling [Delbaere et al. 2010; Skelton and Todd, 2004]. There has been a push, in recent years, towards the implementation of effective strategies to reduce the risk of falls (or fall risk) and promote independent living in seniors. Recent evidence suggests that impairments in muscle strength and balance are the most prevalent and readily modifiable risk factors for falls [Sherrington et al. 2011] and that the most successful way to reduce the rate, and risk, of falls is through a multifactorial intervention, involving the use of specially tailored exercises (physical rehabilitation), to improve strength and balance in seniors [Gillespie et al. 2012; Sherrington et al. 2011].

In many western countries, the most commonly used rehabilitation programmes are based on the Otago Exercise Programme (OEP) [Campbell et al. 1997; Robertson et al. 2001], and the Falls Management Exercise (FaME) programme [Skelton et al. 2005]. The OEP and FaME have been shown, in randomized controlled trials, to reduce fall risk in seniors by over 30% [Campbell et al. 1997; Robertson et al. 2001; Gardner et al. 2001; Skelton et al. 2005]. The exercises contained in both programmes facilitate recovery through repetitive limb movement through particular ranges of movement, to improve muscle strength and balance [Allen et al. 2010]. Seniors can engage in physical rehabilitation, using OEP or FaME, either through physiotherapist-led group therapy sessions, or in the home, using standard care – delivered through booklets (Fig. 1) and videos. Since these exercises are repetitive in nature, people often feel a lack of motivation to exercise [Nyman and Victor, 2012]. Another further problem is that falls rehabilitation is unsupervised; therefore, the absence of therapist...
guidance in the home raises concerns about correct, and safe, movement during exercise [Alankus et al. 2010; Doyle et al. 2010].

Digital games, designed to encourage physical activity or exercise, commonly known as exergames, have seen increasing use in recent times to overcome the aforementioned problems in a variety of musculoskeletal conditions, such as upper limb therapy in stroke [e.g. Alankus et al. 2010, Burke et al. 2010; McNulty et al. 2011] and falls [e.g. Lange et al. 2011, Pietrzak et al. 2014; Uzor and Baillie, 2014]. Most notably, exergames are designed to encourage a less monotonous, and more engaging, experience for users as well as promote improved outcomes of physical function. Due to their relative low cost, commercial exergame platforms (such as the Nintendo Wii and Microsoft Kinect exergames) have seen some success in the rehabilitation space [Saposnik et al. 2010; Sugarman et al. 2009; Laufer et al. 2014; Yong Joo et al. 2010] despite having been designed for a non-specific mass-market audience. However, in the rehabilitation space, this happens to be one of the main drawbacks of commercial games – since they were not designed for rehabilitation, they do not focus on recovery of joint movement, muscle strength and balance in musculoskeletal conditions where particular movements are required for effective therapy, such as in the OEP or FaME programmes [Uzor and Baillie, 2014]. Indeed, it is difficult to determine the effects of commercial exergames (e.g. Wii Fit) on strength, balance and mobility due to differences in methodologies and outcomes used in Wii-related studies [Laufer et al. 2014].

Tailored exergames have been used to address this problem – tailored in the sense that movements required for play are identical to those necessary for effective therapy [Alankus et al. 2010]. Such exergames have been successful at motivating seniors to exercise and improving physical function in conditions such as: stroke [Alankus et al. 2010, cerebral palsy [Hernandez et al. 2013], step reaction [Schoene et al. 2013] and falls [Gachwind et al. 2014; Rademaker et al. 2009; Uzor and Baillie, 2014; Vaziri et al. 2017]. Despite these advancements, there are still gaps in the literature on the effectiveness of exergame technologies for falls, compared to standard (current) rehabilitation care employed in real-world health practice. This investigation is necessary in the sense that it is important to promote effective evidence-based therapy in falls while motivating seniors to adhere to falls rehabilitation programmes in unsupervised scenarios – e.g. the home.

In this paper, we first present a background to our research with a summary of the problem of falls, and its risk factors, and by highlighting recent advancements in exergame-based technological solutions for falls therapy. Following this, we describe the Recov-R system, which was designed to deliver tailored exergames based on evidence-based falls rehabilitation programmes used in health practice in the UK and many other western countries. The Recov-R system comprises of a laptop computer and inertial motion sensors, and it was designed to enable seniors to easily play games, check their progress and receive medals based on this progress and other achievements in home rehabilitation. We discuss the procedure and results.
from a randomized controlled home study to evaluate the use of the Recov-R system with 38 seniors over a period of 8 weeks. The paper ends with a discussion on the home study findings, which provides insights into opportunities for the design of effective tailored exergame systems to prevent falls.

2 BACKGROUND

2.1 Falls and Risk Factors

Falls are one of the leading causes of death and disability, with 1 in 3 seniors over the age of 65 years affected each year [Skelton et al. 2005]. The literature on falls outlines a number of both intrinsic and extrinsic risk factors that increase one’s risk of falling [Graafmans et al. 1996; Sherrington et al. 2011; Skelton and Todd, 2004], and potentially sustaining a fracture [Tinetti et al. 1994]. It is logical, therefore, that reducing one or more of these risk factors could lead to a corresponding reduction in fall risk, and as a result, falls incidents. Extrinsic (also known as environmental) fall risk factors, e.g. type of footwear, slippery surfaces, etc. [Lord and Sherrington, 2000], are influenced by the environment and can be addressed through careful interventions to ensure safety, both in the home and outside [Sherrington et al. 2011]. Intrinsic fall risk factors, on the other hand, affect a person directly, and these can include: multiple medications taken simultaneously [de Jong et al. 2013], poor eyesight [Skelton and Todd, 2004], balance impairments and a decline in muscle strength [Cho and An, 2014].

Reduced muscle strength (in the lower extremities) and balance impairments, normally associated with aging, have been found to be the most prevalent and readily modifiable fall risk factors [Campbell et al. 1997; Skelton and Todd, 2004]. To combat this problem, it is recommended that seniors should engage in a total of over 50 hours of physical rehabilitation exercise [Sherrington et al. 2011]. Researchers have recently developed exercise programmes shown to be effective at reducing this decline in muscle strength and balance. The two main programmes include the Otago exercise programme (OEP), supported by evidence from several randomized controlled trials [e.g. Campbell et al. 1997; Campbell, 1999; Robertson et al. 2001; Liu-Ambrose et al. 2004] and the Falls Management Exercise programme (FaME) [Skelton et al. 2005]. Health services in western countries are currently adopting exercises from these programmes into standard care for physical rehabilitation in falls [Uzor and Baillie, 2014], e.g. the UK National Health Service (NHS).

2.2 Home Rehabilitation

In the UK, seniors who have been hospitalized, after a fall, are often referred to the NHS falls service post-discharge; at this stage, they are asked to attend a 12-week physiotherapist–led group exercise class using the OEP and FaME. Following on from group therapy, seniors are expected to continue to exercise in the home [Uzor et al. 2011; Uzor et al. 2012]. The exercises are usually delivered through booklets and videos, depending on an individual’s preference. A typical booklet or exercise video used in UK homes (as at April 2019 – see Fig. 1) consists of ‘warm–up’ and ‘cool–down’ exercises, to loosen muscles and prevent injury, as well as a number of main (strength and balance) exercises – e.g. the exercises listed in Table 1. In accordance with current research evidence and practice, which advocates for 2 hours of moderate–intensity exercise per week [Robertson et al. 2001], seniors who are at risk of falling are required to complete the entire exercise programme, at least 3 times a week [Uzor et al. 2011; Uzor et al. 2012]. Our research is concerned with the development of technologies to reduce fall risk in seniors; therefore, programmes such as the FaME and OEP (used in current standard practice) provided as a suitable foundation to satisfy this goal.

2.3 Quality of Movement and Effective Therapy

The OEP and FaME rehabilitation programmes achieve their effectiveness by ensuring quality of movement (QOM) during exercise, which is key to maximizing the potential for recovery [Ayoade and Baillie, 2014]. QOM in a rehabilitation sense consists of 2 key factors: range and pace of movement [Uzor and Baillie, 2014]. Effective physical therapy, thus, comprises of ensuring QOM, and repetitive movements according to a set repetition count; we describe these essential components in this section.

2.3.1 QOM – Range of Movement (ROM)

The first main factor of QOM is range of movement (ROM); this defines the distance and direction that a limb should move naturally around its pivot joint and axis. Effective ROM, in falls, is not usually defined as set angles (e.g. bend the
knee 45 degrees) compared to other areas of physical therapy, e.g. knee rehabilitation [Ayoade et al. 2013]; rather it is based on individual capabilities. This is because seniors who fall have varied abilities that are relative to the particular risk factor, or combination of factors, affecting that individual. However, users are expected to achieve the joint angles (range of movement) sufficient for stimulating the required muscles/ groups [Uzor and Baillie, 2014].

2.3.2 QOM – Pace of Movement.

The second main factor of QOM is pace of movement; this is the speed at which a limb rotates around its pivot joint or axis. In falls therapy, it is important that the pace of movement is slow and controlled, both to avoid injury and to challenge muscles to a satisfactory extent [Gardner et al. 2001; Uzor and Baillie, 2014]. In certain OEP exercises it is also important to hold a limb in a particular position, for a certain amount of time, to maximize the effectiveness of the exercise. For instance, in Fig. 1, seniors are asked to hold a ‘half squat’ position for 3 seconds; this ensures that the thigh muscles become stronger than they otherwise would.

2.3.3 Repetition Count.

Repetition count is the final important factor in effective falls therapy. The number of times a limb is moved through a particular direction, and pace, ensures development and sufficient activity in targeted muscles. In the OEP, a 10-repetition count is considered a suitable baseline per exercise [Gardner et al. 2001]. In similar areas of physical rehabilitation, e.g. the knee, patients are also encouraged to perform up to 15 repetitions if they are capable of doing so [Ayoade and Baillie, 2014].

2.4 Technological Solutions for Physical Rehabilitation

Physical rehabilitation consists of repetitive limb movements necessary to regain lost physical function in the body; this leads to a potentially boring experience for users [Alankus et al. 2010; Jurkiewicz et al. 2011; Nyman and Victor, 2012; Radomski, 2011]. Consequently, maintaining adherence to exercise is one of the greatest challenges of rehabilitation, especially in the home where there is no therapist support or supervision. Thus, researchers have sought to implement more effective strategies to make rehabilitation more engaging, with the aim of promoting adherence. Such strategies have included the use of digital games to facilitate an enjoyable rehabilitation experience and to motivate seniors to exercise [Burke et al. 2010; Fitzgerald et al. 2010; Molina et al. 2014; Yong Joo et al. 2010; Ogonowski et al. 2016].

Computer, or video, games designed for the primary purpose of encouraging physical activity have been referred to as exercise games, or ‘exergames’ in the literature. This research area has gained momentum since the advent of affordable motion-based input solutions included with video game systems, such as the Nintendo Wii [Nintendo, 2019] and Microsoft’s Kinect [Microsoft, 2019]. One of the most common applications of the Wii in rehabilitation has been in stroke recovery [e.g. Alankus et al. 2010; McNulty et al. 2011; Saposnik et al. 2010]. For instance, in a study by [Alankus et al. 2010], Wii remotes were used as body worn sensors (on users’ upper and forearms), making it possible for users to control an in-game avatar. The Wii controllers contain a 3-axis accelerometer; hence it is possible to approximate the orientation of the sensor in 3-dimensional space. Both commercial and tailored (or customized) exergames have been studied for the purpose of facilitating an enjoyable rehabilitation experience for seniors; due to the vast literature on the topic, we discuss the most relevant studies.

