Developing an exergame for unsupervised home-based balance training in older adults
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Chapter 1

General introduction
Chapter 1

1.1 | BACKGROUND

Falls are among the leading causes of injury and disability in older adults and account for over 80% of the injury-related admissions of older adults to the hospital [1]. Thirty percent of community living people over the age of 65 years falls at least once per year and approximately 5-20% of the falls result in serious injuries, such as major head trauma, major lacerations or fractures, which may lead to pain, immobility, a reduced quality of life, or even death [2-6]. Fall risk and the severity of injury increase with age, and falls strongly predict placement in a nursing facility [5,7-9]. In the Netherlands 15,000 elderly are admitted with a broken hip after a fall incident each year. The fall-related healthcare expenses including medical treatment, hospitalization and long term care were estimated at €674.5 million per year (2007-2009) in the Netherlands alone [10]. In 2013 these expenses increased to €780 million per year and in 2030 the costs of falls are estimated at €1.3 billion per year [11]. In the United States the costs of falls were estimated at $19 billion in 2000 [12] and $34 billion in 2013 [13]. To contribute to a solution for the significant impact of falls on society, the current thesis aims to develop a training device that enables older adults to improve their postural control, thereby reducing fall risk and ultimately the emotional distress and significant healthcare costs related to falls.

1.2 | APPROACH: METHODICAL DESIGN PROCESS

To realize a solution for the high number of fall injuries, a methodical design approach developed by Verkerke et al. was used, which provides a structured approach for developing biomedical products [14]. Projects in which biomedical products are developed rely on multidisciplinary teams in which knowledge of engineering and medical sciences is integrated. Often, additional fields of expertise such as human movement sciences, information technology, artificial intelligence etc. are involved. The multidisciplinary teams working on biomedical products always consist of stakeholders with different interests and core business. Partners working in companies, for instance, focus on developing commercially viable products or services while researchers working at universities focus on research and scientific output [15,16]. The methodical design process was developed specifically to