2.4.1 Commercial Exergames in Falls Therapy Scenarios.

Closer to the area of falls, the use of Wii technology has been most prevalent in balance retraining [e.g. Agron et al. 2011; Nitz et al. 2010; Bieryla and Dold, 2013; Jorgensen et al. 2013]. Since impaired balance is one of the most common risk factors for falls [Rubenstein, 2006], balance retraining is an effective method for reducing fall risk in seniors [Nitz et al. 2010]. For instance, [Bieryla and Dold, 2013] used the Nintendo Wii Fit game 3 times a week for 3 weeks; their study showed that the Wii Fit training improved balance in some outcomes, but not others, with no overall significant improvement in fall risk. [Jorgensen et al. 2013] provided their participants with Wii training, in addition to muscle conditioning, over a period of 10 weeks. While there was a marked improvement in muscle strength, there was no significant difference in balance outcomes. However, the participants reported high levels of motivation to play the Wii games throughout the study.

In a preliminary study, using the Wii Fit in a nursing home for an average of 12 days, [Laver et al. 2011] found improvements in outcomes of balance and mobility in both study groups (Wii group and a conventional balance therapy group) with marked improvements in the Wii group. Similarly, [Janssen et al. 2013] reported improvements in balance in both a group using the Wii and another that used conventional balance therapy, finding no significant differences between
the groups. These studies are representative of the fact that the use of the Wii games can lead to improved balance and strength outcomes; however, the literature is still inconclusive on the advantages of the Wii games over other balance therapies [Pietrzak et al. 2014]. Nevertheless, the literature demonstrates the potential of the Wii games to improve adherence owing to increased motivation levels [Laver et al. 2011; Jorgensen et al. 2013]. All of the studies described above were carried out in supervised scenarios, as is often the case since balance retraining requires such an environment due to potential safety issues. We are interested in home rehabilitation, where seniors are expected to exercise without therapist supervision; therefore, it is necessary to explore the application of commercial exergames in this regard.

Commercial exergames have 2 possible problems that limit their potential in a home rehabilitation context with regard to therapy effectiveness and user experience. First, quality of movement (QOM) is very specific (range and pace), and this has to be complied with for maximum therapeutic effect. Since commercial exergames were designed with the general population in mind, they do not consider the QOM demanded of rehabilitation exercise [Alankus et al. 2010; Deutsch et al. 2009; Pietrzak et al. 2014], thereby not entirely satisfying the requirements for effective falls therapy. Secondly, because of the target market, most commercial exergames utilize mechanics based on quick user reaction, and precise timing, in a relatively fast-paced virtual environment [Hernandez et al. 2013]. Therefore, it is possible that seniors undertaking rehabilitation might not possess the physical, and in some cases cognitive, abilities necessary to cope with the pace of these exergames. This problem is evident in one study, by [McNulty et al. 2011], where stroke patients were asked to play Nintendo Wii Sports over 14 days with additional therapy. [McNulty et al. 2011] found consistent levels of user frustration with the inherent speed and feedback; this is likely to result in a decline in adherence in an unassisted real-world scenario. To overcome these limitations with commercial exergames, therefore, there is a need for more ‘tailored’ or customized exergames; tailored in the sense that the movements used for play are identical to those necessary for effective exercise [Vieira et al. 2015]. By doing this, designers can ensure an enjoyable experience while, at the same time, maximizing the therapeutic benefit of the exercise(s).

2.4.2 Tailored Exergames.

Due to the obvious benefits, researchers have turned to tailored exergames for physical rehabilitation in a variety of scenarios [e.g. Alankus et al. 2010; Hernandez et al. 2013; Rademaker et al. 2009; Uzor and Baillie, 2014]. An example of this can be seen in the work on the ‘SilverFit virtual gaming rehabilitation system’ by [Rademaker et al. 2009], which showed improved outcomes of enjoyment and physical function in users who played the SilverFit exergames. As is the case with commercial exergames, most of the research on tailored exergames has focused on balance retraining [e.g. Deutsch et al. 2009; Lange et al. 2011; Nitz et al. 2010; Schoene et al. 2013]. For instance, in the study by [Fitzgerald et al. 2010], both younger and healthy older adults performed balance tasks using a wobble-board. [Betker et al. 2005] found increased motivation in participants through the use of the exergames, leading to positive outcomes compared to conventional therapies. [Schoene et al. 2013] took this one step further by investigating the use of a tailored exergame for improving step reaction (a vital component to balance retraining). They found that, in general, their participants were able to effectively play the stepping exergame in the home for 8 weeks. [Okubo et al. 2016] also found step training to be beneficial at improving mobility and balance in seniors. One of the common challenges identified in the literature regarding balance retraining involves having the subject stand in such a manner as could compromise safety – this is especially problematic in individuals who have balance impairments [Betker et al. 2005]. Additional safety concerns arise in a home exercise scenario with no therapist (or other) support. As a result, only relatively healthy seniors (low fall risk) have been included in such studies. Given that a significant number of seniors are at a high risk of falling (e.g. have balance impairments and other concurrent fall risk factors), there are opportunities for tailored exergames to cater to such individuals.

By focusing on evidence-based exercise programmes, e.g. Otago and FaME, certain tailored exergame systems have found success in overcoming the issues with balance retraining [e.g. Gschwind et al. 2014; Uzor and Baillie, 2014, Vaziri et al. 2017], with certain systems receiving high levels of user acceptance in the home setting [e.g. Uzor and Baillie, 2014; Vaziri et al. 2016]. For instance, [Vaziri et al. 2017] investigated the use of an ICT-based falls prevention system, called iStopFalls (also described in the work by [Gschwind et al. 2014]), incorporating exergames, visual feedback and a mobility monitor in a 16-week home study. Participants followed a recommended exercise regimen for both balance and strength exercises (from the same Otago exercise programme used in our work) using the Kinect sensor. They outline a number of usage indicators, which were felt necessary to promoting adherence to home rehabilitation using exergame systems. [Vaziri et al. 2017] also compare adherence, physical function and other outcomes between a control group that received no extra therapy and an intervention group that received: balance exergames, demonstrated strength exercises (identical to the...
virtual physiotherapist used in [Uzor and Baillie, 2014] and the mobility monitor. They found improved outcomes of adherence and physical function – strength, balance and the physiological profile assessment (PPA) tool for assessing fall risk.

Despite all of this work, it is still unclear what effects exergames have on adherence and physical function (especially outcomes of gait closely associated with fall risk) versus a suitable control group [Skjæret et al. 2016], i.e. that receives the same therapy, albeit through a different medium (e.g. standard care – Fig. 1). Our Recov-R system addresses the gaps in the literature in a number of important ways: first, by modeling exergames on standard care, i.e. already currently used in the home by seniors who have fallen, we ensured that seniors with a variety of levels of fall risk could play the exergames unassisted. Secondly our system consists of 2 body-worn inertial sensors and a laptop computer; therefore, it was designed to be accessible and used in various locations in the home, without further support from a specialist or technician (as may be the case with optical sensor systems, such as Kinect). Third, we provided all of the exercises (both balance and strength) as exergames, in the Recov-R system, with quality of motion strictly governed by the exergame mechanics (more information is provided in 4.2). Fourth, our exergames were designed, in the initial concept, through co-design sessions with seniors [Uzor et al. 2012], who played a lead role in the generation of game ideas to address the promotion of effective quality of motion. Thus, we carefully considered the stakeholder needs (from a user and physiotherapist standpoint) and requirements prior to the development of the Recov-R system [Uzor et al. 2011].

2.4.3 Our previous work vs. the current work.

In our previous work, we found that in a 12-week home study, seniors were motivated to exercise using an early prototype of the Recov-R system [Uzor and Baillie, 2014]. Furthermore, we found positive results on outcomes of physical function (gait and balance) and quality of life; however, the findings were not found to be statistically significant. The current work differs from our previous work in the following ways:

a) We investigate the use of an updated Recov-R system prototype, with additional exergames that focus on enhanced quality of motion (i.e. duration of hold).

b) We investigate functionality for tracking progress and progression (in terms of game difficulty) and rewards in the form of medals.

c) We include a larger sample of participants in a home study (N=38), thereby increasing statistical validity, compared to our previous work.

d) In addition to adherence and walking speed, we investigate other outcomes of gait and balance that are associated with fall risk, i.e. variability in stride length and double support time.

e) The findings on adherence and physical function, from the current work, achieve statistical significance, compared to our previous work, strengthening the evidence for the use of the Recov-R system (and exergame systems in general).

2.4.4 Sensor Technologies in Rehabilitation Exergames.

Input mechanisms are needed to enable interaction between users and computer-based tools, such as exergames. Therefore, depending on the level of interaction required (e.g. how much movement needs to be captured), capable sensor technologies should be chosen to aid the effective interaction between the user and the system. From the literature, on exergames and physical rehabilitation, various sensor technologies have been used; the most common types include optical tracking or camera-based (e.g. PlayStation camera, Kinect and Webcam), pressure (e.g. Wii balance board) and inertial sensors (inertial measurement units – IMUs). We briefly explore these sensors, in this section, to provide context for our work.

Camera-based sensors: These sensor systems rely on capturing movement using a visual projection of the user. The potential to capture full body movement using such optical tracking systems has made them popular among researchers [Lange et al. 2011; Rademaker et al. 2009; Garcia et al. 2012]. The most common relatively cheap systems, that have shown potential for home rehabilitation use, include: the standard computer webcam [Burke et al. 2010], the PlayStation Eye camera [Flynn et al. 2007; Rand et al. 2008], and the Kinect sensor [Ejupi et al. 2016; Garcia et al. 2012; Lange et al. 2011; Gschwind et al. 2014]. The Kinect sensor is the most powerful relatively cheap camera system in the sense that it can capture depth, in addition to standard color (RGB), information; this gives it the ability to track movement with accuracy similar to what can be achieved by an expensive motion analysis system [Müller et al. 2017]. In a practical sense, however, camera systems are limited as far as falls rehabilitation in the home is concerned. First, cameras, such as the Kinect, often require the
user to stand within an optimal range [Zhang, 2012]. For the Kinect sensor, this effective distance is between 0.7 and 6 meters [Galatas et al. 2012]; in smaller homes, therefore, modifications would need to be made to accommodate the technology (if there is enough available space at all). Second, due to balance impairments, high-risk seniors need a chair for seated exercises, and for support in accordance with falls therapy guidelines (e.g. see Fig. 1). This opens up the possibility of failed, or inaccurate, user tracking due to occlusion from such objects. The Kinect, in particular, is known to have problems with tracking when limbs are pointing towards the camera [Tang et al. 2015], also resulting in a potentially frustrating experience for the user.

**Pressure sensors:** These sensors measure the amount of exerted force to capture the movement of the user. The most common pressure sensor system used in exergame research is the Wii balance board due to its relative inexpensiveness and ease of use [Pietrzak et al. 2014]. Using 4 pressure sensors (one on each leg), the board can measure a user’s average center of pressure. Pressure mats have also been used to play exergames (e.g. in the works by [Betker et al. 2005] and [Schoene et al. 2013]). In a falls therapy context, perhaps, the main issue with pressure sensors is that they are limited in what kind of limb movements they can capture. For instance, while they can capture information such as weight and foot positions, they cannot capture range or pace of movement, or orientation in space, of limbs; this makes it impossible to know how well a user performs falls exercises (such as included in the OEP/ FaME). In the case of some pressure sensors, e.g. the Wii balance board, these also pose a potential trip hazard [Pietrzak et al. 2014; Uzor and Baillie, 2014], which is an undesirable outcome in an unsupervised rehabilitation scenario, especially with high-risk seniors.

**Inertial (IMU) sensors:** IMU sensors capture orientation data in 3-dimensional space. In simpler forms, IMUs may consist of just an accelerometer; however more advanced forms can include extra sensors (such as a magnetometer and gyroscope) to improve the accuracy of the captured orientation data. Due to their relatively small size, and accuracy, IMUs can be used in a variety of locations [van Acht et al. 2007; Vlasic et al. 2007]; consequently, they have been used in numerous research scenarios, including physical therapy [e.g. Ayoade and Baillie, 2014; Lim et al. 2010] and motion-based exergames [e.g. Whitehead et al. 2007; Uzor and Baillie, 2014]. Perhaps the cheapest and most commonly used IMU-based device is the Nintendo Wii remote; this has made it a viable choice for researchers in the rehabilitation space [e.g. Alankus et al. 2010]. However, since Wii remotes were designed to be handheld controllers, their size and configuration makes them cumbersome for use as body-worn sensors. Therefore, other research studies have included bespoke inertial sensor designs that are smaller and have proved more practical for unassisted rehabilitation in the home [Wu et al. 2010; Whitehead et al. 2007; Ayoade and Baillie, 2014; Uzor and Baillie, 2014].

We used IMUs because this technology has been shown to be both: a) an accurate and effective movement detection solution [Morton et al. 2013]; and b) simple to use [Whitehead et al. 2007]. Furthermore, IMUs do not suffer from possible occlusion and tracking effects inherent in optical systems that could make them unreliable for unsupervised home use [Huang et al. 2014; Tang et al. 2015]. Given that the Recov-R system was intended for use in an unassisted rehabilitation scenario (e.g. the home), IMUs seemed the most reliable solution for delivering accurate and problem-free tracking of the use; our sensors are described in more detail in section 4.3.

### 3. RESEARCH QUESTIONS

To investigate the potential of the Recov-R system to enhance home-based falls rehabilitation, we were guided following research questions:

- Q1: Can the use of a tailored exergame system improve adherence to home rehabilitation, compared to standard rehabilitation care used in health practice?
- Q2: Can the use of a tailored exergame system improve gait/ balance outcomes related to fall risk, compared to standard care?
- Q3: What are the benefits of using a tailored exergame system for falls rehabilitation in the home?

### 4. SYSTEM DESCRIPTION

Our goal was to enable seniors to do exercises that are: a) supported by sufficient research evidence, and b) already adopted in practice by health services (i.e. current rehabilitation care). In this section, we start by summarizing preliminary work on the design of the Recov-R system. We then describe the system, including the exergames and other functions as well as human factors around the design that enable seniors to use it effectively in the home.
4.1 Preliminary Studies

To understand how best to satisfy users’ needs regarding effective technologies for rehabilitation in the home, we adopted a user–centered design (UCD) methodology. We first set out to identify requirements for effective falls therapy in a health context. To this end we interviewed physiotherapists [Uzor et al. 2011], who had several years of experience in delivering falls prevention interventions in the UK National Health Service (NHS). The main outcomes from the study highlighted the need for tools that are interactive, motivating and can track rehabilitation progress. Following the interviews, we conducted two design workshops with seniors both with and without previous falls rehabilitation experience. The goals of the workshops were to: a) determine how the requirements for effective rehabilitation could be satisfied through exergames, and b) actively involve seniors in the design of exergames for therapy, with the aim to reduce fall risk [Uzor et al. 2012]. To this end, several game prototype concepts were suggested, which provided a framework for the design and development of the individual games.

After developing a suitable prototype exergame system, we conducted two user studies to ensure that the system was easy to use [Uzor and Baillie, 2013]. These user studies highlighted problems with standard care, with regard to quality of motion, which the games were able to alleviate through their fundamental mechanics. For instance, when doing a Sit-to-stand exercise with the booklet (Fig. 1), participants would rapidly sit and stand; whereas with the corresponding game, they were encouraged to gradually transition between sitting and standing (which is more appropriate for building strength and reducing fall risk). Other issues with the prototype system were also identified (e.g. sensor placement), which were addressed to make it more accessible and suitable for home use.

Finally, we evaluated the prototype Recov-R system, in a pilot home study, over 12 weeks [Uzor and Baillie, 2014]. Throughout our preliminary work, we involved seniors who had either undertaken rehabilitation in the past or were at risk of falling – through age (65+ years) or a previous recent history of falls. Hence, we catered to the relevant user group of interest to our research. Through the pilot study, we evaluated four early prototypes of the Recov-R exergames (described in 4.2), in addition to the use of a ‘virtual physiotherapist’ to communicate exercise movement to users. The study findings suggested that the exergames had the potential to improve adherence to exercise, versus standard care. Furthermore, we also found that the Recov-R system had the potential to reduce fall risk, by improving gait and balance – evaluated through walking speed and the timed up and go (TUG) test [Uzor and Baillie, 2014]. Finally, we provided recommendations for the design of exergame systems to enable an effective, accessible and enjoyable rehabilitation tool for the home. In 4.2, we describe the Recov-R system, in detail, as used in the current work.

4.1.1 Design Modifications to the Current Recov-R Prototype from the Previous One.

Following the pilot 12-week study, described above, the Recov-R system was redesigned to include some of the suggestions arising from our previous studies [Uzor and Baillie, 2013; Uzor and Baillie, 2014]. Not all of these suggestions were implemented; however, we were guided by the participants’ feedback regarding their most desirable suggestions when developing the current prototype. Consequently, the following modifications were made to the current prototype system:

- Two additional games were included to expand on the available exercise options – Fire Rescue and Snow Flags (see Fig. 2 and Table 1).
- The ability to view progress over time was included, with two options – frequency progress (exercises completed) and performance progress (game scores achieved). Progress is described in detail in 4.5.
- Users were rewarded with medals, which highlighted rehabilitation goals in terms of both performance and frequency metrics. Medals are described in detail in 4.6.
- Users could change the level of difficulty associated with the exercises, allowing for progression in rehabilitation. Progression is described in detail in 4.7.

4.2 Recov-R System Description

The Recov-R system was designed with minimalism in mind; by this we mean the minimum number of technological components to enable seniors to independently undertake physical rehabilitation while maximizing therapeutic benefit. The entire system consisted of 2 IMU sensors (with velcro straps) and a (medium–range specification) laptop computer, running the system software. The Recov-R software contained 6 exergames (shown in Fig. 2) based on exercises from the standard care booklet (Fig. 1). To ensure effective QOM, each exergame required the exact movements of its parent exercise to accomplish the goals necessary to succeed – this is explained in detail in Table 1.
Table 1. Otago/ FaME exercises and corresponding Recov-R games – game images are shown in Fig. 2 (a - f)

<table>
<thead>
<tr>
<th>Exercise [Game name]</th>
<th>Type [target muscles]</th>
<th>Procedure</th>
<th>Game details [ensuring quality of movement]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sit-to-stand [Pigeon Express]</td>
<td>Strength [thighs]</td>
<td>Subject sits down and stands up slowly, and carefully, for 10 repetitions (reps).</td>
<td>Player controls the flight of a bird in the game (Fig. 2a). By standing up, the bird flies upward, and by sitting down, the bird flies downwards. The goal of the game is to catch all of the fruits that fall out of the van [the arrangement of the fruits (according to a sine wave) encourages slow and controlled transitions between sitting and standing motions].</td>
</tr>
<tr>
<td>Side steps [River Gems]</td>
<td>Balance [lower body]</td>
<td>Subject stands behind a chair and steps from side to side, at a slow pace (10 reps).</td>
<td>Player controls a beaver character, which jumps from one floating log to another depending on the direction of step (Fig. 2b). Gems come toward the character on either side of the screen. The goal is to get as many gems as possible [the gems appear on different sides of the screen, requiring the player to step from side to side to collect them all].</td>
</tr>
<tr>
<td>Marching [Panda Peak]</td>
<td>Balance [lower body]</td>
<td>Subject marches on the spot, at a steady pace, for up to 30 seconds.</td>
<td>Player controls the movement of a panda character walking across a log covered in snow (Fig. 2c). The goal of the game is to get the panda to the end of the log [the panda walks faster depending on the player’s marching pace, and it falls off the log if the player marches too quickly].</td>
</tr>
<tr>
<td>Knee bends [Horse Hurdles]</td>
<td>Strength [thighs]</td>
<td>Subject stands, bends at the knee into a ‘half squat’ position. They hold this position for 3 seconds and return to a standing position (10 reps).</td>
<td>Player controls the jumps in a horse racing game, where the objective is to successfully jump over a certain number of hurdles (Fig. 2d). By bending at the knee, the horse gallops faster and builds up power. Standing up makes the horse jump high, depending on how long the squat was held for [the horse is only able to jump high enough to clear the 10 hurdles if the player holds each bend for 3 seconds].</td>
</tr>
<tr>
<td>Front knee strength [Fire Rescue]</td>
<td>Strength [thighs]</td>
<td>Subject sits on a chair, extends one leg at the knee, moving it through a 90-degree range. Leg is held for 3 seconds at extension to facilitate strength recovery (10 reps).</td>
<td>Player controls the movement of a fire truck platform using their leg movements (Fig. 2e). By raising each leg, they raise the platform to rescue characters in the building. By lowering the leg, the platform is lowered to enable the rescued characters to escape. The goal is to rescue as many characters (up to 10) with each leg [if the player does not hold the leg extension for 3 seconds, or lowers the platform too quickly, the character falls into the water below].</td>
</tr>
<tr>
<td>Side hip strength [Snow Flags]</td>
<td>Balance [lower body]</td>
<td>Subject stands, lifts one leg out to the side, holds this position for 3 seconds and drops the leg. Movement is repeated on other side (10 reps).</td>
<td>Player controls a character snowboarding down a hill (Fig. 2f). By lifting each leg, the character moves to one side of the screen depending on the lifted leg. The goal of the game is to collect as many flags as possible [flags are laid out on the course so that the player can only get the flags if they hold the character, using their raised leg, at one side of the screen long enough (in this case, 3 seconds)].</td>
</tr>
</tbody>
</table>
4.3 Inertial Sensors (IMUs)

Our sensors (shown in Fig. 3) comprised of a 3-axis accelerometer, a rate gyroscope and a magnetometer – allowing for 9 degrees of freedom and more accurate tracking than just a 3-axis accelerometer (as in the Nintendo Wii remote).

All of these sensor components were mounted within a labeled 3D-printed housing, along with an external power indicator LED, a power switch and a mini-USB charging port. The sensors are attached, using an elastic Velcro strap, to any 2 of the following parts of the body: left shin, right shin, left thigh and right thigh – depending on the exercise. The sensors...
could be charged through a micro USB cable, connected to the laptop. Each sensor could be used for up to 4 hours on a full charge – note that a complete exercise session with standard care lasts about 30 minutes.

4.4 Interaction Modalities

Users were able to interact with the Recov-R system using the numerical keys on the laptop keyboard. On-screen buttons, with corresponding numbers, were used to highlight the related keyboard commands. For instance, to play the Pigeon Express (Sit-to-stand) game, the user presses the ‘1’ key, on the keyboard (Fig. 4), at the main menu. Note: at the time of the study, the provided exergames were available through options 1 – 6 only. To make the controls more accessible, keyboard stickers were used to highlight the keys required to interact with the system (numerical keys 1 to 9). Before each game, a pop-up screen reminded the users to check that their sensors were attached to the correct leg positions. Following this, sensor calibration was done automatically as the users were asked to assume 1 of 2 positions, for a duration of 5 seconds: for seated exercises, they were asked to sit still, whereas for standing exercises they stood upright. In either case, it did not matter what direction they faced. The orientation data, from the sensors, were processed and used to control the character movements in each game.

![Fig. 4. Recov-R system setup showing the main interface, keyboard labels and inertial sensors.](image)

4.5 Progress Tracking

With the Recov-R system, users could check their rehabilitation progress using 2 definite metrics: ‘frequency’ (number of exercises completed) and ‘performance’ (measured in game scores, which directly corresponded to QOM). Frequency progress enabled the users to check their progress according to physiotherapist–recommended guidelines for completing all exercises at least 3 times a week [Uzor and Baillie, 2014]. Performance progress allowed them to compare their game scores to previous scores or grades, from ‘A+’ (100% achievement) to ‘E’ (20%). A graph layout was used to show the progress charts; this was done to provide a simplistic and easy-to-understand diagrammatic view. Drawing on previous work [e.g. Ayoade and Baillie, 2014; Loudon et al. 2012], as a starting point, a traffic-light-style color system was used to categorize performance level (Fig. 5). We, however, used a ‘rainbow’ gradient for a wider range of performance from worst to best – red, orange, yellow, green and blue, to detect more subtle differences in progress.
4.6 Medals and Rehabilitation Goals/ Milestones

To enable users to track rehabilitation goals or milestones over time, through the Recov-R system, we included the concept of rewards using medals, which are often used in commercial exergames, e.g. Wii Sports. Since we defined rehabilitation progress in terms of exercise frequency and performance, our medals represented these goals accordingly, with categories of gold, silver and bronze awarded, depending on the difficulty associated with achieving each medal. Table 2 shows the available medals, according to our own developed ranking system, with their associated categories and descriptions.

Table 2. Medal concept and categories based on exercise frequency and performance

<table>
<thead>
<tr>
<th>Medal Name (Type)</th>
<th>Category</th>
<th>Rehabilitation goal description</th>
</tr>
</thead>
<tbody>
<tr>
<td>High scorer (Performance)</td>
<td>Bronze</td>
<td>Achieve at least a ‘B’ grade (60% score) in every game</td>
</tr>
<tr>
<td>Marathon (Frequency)</td>
<td>Bronze</td>
<td>Complete 100 exercises in total</td>
</tr>
<tr>
<td>Perfectionist (Performance)</td>
<td>Silver</td>
<td>Achieve an ‘A’ (80%) or ‘A+’ (100%) grade in every game</td>
</tr>
<tr>
<td>Completionist (Frequency)</td>
<td>Silver</td>
<td>Complete each game at least 3 times a week, for 12 weeks (minimum standard care)</td>
</tr>
<tr>
<td>Master (Frequency)</td>
<td>Gold</td>
<td>Complete each game at least 5 times a week, for 12 weeks (daily exercise, with weekend rests)</td>
</tr>
</tbody>
</table>

As with the progress charts, medals could be accessed at any time using the system. If a medal was locked, the users could see what they needed to do to accomplish the associated rehabilitation goal/ milestone (Fig. 6).
4.7 Exercise Progression

Recognizing the need to allow the users to change the difficulty of the exergames, due to their varying abilities and need to progress to more difficult levels over time [Skjærset al. 2016; Ogonowski et al. 2016; Vaziri et al. 2017], we included 3 levels of difficulty: easy, normal and difficult. These levels varied by the number of repetitions and amount of time required to hold a limb in a particular position. For instance, in the Front knee strength exercise, users could rescue 10 characters under the normal setting and progress to 15 in the difficult setting. Furthermore, the user was required to hold the leg for up to 5 seconds, instead of 3, in the difficult setting; they could choose a different difficulty level at any point while using the system.

5. METHOD

In this section, we describe an empirical study to evaluate the use of the Recov-R system in the home.

5.1 Study Procedure

We conducted an 8-week (within participants) home study, employing a randomized controlled trial (RCT) design with the following 2 groups (between participants): (1) a control group that used the standard care (booklet and exercise video), and (2) an experimental group that received the Recov-R system (a laptop computer, 2 inertial sensors and USB charging cables for the sensors) in addition to standard care. The study procedure is highlighted in Fig. 7. Participants in both groups were given a diary, with which they could record their exercise sessions. The participants visited the researchers’ laboratory, twice, for measures to be taken at baseline (before the study) and outcome (after the study) stages. The measures included:

- Laboratory tests for Gait and Balance (Walking speed, Stride length, Double support time)
- Assessment of participants’ homes for potential hazards (by researchers)
- Training (on using standard care and Recov-R system)
- Exit questionnaire
- BMI Scale
outcomes of gait and balance (physical function), a questionnaire given at the start of the study to capture demographic information, an exit questionnaire, interview and the Intrinsic Motivation Inventory (IMI) scale at the end of the study (see 5.6 for a detailed description).

At the start of the study each participant, from both groups, was visited by the researchers. The purpose of the home visit was to identify any potential hazards (e.g. trips), ensure a safe environment for exercise, and train the participants on how to use the rehabilitation tools – standard care and the Recov-R system. The participants used a variety of surfaces for support during exercise, e.g. chairs, tables and kitchen worktops. There were no additional visits, by the researchers, to the participants’ homes until the end of the study (to retrieve the equipment).

5.2 Recruitment

Participants were recruited from 2 sites: 1) the UK NHS Greater Glasgow and Clyde (NHSGGC) Community Falls Prevention Programme (CFPP), and 2) North Glasgow Homes (NGH) – a local housing association that provides homes and services in retirement communities. Ethical approval was obtained through both the UK NHS ethics committee and the researchers’ university ethics board. Potential participants, at both recruitment sites, were first provided with an oral description of the study; this included a summary of the home study details, e.g. duration of the study, rehabilitation tools involved, and visits to the researchers’ university for baseline assessments. Seniors, who were interested in the study, were included if they were: 1) older than 65 years and living in their own homes; 2) had fallen, at least once, in the 12 months prior to participation in the study; and 3) were able to do home exercise (using the standard care booklet or video). The main inclusion criteria (1 & 2) were intended to target seniors with a relatively high risk of falling – i.e. those with multiple risk factors [Sherrington et al. 2011].

The Recov-R system, just like standard care (i.e. booklet and video) was intended for unsupervised rehabilitation in the home; therefore, potential participants were excluded from the study if they met any of the following criteria, which could negatively affect their rehabilitation or pose a safety hazard: a) had major cognitive impairment (e.g. Dementia), b) had major visual impairment (i.e. were unable to see the games or booklet clearly enough to effectively use them, or to navigate the environment safely during exercise) and c) were unable to communicate in the English language (since the rehabilitation tools were limited to English in their current forms). The physiotherapists at both the CFPP and the NGH assisted with determining those participants who were eligible to take part in the study, based on these criteria. Ultimately, participants were included if the physiotherapists deemed them able to safely undertake the rehabilitation exercises, unsupervised in the home, for the 8 weeks.

5.3 Participants

Fifty-two participants were initially recruited on a rolling basis and randomized, by an external independent establishment, to the study. During the course of the study, 14 participants dropped out (approximately 27% dropout rate) due to various reasons, which included the following:

- Falls, that led to hospitalization (2); these occurred outside the home as a result of trips – getting out of a taxi (1) and on the door step (1).
- Health problems that made exercise difficult, and in some cases required hospitalization (3); these included breathing difficulties (1), painful knees or hips (2).
- Family commitments or issues (5) that made it impossible or difficult to commit to the study.
- Travel or holiday commitments (4), where participants would have been unavailable to the study for more than a week.

None of the participants reported that they dropped out as a result of using the intervention tools (Recov-R system, booklet or video); however, those with knee or hip pain found it difficult to cope with exercise in general. Those participants who left the study for reasons other than health (c and d) stated that they would have wanted to continue the study if they could do so at a more convenient time. The findings, reported on in this paper, are based on the remaining 38 participants who completed the study. All of the participants were educated to at least high school level (15 had high school diplomas, and the rest had college, or higher, qualifications), with 60% of them having worked in professional fields.

A majority of the participants (29/38) had not previously played games, on any device, while most of them had used other kinds of technologies, including: computers (24/38), mobile phones (29/38), tablets (16/38), DVD players (38/38) and digital
televisions (38/38). A majority of the participants (32/38) had also previously attended, or were attending, a 1hr/week physiotherapist-led group exercise class in their living community. All of the participants had previously used the standard care booklet, while 16/38 of them had used the exercise video.

5.4 Fall History

Falls rehabilitation exercises are effective for reducing fall risk and preventing future falls, and seniors who have a higher risk of falling are in the most need, and benefit most, from falls prevention programs [Skelton and Todd, 2004]. We recruited participants with a high risk of falling (1-year history of 1 or more falls, prior to the study, and were over the age of 65 years. Our study participants had varied falls incidents (Fig. 8); this highlights a relatively high-risk demographic – 66% had fallen twice, or more, in the last year.

![Fig. 8. Participant history of falls in the year prior to taking part in the study.](image)

5.5 Age Distribution

Participants were of a wide variety of ages (65 – 99 years), with a mean age of 76 years (SD = 6.13). Control group participants ranged from 65 – 99 (Mean = 75.4; SD = 6.04) years, while the Game group participants ranged from 65 – 88 (Mean = 76.4; SD = 6.41) years (Table 3).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Males</th>
<th>Females</th>
<th>Dropped out (pre-dropout)</th>
<th>Completed</th>
<th>Dropout rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>8</td>
<td>14</td>
<td>8(30)</td>
<td>22</td>
<td>26.67%</td>
</tr>
<tr>
<td>Game</td>
<td>6</td>
<td>10</td>
<td>6(22)</td>
<td>16</td>
<td>27.27%</td>
</tr>
</tbody>
</table>

5.6 Study Outcomes

5.6.1 Adherence.

To track the number of exercises that the participants had completed, they were given diaries that showed a list of the exercises with empty boxes that could be ticked using a pen. Adherence was the primary outcome of the study; therefore, the researchers did not visit the participants during the study, because this could affect the outcome. We relied on adherence as a self-report outcome, through diaries, since this has been used in similar studies and was suitable for capturing the data [Ayoade and Baillie, 2014; Uzor and Baillie, 2014] in an unsupervised environment.

5.6.2 Gait and Balance.

Certain outcomes of gait have been shown to be strong predictors of fall risk, by exposing indicators of mobility and balance problems in seniors [Judge et al. 1993; Hausdorff et al. 2001; Quach et al. 2011]. We captured 3 of these key gait outcomes, at the start and the end of the study, in a laboratory using a GAITRite® portable gait analysis system; the
outcomes we measured included: walking speed, variability in stride length (the distance between successive steps of the same leg during the walk cycle) and variability in double support time (DST) – the amount of time that both feet are simultaneously touching the ground during the walking cycle.

5.6.3 Usability, User Experience and Motivation.

These were explored quantitatively through the System Usability Scale (SUS) to measure usability [Lewis and Sauro, 2009] and the Intrinsic Motivation Inventory (IMI), which are both validated tools for assessment [Bangor et al., 2008; McAuley et al. 1989; Plant and Ryan, 1985]. The Recov-R system was relatively new to the participants; therefore the IMI scale was intended to understand the participants’ reactions to the exergames, as a rehabilitation aid, under the dimensions of the various IMI sub-scales – Interest / Enjoyment (a measure of how much interest they had in using the games), Perceived Competence (a measure of their ability to use the system), Perceived Choice (a measure of their willingness to use the system for rehabilitation) and Perceived Value (a measure of how useful they felt the system was to their rehabilitation).

5.6.4 Exit Questionnaire and Interviews.

These tools captured qualitative information on experiences with the booklet and Recov-R system to gain insights into motivators for adherence to exercise, rehabilitation goals and participants’ experiences in general. The exit questionnaires contained both open and close-ended questions to allow for a wide variety of participant responses.

5.7 Data Analysis

Quantitative data on gait outcomes were obtained through the GAITRite system and for adherence through the diaries. The SUS and Likert scales (in the exit questionnaire) were used to collect data on usability. These quantitative data were analyzed using IBM SPSS Statistics (Version 25) and Microsoft Excel for Mac. Qualitative data were recorded using notes and an audio recorder and later transcribed manually. The qualitative data were collected to provide further insights into the participants’ use of standard care and the Recov-R system, through open-ended questions, in the exit questionnaire, and a semi-structured interview.

The interview data were analyzed using thematic analysis, by two members of the research team, and verified by an additional individual who was not directly involved in the study. Using a deductive approach, the data were organized into the following themes according to the topics of interest and related to adherence to exercise: a) motivation to exercise, b) enjoyment and excitement, c) confidence and challenges (with using standard care and the Recov-R system), and d) competition and achievements. These themes were derived from the most commonly mentioned motivators for adherence in our previous work, with our initial prototype system [Uzor and Baillie, 2014]. The themes were also confirmed as being the most relevant to the participants’ comments, in this regard (motivation to exercise – 7 comments, enjoyment and excitement – 10, confidence and challenges – 9, competition and achievements – 11).

Finally, direct participant quotes, from the exit questionnaire, are highlighted, in this paper, to expand on the quantitative findings on rehabilitation goals (6.3), usability and user experience (6.5) and progress (6.6). In these cases, quotes are defined using the prefix ‘C’ for Control (C1, C2, C3…) group and ‘G’ for Game (e.g. G1, G2, G3…) group participants.

6. FINDINGS

6.1 Adherence

6.1.1 Quantitative Findings on Adherence.

Adherence, in this work, was explored through daily and weekly exercise sessions – in particular, average number of exercises completed per day and per week. Table 4 shows adherence in terms of average number of exercises a week, while Fig. 9 highlights the adherence trend over the 56 days of the study.

<table>
<thead>
<tr>
<th>Group</th>
<th>Week 1</th>
<th>Week 2</th>
<th>Week 3</th>
<th>Week 4</th>
<th>Week 5</th>
<th>Week 6</th>
<th>Week 7</th>
<th>Week 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>2.55</td>
<td>2.27</td>
<td>1.91</td>
<td>1.55</td>
<td>1.09</td>
<td>1.45</td>
<td>1.32</td>
<td>1.27</td>
</tr>
<tr>
<td>Game</td>
<td>3</td>
<td>2.94</td>
<td>2.9</td>
<td>2.5</td>
<td>2.75</td>
<td>3.19</td>
<td>3.25</td>
<td>4.13</td>
</tr>
</tbody>
</table>

ACM J. Trans. Comp. Hum. Int., Vol. XX, No. XX, Article XX. Publication date: Month 20XX.
A repeated measures ANOVA was performed to compare the effects of the rehabilitation tools (booklet/video and games) on adherence to exercise. We assumed normality of data distribution based on our sample size (N >= 30) and the Central Limit Theorem. Equal variances are also assumed, on adherence between groups, based on the results of Levene’s test (F1, 36 = 0.146, p = 0.705). The results suggest a statistically significant difference, in adherence, between both groups (F1, 36 = 6.28, p = 0.017, \( \eta^2 = 0.15 \)). As is evident in Fig. 9, there is a decline in adherence in the Control group compared to a relatively constant trend in the Game group. These results suggest that the Recov-R games encouraged the participants to maintain the rehabilitation programme throughout the duration of the study. These findings support our previous work [Uzor and Baillie, 2014]; however, the findings in this work achieve statistical significance, thereby providing more evidence for the use of tailored exergames to improve adherence to exercise versus standard care.

6.1.2 Qualitative Findings on Adherence.

Motivation to Exercise: In the Control group, participation in the study appeared to be the primary motivator for exercise, as noted by C10: “[...]the fact that [the exercises] are there and I am part of the study, so I feel I need to do them.” C18 felt that, in addition to taking part in the study, he also wanted to keep fit: “I did the exercises to keep fit and for the study.” For certain participants, such as C13, just having the exercises motivated them to exercise: “I had the exercises with me, so it made me do them.” It was interesting to find that, for certain participants in the control group, the presence of the diary was the primary motivator for adherence to the exercise programme. For instance, C8 said: “Yes I tried to keep up with the diary.” C12 supports this finding, stating that ticking boxes in the diary motivated her to do the exercises; “[...]I wanted to fill the diary as much as possible.”

In contrast, although the Game group participants could also use standard care tools (booklet and video) during the study, these participants were primarily motivated to exercise because of the games, preferring to use the Recov-R system to standard care. To illustrate this point, G3 commented: “[The video] wasn’t motivating; I found the games more fun.” G4 echoes this sentiment but found no particular issue with using the video: “I was certainly more motivated using the games, but it was no problem using the video.” In terms of preference, the participants in the game group generally preferred using the Recov-R system, as expressed by G6: “No not really, I preferred using the laptop,” and G16: “No, the games were definitely better at motivating me.”

Enjoyment and Excitement: None of the participants in the Control group expressed excitement or enjoyment regarding using standard care tools for their rehabilitation. Indeed, certain participants claimed that they found the experience boring, as C16 remarks: “[I used the booklet] a few times; I wasn’t able to exercise much; plus, it is just boring doing the exercises.” Conversely, the game group participants expressed numerous comments on their enjoyment of the games. For instance, G5 enjoyed using the system so much that she could have purchased one: “I thoroughly enjoyed them. I asked my grandson ‘could you not buy a laptop and have the games on it?’ I thought it was fantastic; I tried it every single day. I tried it on easy, normal and hard.” For certain participants, the presence of the Recov-R system was instrumental to their engaging in...
rehabilitation, e.g. G13 noted that without the Recov-R system, which enabled an exciting experience, she would not have exercised much: “I would not have exercised much without [the games]; they were exciting to play.”

G9 was able to maintain adherence to the exercise program because she was particularly interested in games: “I like playing the games… I like the concept of playing games.” This sentiment was repeated by G14, who had previously experienced motion gaming using the Nintendo Wii: “Indeed, I love them; it's just like the Wii, I find them enjoyable.”

**Competition and Achievements:** In our previous work, we found that the game scores were pivotal to encouraging continued participation in home rehabilitation. The findings in this study elaborate on the factors responsible for boosting adherence in accordance with this theme. ‘Accomplishing rehabilitation goals’ was the main reason for G9’s preference for using the Recov-R system over standard care: “I found the games much better; the video did not have the same goals to accomplish.” G2 expressed a sense of accomplishment as a consequence of completing the games; this she felt also helped to reduce anxiety associated with doing the exercises: “Yes, it takes your mind off anxiety; it also makes you feel good when you beat it.”

The sense of self-competition (e.g. surpassing one’s previous scores) was found to be a strong factor for encouraging more exercise. For instance, G9 commented: “The games make you competitive; you knock one [hurdle] over and go ‘oh dear, I have to do that again’.” G3 made a similar comment: “I enjoyed the games… it's exciting to see the score at the end; it makes you want to try again.”

The comments by G14 and G15 also echo this sentiment, demonstrating the effectiveness of self-competition for promoting engagement in exercise through exergames: “[The games] make you want to do more [exercise]; […] sometimes you miss one of the pearls and you get annoyed and want to start over” and “Yes, the [games] were engaging. Every time those people fell in the water, it made me want to start over. I liked the games; I thought they were good.”

**Confidence and Challenges:** Most of the participants in the Control group found standard care tools easy to use, and most of them were confident in their use. C20’s comment expresses the general opinion on this matter: “Yes, I [used the booklet a lot]; I found it easy[…].” The comment by C18 further supports this finding: “It was suitable for what I was doing, and it was easy enough to do.” However, certain participants in this group did not feel as confident. For instance, C17 disagrees, commenting that it was difficult to do the exercises since it was not clear what she had to do: “I know the exercises are meant to help but I was just unable to do them; I found it difficult to understand.”

Similarly, most the participants in the Game group felt confident in using the Recov-R system. This is evident in the comments by G4: “Oh yes, no problem really; you just had to make sure that the sensors were activated, and it was fine” and G15: “Yes, oh [the games] are amazing. I love them. I wish I could keep using them.” G14 was experienced with computers and felt confident with the system as a result: “Yes, I don’t have trouble with computers; I found it quite easy.”

For certain participants in this group, such as G12, challenges were alleviated by distraction while playing the games, thereby reducing anxiety with regard to using the technology: “Yes I felt confident; you forget what happens around and can get carried away.” G13 made a similar comment, which while expressing confidence, hinted at a challenge in putting on the sensors: “Yes I was confident; the games have a way of distracting you; but that's when you've already put on the sensors.”

G3 initially did not feel confident in using the system; however, his confidence improved over time: “I found it difficult at first, but it got better over time; I think I am very good at it now.” G1 struggled with the Recov-R system, mainly because he did not feel confident in his abilities: “I thought the games were fine, I just thought I was quite inadequate; my brain coordination is not great with the activity.” Participant G8 also struggled to use the system, however their difficulty was due to arthritis and knee pain, which made it difficult for them to do certain exercises: “I struggled with most of the games due to rheumatoid; I found [the sit to stand exercise] difficult because of the rheumatoid, also found it difficult due to knee pain.”

These comments highlight that other health issues can be an obstacle to the use of rehabilitation technologies in the home.

### 6.2 Intrinsic Motivation Inventory (IMI) Scale

Table 5 shows the findings from the IMI, which provide further insights on motivation (cells highlighted in bold show very positive results – towards 6/7 or 7/7). The IMI scale results show very positive results with regard to interest/enjoyment, supporting the above findings, with 81% of the respondents rating the Recov-R system approximately a 6 or 7 on this subscale. The findings from the other subscales indicate that a majority of the participants: a) felt competent in their use of the Recov–R system, with above average, or high, confidence in their ability to use it (perceived competence subscale); b) willingly used the system for their rehabilitation (perceived choice subscale); and c) considered the system essential to their rehabilitation (perceived value subscale).
Table 5. IMI scores for each of the individual sub-scales

<table>
<thead>
<tr>
<th>Participant</th>
<th>Interest/Enjoyment</th>
<th>Perceived competence</th>
<th>Perceived choice</th>
<th>Perceived value</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>4</td>
<td>1.75</td>
<td>2.5</td>
<td>3.25</td>
</tr>
<tr>
<td>G2</td>
<td>7</td>
<td>5</td>
<td>6</td>
<td>6.75</td>
</tr>
<tr>
<td>G3</td>
<td>6.6</td>
<td>5.75</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>G4</td>
<td>6.4</td>
<td>6.25</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>G5</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>G6</td>
<td>7</td>
<td>5.25</td>
<td>6.5</td>
<td>6.75</td>
</tr>
<tr>
<td>G7</td>
<td>7</td>
<td>6.5</td>
<td>6.5</td>
<td>6.75</td>
</tr>
<tr>
<td>G8</td>
<td>4.8</td>
<td>4.75</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>G9</td>
<td>5.8</td>
<td>4.75</td>
<td>7</td>
<td>6.25</td>
</tr>
<tr>
<td>G10</td>
<td>6.6</td>
<td>4.25</td>
<td>5.5</td>
<td>6.25</td>
</tr>
<tr>
<td>G11</td>
<td>5.2</td>
<td>4.5</td>
<td>7</td>
<td>6.5</td>
</tr>
<tr>
<td>G12</td>
<td>7</td>
<td>6.5</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>G13</td>
<td>7</td>
<td>5.25</td>
<td>7</td>
<td>6.75</td>
</tr>
<tr>
<td>G14</td>
<td>7</td>
<td>6.5</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>G15</td>
<td>7</td>
<td>7</td>
<td>6.5</td>
<td>7</td>
</tr>
<tr>
<td>G16</td>
<td>6.2</td>
<td>6.75</td>
<td>7</td>
<td>7</td>
</tr>
</tbody>
</table>

6.3 Rehabilitation Goals

At the start of the study the participants were asked if they had any rehabilitation goals that they wished to achieve; it was expected that these goals, if any, could potentially encourage more exercise. There were similar percentages of participants, in both study groups, that stated there were rehabilitation goals that they hoped to achieve at the end of the study. Most of the rehabilitation goals were similar across both groups (as evident in Table 6) with improve mobility, improve activity and improve balance being the most prevalent. Only one of the participants in the Game group believed that they had not accomplished their rehabilitation goal; this goal: ‘to play tennis, be more active and run’ seemed impossible to achieve, said the participant due to weather – mostly rain. In comparison, 5/18 participants who had goals in the Control group felt that they accomplished their goals.

Table 6. Common goals and number of participants who believed that they achieved goals

<table>
<thead>
<tr>
<th>Group</th>
<th>Participants who had rehabilitation goals (total in group)</th>
<th>Participants who believed they achieved their goals (total with goals in group)</th>
<th>Commonest goals (number of participants that stated this goal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>18 (22)</td>
<td>5 (18)</td>
<td>• Be more mobile (4)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Be more active (4)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Improve balance (3)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Other goal (7)</td>
</tr>
<tr>
<td>Game</td>
<td>12 (16)</td>
<td>11 (12)</td>
<td>• Be more mobile (5)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Be more active (3)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Improve balance (2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Other goal (1)</td>
</tr>
</tbody>
</table>

The main reasons they did not accomplish their goals included the weather, for those whose goals included outdoor activities (2 participants) and not exercising enough (3 participants). For instance, C7 commented: “I just haven’t been able to exercise much,” and C8 remarked: “Yes, but I need the weather to get better for the gardening.” Those participants who felt that they accomplished their goals attributed their success to exercise (in both groups) and the Recov-R system in the Game group, expressing that they felt more active and fitter as a result. This is evidenced in the comments by G12:

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"Definitely, I liked doing the exercises; it stimulates you to do other activities," G5. "Aye I think so. That’s what I liked most about the laptop; I hate being stuck in the house, especially in the winter, but it helps if you have the likes of this. You have something to look forward to," and G13: "Yes, I am exercising more, and I am more conscious of it, so I will keep trying."

6.4 Fall risk (Assessed through Gait)

For quantitative evaluations of gait, we conducted independent samples T-tests to investigate potential differences between groups, for each of the outcomes, in terms of change (from pre-test to post-test). Table 7 highlights the results from the tests.

<table>
<thead>
<tr>
<th>Outcome</th>
<th>T-Test results</th>
<th>Levene’s test of equal variances</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walking speed</td>
<td>T = -2.796, p = 0.048</td>
<td>F = 0.199, p = 0.658</td>
</tr>
<tr>
<td>Stride length variability</td>
<td>T = 2.700, p = 0.010</td>
<td>F = 0.160, p = 0.691</td>
</tr>
<tr>
<td>Double support time (DST) variability</td>
<td>T = 2.551, p = 0.015</td>
<td>F = 3.051, p = 0.089</td>
</tr>
</tbody>
</table>

6.4.1 Walking Speed.

The findings (highlighted in Fig. 10 and Table 7) suggest that the average improvement, in walking speed, was greater in the Game group (average of 4.12cm/s improvement) than in the Control group (average of 2.02cm/s decline); these results also highlight a statistically significant difference, in walking speed, between subject groups (Table 7). Twelve, out of the 16, participants in the Game group (75%) improved in average walking speed compared to a corresponding 8, out of 22, participants in the Control group (36%), suggesting that the Recov-R games encouraged better QOM during exercise. Three participants in both groups achieved a significant average improvement in walking speed (10cm/s) [Chui et al. 2012]. Those who achieved this positive change adhered to the minimum physiotherapist-recommended rate of 3 sessions per week.

Fig. 10. Change in walking speed over the 8-week study (higher values show improvement).

6.4.2 Variability in Stride Length.

Less variability in stride length is associated with a reduced risk of falling. Our findings show a higher reduction in stride length variability in the Game group, compared to the Control group (Fig. 11). The differences between groups was found to be statistically significant (Table 7).
6.4.3 Variability in Double Support Time (DST).

Less variability in double support time (the amount of time both feet are on the ground, simultaneously, during the walking cycle) is also associated with a reduced risk of falling. Similar to walking speed and stride length variability, we found higher improvements in DST variability in the Game group, compared to the Control group (Fig. 12). The difference in this outcome, between groups, was also found to be statistically significant (Table 7), which also indicates an improvement facilitated by a combination of increased adherence to the programme, in the Game group, and potentially better QOM encouraged by the games.
6.5 Usability and User Experience

6.5.1 System Usability Scale (SUS).

The findings from the SUS (highlighted in Fig. 13) were generally positive (mean score of 83%), with only 2 participants rating the Recov-R system less than “good” (72%). This suggests sufficient usability and satisfaction, on average, with the use of the system [Bangor et al. 2008]. This user satisfaction is expected to be as a result of a combination of enjoyability, effectiveness and the ease of use of the system and its games – discussed below.

6.5.2 Ease of Use and Enjoyability.

Ease of use was measured on a 5-point Likert scale of 1 (very easy) to 5 (very difficult). The findings were positive (median = 2; interquartile range (IQR) = 2), with only 2 of the Game group participants commenting that the system was difficult for them to use (Fig. 14).

Fig. 13. SUS adjective ratings from using the Recov-R system.

Fig. 14. Ease of use for the Recov-R system (Likert rating of 1 = very easy; 5 = very difficult).
Enjoyability was also rated, in both groups, using a 5-point Likert scale of 1 (not very enjoyable) to 5 (very enjoyable). The results (Fig. 15) show that a majority of the participants in the Game group found the games (and Recov-R system as a whole) enjoyable, or very enjoyable (median = 4.25, IQR = 0.88). In comparison, the median rating for standard care, in the Control group, was 2.5/5, IQR= 1, indicating an average response, with some participants either not enjoying or enjoying using standard care. A majority of these participants claimed no further opinion on the matter.

![Fig. 15. Enjoyability rating for the Recov-R system games (Likert rating of 1 = very easy; 5 = very difficult).](image)

6.5.3 Enjoyability and Effectiveness of Individual Games.

The Recov-R games encouraged the Game group participants to maintain adherence to the falls rehabilitation programme in our study, and based on their comments a significant reason for this was due to the fact that they enjoyed playing the games. All of the games were different in aesthetics and functionality, since they were tailored to the different exercises; therefore, it was necessary to understand: a) how much the participants enjoyed each individual game, b) their favorite game(s), and c) how effective they thought each game was at achieving the quality of movement necessary for the respective exercises. Participant comments, in this section, are derived from the exit questionnaire data and serve to elaborate on the quantitative results.

<table>
<thead>
<tr>
<th>Exercise</th>
<th>Pigeon Express</th>
<th>River Gems</th>
<th>Panda Gems</th>
<th>Horse Hurdles</th>
<th>Fire Rescue</th>
<th>Snow Flags</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Enjoyability</strong> (1 = Not very enjoyable; 5 = very enjoyable)</td>
<td>4.5 (1)</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>4 (1)</td>
<td>5</td>
</tr>
<tr>
<td><strong>Effectiveness</strong> (1 = Not very effective; 5 = very effective)</td>
<td>4 (1)</td>
<td>4 (2)</td>
<td>4 (0)</td>
<td>5 (1)</td>
<td>5 (1)</td>
<td>5</td>
</tr>
</tbody>
</table>

With regard to enjoyment of the individual games, the participants had varied preferences, as expected; however, it is evident that certain games were preferred over others (Table 8 and Table 9). For instance, G8 commented: “I really enjoyed the [Pigeon Express game] and it is very encouraging when you win because it makes you want to go to the next one. Fire Rescue was my favorite. I felt I could feel the benefit of that one because of my knees. I think I really clicked with the [Snow..."
Flags game: initially I wasn’t reacting quick enough, but I feel I got better” and G7 stated: “I really enjoyed the horse hurdles and the fire man game.”

The River Gems (Side steps exercise), Horse Hurdles (Knee bends exercise) and Snow Flags (Side hip strength exercise) games were rated highest, even though all games were rated either a 4 (enjoyable) or a 5 (very enjoyable) on the Likert scale (Table 8). Considering favorite games, the Snow Flags and Fire Rescue (Front knee strength exercise) games were favored the most by the participants (Table 9) – some participants noted more than one game as a favorite.

Table 9. Favorite games and number of participants who favored them, out of the 16 participants in the Game condition

<table>
<thead>
<tr>
<th>Exercise</th>
<th>Pigeon Express</th>
<th>River Gems</th>
<th>Panda Peak</th>
<th>Horse Hurdles</th>
<th>Fire Rescue</th>
<th>Snow Flags</th>
</tr>
</thead>
<tbody>
<tr>
<td>Favorite game(s)</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>5</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>

Participant G5 enjoyed all of the exergames, having no personal favorite: “I liked every single one. They were funny and not boring. With the [Panda Peak game], I was determined to get the panda to the end. I rejoiced when I did; you would think someone gave me money. I wish there were more [games].” The Panda Peak (Marching) game received the lowest average score; participant G6 commented that it was not as interactive as the other games, since all they had to do was make the character walk forward by marching constantly: “There wasn’t much to do; [the Panda Peak game] wasn’t as exciting as the [Horse Hurdles game].”

6.6 Progress Charting, Medals and Progression

The participants’ preferences, for the various methods of tracking progress, medals and progression were also investigated. Table 10 shows the results from a Likert scale on usefulness [1 = not very useful; 5 = very useful] using the median and interquartile range (IQR). We discuss these results in the following subsections.

Table 10. Likert scale results on usefulness of Recov-R system features

<table>
<thead>
<tr>
<th>Outcome</th>
<th>Median</th>
<th>IQR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Progress charts</td>
<td>4</td>
<td>1.25</td>
</tr>
<tr>
<td>Medals</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Progression</td>
<td>5</td>
<td>1</td>
</tr>
</tbody>
</table>

6.6.1 Tracking Progress.

Participant feedback was positive for progress tracking using either the frequency or performance methods (Table 10). Regarding the preferred method of viewing progress, 44% preferred using both methods. More participants preferred viewing progress in terms of performance or scores (31%) to frequency or exercises completed (25%); however, these numbers are not varied enough to conclude which of the two methods is more useful for displaying progress. The charts were considered useful, by the participants, for displaying progress, using either method, as evidenced by the comments from participants G3: “Oh yes [the charts] were interesting; I like to keep active, and I found it good for helping me keep track of both [frequency and performance]” and G6: “I prefer both [charts], I think it is important to see both as they talk about two different things, which are important in different ways.”

The ability to view game performance, as a measure of progress, was appreciated by the participants, since this feature allowed them to determine whether the exergames, and the exercises in general, provided any therapeutic benefit during the rehabilitation period. For instance, participant G6 remarked: “Because I was doing them properly. When you get a chat with the physiotherapist you don’t know if you were doing [the exercises] right, but the laptop told me how many fruits I got. I would use that every single day and I wish I could keep it; I will miss it” and participant G14 stated: “It’s exciting to see the score chart at the end; it makes you want to try again.”

Those participants who preferred to view progress as a measure of frequency were interested in how many exercises they had done, especially with regard to the physiotherapist-recommended frequency of 3 sessions per week [Uzor and Baillie].
On this point, participant G12 noted: “Like I said, I could keep track of which exercises I’d done, and when, that is helpful; I tried to do more than the average [of 3 sessions per week].”

6.6.2 Medals.

Medals were also considered very useful for tracking rehabilitation goals/milestones over time (Table 10). The participants’ comments reveal that the medals helped them to accomplish exercise goals and establish some discipline around integrating exercise into their daily routines. For instance, participant G15 stated: “[Medals] allowed me to set an agenda and find time to do the exercises” and G4 said: “That’s what I like best [about the system]; it helps if you have the likes of this, as you have some exercise goals to accomplish.”

6.6.3 Progression.

Progression (the ability to change difficulty level) was rated highly on the usefulness Likert scale, with a median of 5/5 (Table 10). We also tracked how many times the participants changed the game difficulty using the system. All of the participants started with the normal setting and were told that they could change the difficulty whenever they felt like it. Most of the participants did not change the setting over the 8 weeks. Two of the participants changed to the difficult setting after 3, and 5, weeks of the study, citing a need for an increased challenge, as evidenced by participant G12’s comment: “I want all of the fruits [in-game items], so I try to prove to myself that I can get them all.” Most of the participants did not change the difficulty during the study; however, they all appreciated having the option. Evidently, it would appear that this feature was underutilized during the 8 weeks, and it is possible that we need further insights into each participant’s individual reasons. However, the comment by Participant G3 summarizes a general opinion on why this might be the case: “I didn’t change [the difficulty setting], I was happy with mine, but I want to be able to change [the difficulty] if I want.”

6.7 Acceptance

To understand how likely the Game group participants were to use the Recov-R system in future, if given the chance, they were asked to rate this likelihood using a Likert scale (1 = not very likely; 5 = very likely). The findings were also positive (median = 4, IQR = 2), with 11/16 participants, in the Game group, rating above average and 1 person rating below average; this suggests a relatively high acceptance of the system. The participants’ comments on the system, highlighted in the previous sections, provide insights into their willingness to use it for falls rehabilitation in the home. Two of the participants cited health reasons and low confidence, individually, as reasons why they would not use it in the future – detailed in 6.1.2.

7. DISCUSSION

7.1 Encouraging Adherence to Exercise using the Recov-R System (Q1)

Our work suggests, through our statistically significant findings, that the Recov-R system can encourage adherence to a home-based fall rehabilitation programme – in this case exercises used as part of standard care. It is not surprising that the Recov-R exergames were the main motivator for sustained adherence. We found that there are various factors, which were different amongst the participants, responsible for driving the motivation to continue with the programme. First the Recov-R exergames were aesthetically pleasing to the participants, and the activities were found to be enjoyable, engaging and interactive. We can attribute much of this credit to the fact that from the initial concept stage, all of the exergames were co-designed with seniors (see [Uzor et al. 2012]), who determined that a simple look, clear objectives and relevant (to each exercise) goals and scores be key design requirements. Secondly the technology involved was accessible to a majority of the participants, thereby reducing barriers to use. In particular, it was easy to put on the required inertial sensors and access the various functions of the Recov-R system using the keyboard. With the exception of strapping on the inertial sensors and pressing keyboard keys, the participants were not required to do any activity different from expected using standard care, e.g. they were not required to set up a relatively complex system, stand facing any particular direction (for calibration purposes), exercise in a particular location in the home or exercise in a manner that compromises the safety of individuals with balance impairments (e.g. exercising without a stable chair or other suitable surface due to technological limitations). Third, through charts and medals, our participants felt confident that the system catered to their needs regarding progress during therapy; we consider this sentiment paramount to maintaining a continuous interest. To this end, we recommend that...
designers of rehabilitation systems, for the home, ensure that end users be able to undertake their exercises in locations that are accessible with standard care (i.e. the booklet and available space for exercise), whilst ensuring safety, ease of use and an interactive and engaging rehabilitation experience.

Our work agrees with the literature that exergames can encourage adherence to exercise, and our experience, through participant feedback, is similar to other studies that have investigated adherence to exercise through the use of games [e.g. Skjæret et al. 2016 and Vaziri et al. 2017]. For instance, [Vaziri et al. 2017] identified 9 usage indicators that could positively affect adherence, most of which are already employed in our Recov-R system. However, it is difficult to confirm the longer-term (e.g. >12 weeks) effects of the use of exergame systems, such as Recov-R, on adherence to falls rehabilitation in the home, or how seniors will incorporate the use of the system into their daily routines. We expect such longer-term use of an exergame system to be proportional to the perceived value of the system, in terms of the potential benefit for therapy and fall risk, as suggested in the works by [Ogonowski et al. 2016] (6-month study) and [Vaziri et al. 2017] (16-week study).

7.2 Reducing Fall risk through Tailored Exergames (Q2)

From the initial concept, the Recov-R system is unique in that the exergames have been developed on a foundation of exercises used as part of standard care (the OEP and FaME programmes), with effective QOM paramount to the design. It is not surprising, therefore, that our findings reveal statistically significant differences in outcomes of gait associated with fall risk (walking speed, variability in stride length and variability in double support time – DST), between the use of the Recov-R system and standard care. These findings show that the Recov-R exergames have the potential to reduce fall risk by improving these key outcomes of gait [Lee et al. 2014]. There are parallels in the literature that highlight the potential of tailored exergames to reduce fall risk, using other assessment methods, e.g. physiological profile assessment (PPA) [Gschwind et al. 2014] and step reaction time [Schoene et al. 2013].

Upon further reflection, it is possible that the differences in physical function between our study groups can also be due to the fact that the Game group participants adhered more to the programme, thereby completing more exercises over 8 weeks. However, we expect that the differences, in total exercises completed during the study, are not enough to result in such a difference in physical function and that the results would be different had both groups used the same tools for rehabilitation. An example of this situation can be seen in the study by [Ayoade and Baillie, 2014] where it was found that although a control group (using standard care) did more exercises in 6 weeks than an intervention group that received visual feedback during therapy, the latter improved more in outcomes of physical function; the guided visual feedback was credited for this improvement. What implications, then, does this have on the design of exergame systems? We recommend that QOM (recommended range and pace of movement) be embedded in exergame mechanics for maximum therapeutic effect. Furthermore, we suggest that the game objectives reflect QOM, so that scores achieved by completing these objectives can portray a good representation of movement quality. The best way to achieve this, in our experience, is by involving stakeholders in the design of exergames [Alankus et al. 2010; Wulf et al. 2011; Ogonowski et al. 2016], to determine effective metrics of quality and how best these can be incorporated into the design [Uzor et al. 2012].

We suggest, as an opportunity for future work, an investigation into the effects of QOM alone on gait and balance outcomes, that ignores adherence in favor of supervised (or observed) exercise sessions.

7.3 Benefits of using the Recov-R System in Home-Based Falls Rehabilitation (Q3)

The Recov-R system was well received by our participants who rated it highly, on average, with the System Usability Scale (SUS) as well as our Likert scales on effectiveness, enjoyability and ease of use. These findings are not surprising given that the original concepts for the exergames were co-designed with seniors [Uzor et al. 2012]. Furthermore, the Recov-R system as a whole has undergone several design modifications, informed by stakeholder feedback and guided by key HCI design principles in numerous research studies (e.g. [Uzor and Baillie, 2013; Uzor and Baillie, 2014]), to facilitate an accessible and effective rehabilitation tool. Given the study results, we can suggest that the positive experiences with the Recov-R system were influenced by the factors listed in this section.

7.3.1 Tailored exergames.

The Recov-R exergames were modeled on balance and strength exercises, adapted from the Otago (OEP) and FaME Exercise Programmes, used as current standard rehabilitation care in the UK and in many western countries. The design approach for the Recov-R system enabled seniors to perform these same exercises in a way that is more useful to them (e.g. [Lee et al. 2014]).

Furthermore, it is possible that the differences in physical function between our study groups can also be due to the fact that the Game group participants adhered more to the programme, thereby completing more exercises over 8 weeks. However, we expect that the differences, in total exercises completed during the study, are not enough to result in such a difference in physical function and that the results would be different had both groups used the same tools for rehabilitation. An example of this situation can be seen in the study by [Ayoade and Baillie, 2014] where it was found that although a control group (using standard care) did more exercises in 6 weeks than an intervention group that received visual feedback during therapy, the latter improved more in outcomes of physical function; the guided visual feedback was credited for this improvement. What implications, then, does this have on the design of exergame systems? We recommend that QOM (recommended range and pace of movement) be embedded in exergame mechanics for maximum therapeutic effect. Furthermore, we suggest that the game objectives reflect QOM, so that scores achieved by completing these objectives can portray a good representation of movement quality. The best way to achieve this, in our experience, is by involving stakeholders in the design of exergames [Alankus et al. 2010; Wulf et al. 2011; Ogonowski et al. 2016], to determine effective metrics of quality and how best these can be incorporated into the design [Uzor et al. 2012].

We suggest, as an opportunity for future work, an investigation into the effects of QOM alone on gait and balance outcomes, that ignores adherence in favor of supervised (or observed) exercise sessions.

7.3 Benefits of using the Recov-R System in Home-Based Falls Rehabilitation (Q3)

The Recov-R system was well received by our participants who rated it highly, on average, with the System Usability Scale (SUS) as well as our Likert scales on effectiveness, enjoyability and ease of use. These findings are not surprising given that the original concepts for the exergames were co-designed with seniors [Uzor et al. 2012]. Furthermore, the Recov-R system as a whole has undergone several design modifications, informed by stakeholder feedback and guided by key HCI design principles in numerous research studies (e.g. [Uzor and Baillie, 2013; Uzor and Baillie, 2014]), to facilitate an accessible and effective rehabilitation tool. Given the study results, we can suggest that the positive experiences with the Recov-R system were influenced by the factors listed in this section.

7.3.1 Tailored exergames.

The Recov-R exergames were modeled on balance and strength exercises, adapted from the Otago (OEP) and FaME Exercise Programmes, used as current standard rehabilitation care in the UK and in many western countries. The design approach for the Recov-R system enabled seniors to perform these same exercises in a way that is more useful to them (e.g. [Lee et al. 2014]).
provides feedback) and promotes QOM and self-management of rehabilitation in unassisted scenarios, e.g. the home. While commercial exergames can improve balance in seniors [Bieryla and Dold, 2013; Laver et al., 2011], they are limited in the sense that they are not always effective for rehabilitation [Alankus et al., 2010; Lauffer et al., 2014], which is key to reducing fall risk in seniors [Campbell et al., 1997]. In our home study, we found statistically significant results on physical function, highlighting improved gait and balance performance, in a period of 8 weeks. Since our Recov-R exergames were tailored to specific evidence-based exercises, we expect the relatively rapid improvement in physical function to be due to both a combination of increased adherence to exercise and effective QOM promoted through exergame mechanics, with the latter potentially having a greater influence on the outcome.

7.3.2 Interactivity and feedback.

The benefits of digital exergames for providing an interactive experience for seniors is not a new concept and has been reported on in numerous research studies discussed in this paper [e.g. Schoene et al., 2013; Vaziri et al., 2017]. Compared to commercial exergames, tailored exergames have an advantage of providing meaningful feedback during rehabilitation; meaningful in the sense that the feedback is relevant to improved physical function with a direct influence on falls therapy. Through our work we emphasize that, in addition to promoting fun and engagement, the goal of interactivity in such exergames should be to direct the user to accomplishing effective QOM, in a subtle manner, with meaningful scores that correspond to successful achievement. Specific actions in the Recov-R exergames provided our participants with immediate feedback, per repetition, on whether they had accomplished (or failed) an action. The consequence of this is that a greater effort is made on every subsequent repetition in an attempt to correct a failed one or maintain a good performance in the game.

7.3.3 Tracking progress.

One of the more important advantages of technological rehabilitation systems (in comparison to standard care) is the ability to objectively capture information on rehabilitation outcomes, including QOM [Ayoade and Baillie, 2014], as well as provide feedback to users on exercise performance [Alankus et al., 2010; Vaziri et al., 2017]. By observing this progress over time, our participants felt that they were able to track their own personal rehabilitation goals (e.g. improved mobility and activity). Our findings agree with existing work on the importance of communicating rehabilitation progress using simple charts [Ayoade and Baillie, 2014; Vaziri et al., 2017]. However, we also recommend eliciting stakeholder feedback (seniors and physiotherapists) on how this progress can best be communicated to users using suitable means, i.e. how charts elements can be represented so as not to appear complex to users [Uzor and Baillie, 2017].

7.3.4 Accessibility, confidence and ease of use.

The primary goal of HCI is improving interactions between computer systems and users. In falls rehabilitation, there is a special need for HCI in that the primary users of focus, seniors who are at risk of falling, encounter 1 of 2 main problems: a) they likely have little or no experience with digital exergames [Ogonowski et al., 2016], and b) existing health problems (including balance and strength impairments) may limit how much activity they can do, or even where in the home they can do such activities. Although a few of our participants initially did not feel confident in using the system, confidence seemed to improve over time with continued use. This is not surprising, since there is a learning curve associated with the use of any technological system. Nevertheless, our findings indicate that, in addition to the use of technological systems, confidence in rehabilitation exercise can indeed be affected by other health factors or, as found with standard care, a lack of clarity in instruction for effectively performing the exercises. Through our preliminary work [Uzor et al., 2011; Uzor et al., 2012], the Recov–R system incorporated useful exercise movements in the core game mechanics, thereby reducing possible confidence issues due to clarity. Therefore, we reiterate the design of effective exergames should be user centered with seniors playing an active role to identify how to reduce such barriers to successful rehabilitation in the home.

Another useful way to reduce barriers to accessibility is to develop a system that can be used in different parts of the home, as is the case with standard care, rather than restricting users to one location of the home, as may be the case with camera–based (e.g. Kinect) systems. Thus, the Recov–R system was designed with the following philosophy in mind: with a focus on familiar (and evidence-based) exercises, seniors can perform physical rehabilitation in a familiar and natural manner, with minimal training, and in various locations in the home, based on their preferences. With the advancement in recent motion capture/ sensor technologies, making it possible to bridge the apparent divide between standard care and technology–based rehabilitation, we emphasize this as essential in the design of exergames for the home.
7.3.5 Rehabilitation goals.

We found, in our home study, that not all of the participants stated that they set any rehabilitation goals; however, for those that did, the most common goals were related to improving mobility, balance and general activity. These findings suggest the following interesting insights: a) frequent exercise enabled some of the participants to feel like they were fitter and more active at the end of the study; and b) using the progress charts and medals, included in the Recov-R system, the participants felt that they were able to set personal exercise routines, which defines a systematic way of accomplishing their rehabilitation goals. With the ability to track this progress, some seniors felt more confident that they had achieved their goals. The medals, in particular, were considered useful for communicating functional rehabilitation goals and establishing some sort of routine, and discipline, around exercise. This supports existing work, which highlights the benefits of gamification affordances, such as achievements and progress rewards [e.g. Hamari et al. 2014].

It is worth noting that motivational affordances offered by such gamification elements can depend on the qualities of the users and the context in which these affordances are provided [Hamari et al. 2014]. Therefore, further research is needed to investigate the use of medals for rewarding milestones, as described in this paper. With regard to the preferred method of viewing progress (exercise frequency vs. performance), both methods were found to be important, and when used together, they provide a complete picture of rehabilitation progress.

7.3.6 Progression.

Our findings indicate that the ability to progress, to higher levels of difficulty, is an important option for seniors to have in order to support unsupervised therapy. This supports the literature, which is generally positive on the use of progression mechanics [Ejupi et al. 2016; Ogonowski et al. 2016; Skipert et al. 2016; Vaziri et al. 2017], in the design of exergame systems. In this paper, we have demonstrated one method of implementing progression in an exergame system: by adding difficulty levels, based on the effectiveness of rehabilitation exercise, according to established therapy practice (standard care), i.e. elements such as repetition count [Vaziri et al. 2017] and duration of hold for certain movements.

We reflect, here, on our finding that most of our participants did not change the difficulty of the Recov-R exergames, during the study. Most of our study participants were content with the difficulty with which they started. We expect that the following factors may further explain why changing difficulty was not done more frequently in the study: a) the participants might have forgotten that this feature existed in the system, as they might not have remembered everything about the system in the relatively short training time, b) they did not feel like they were ready to progress to a higher difficulty during the 8 weeks, and c) increasing the difficulty could affect their progress record if they did not perform as well, possibly leading to discouragement. It is also important to note that the willingness to progress to higher levels of difficulty might depend on the user and the duration of therapy [Ogonowski et al. 2016]; therefore, additional work is needed to investigate progression in home-based rehabilitation over time.

7.4 Limitations

Firstly, we used outcomes of gait to investigate fall risk. Our chosen outcomes of gait (walking speed as well as variability in stride length and double support time) are effective at predicting fall risk, with walking speed proving a more reliable outcome, than the Timed up and go (TUG) test, to predict falls in certain cases [Viccaro et al. 2011]. However, we did not employ common outcomes of balance used in the clinic and in research, e.g. the TUG test and the clinical Romberg test, that may provide more subtle predictors of impaired balance [Khasnis and Gokula, 2003; Viccaro et al. 2011]. We recommend that future works utilize such alternative outcomes of fall risk (e.g. balance and muscle strength) to further investigate the use of exergame systems to reduce fall risk in seniors.

Secondly, we targeted participants who had multiple fall risk factors, in order to include those who were at high risk and who could benefit most from falls rehabilitation programmes. However, we recruited seniors who were without significant cognitive impairment; this is unavoidable, from an ethical standpoint, to ensure the safety of the individual. Nevertheless, questions remain as to the effectiveness of exergames to assist those with cognitive impairment (e.g. Dementia), during home rehabilitation. Further work is recommended to identify opportunities for the use of exergames by such seniors and those who did not fit within our inclusion criteria.

Thirdly, we measured adherence using self-report diaries; this was necessary because there was no other viable solution to capturing this data (i.e. in the control group) – any influence from the researchers (e.g. visits, observations, etc.) could have affected the outcome. Self-report bias, between groups, is negated by the fact that both study groups reported adherence
using the diaries; however, there are limitations regarding the use of self-report outcomes as employed in this study, e.g., inaccurate reporting. It is also worth noting that we cannot determine how much of adherence can be attributed to the novelty of the Recov-R system; however, this is a general limitation which applies to most, if not all, novel technological exercise solutions, e.g., Nintendo Wii.

Fourthly, although outside the scope of the current paper, it is possible that we could have obtained richer insights into the attitudes, practices and behaviors regarding the use of the Recov-R system, by visiting the participants and collecting such data during the study. However, since this would have potentially confounded our findings on adherence (our primary outcome) it is a potential methodological limitation of our work, in this regard. We direct the reader to the literature, e.g., [Ogonowski et al. 2016], for an example study that discusses the day-to-day use of an ICT falls system in the home.

Finally, the sample size of participants, discussed in the home study, was relatively small for a clinical randomized controlled trial. Therefore, no power calculation was done to determine the effective sample size to achieve statistically significant results [Moher et al. 1994], although our main outcomes of adherence and physical function did achieve statistical significance. We see our findings as preliminary and recommend future work, and larger RCTs, employing power calculations to determine effective sample sizes for further investigations into adherence, gait and balance in falls therapy.

8. CONCLUSION

In this paper, we described the evaluation of an exergame system (called Recov-R) to enhance home-based falls rehabilitation. It is known that physical rehabilitation (evidence-based strength and balance therapy) has the potential to reduce fall risk in seniors. However rehabilitation is not as effective in the home, as it is in group-based therapy, mainly because standard care (booklets and videos of illustrated exercise) is limited in 2 main ways: a) rehabilitation exercise is repetitive in nature and booklets/videos are not interactive, thereby potentially facilitating a boring experience for users, and b) users receive no feedback, on rehabilitation performance or progress, from standard care. Therefore, it is impossible for them to objectively tell if they are benefiting from the exercise programme, with regard to fall risk. These limitations can negatively impact adherence to rehabilitation in the longer term, leading to an increased risk of falling.

The Recov-R system addresses the aforementioned issues in 3 main ways. First the exergames provided an interactive and enjoyable experience for our study participants, thereby motivating them to persist with the exercise programme over time. Secondly, since the exergames were tailored to (designed based on) evidence-based exercises (currently adopted as standard care in the UK and many western countries), the Recov-R system promoted optimal quality of movement (QOM) in each exercise, ensuring that game scores and achievements were in accordance with therapy guidelines. Furthermore, the system provided charts highlighting rehabilitation progress, in terms of performance (QOM) and frequency (number of exercises done) as well as medals highlighting extended therapy goals and milestones. This was done to ensure (and communicate) therapeutic effectiveness – a limitation of commercial exergames currently used in rehabilitation. Thirdly the Recov-R system consisted of a laptop computer (with the software installed) and 2 inertial sensors. This was done to facilitate an accessible system that can be used in various locations of the home (as is the case with standard care), unlike most current solutions, which are often restricted to one location due to the limitations of the employed technologies.

We evaluated the Recov-R system in an 8–week randomized controlled home study, with 38 seniors at high risk of falling. One group, out of 2, received standard care while the other primarily used the Recov-R system in addition to standard care. The study findings suggest that the use of the system can encourage adherence to falls rehabilitation programmes in the home as well as improve physical function (in this case, gait and dynamic balance), thereby reducing fall risk, compared to standard care. Factors that contributed to improved adherence to exercise arose from the aforementioned benefits of the Recov-R system, including: a) enjoyable and interactive games based on standard care, b) the ability to view progress in terms of exercise frequency and performance and c) easy-to-use and accessible technologies that could be used in any part of the home. The findings and resulting discussion in this paper provide useful insights into seniors’ opinions with the use of exergame technologies in the home. These insights can be useful to researchers and designers interested in the development of more effective and useful technologies for rehabilitation in unassisted therapy scenarios, such as the home.

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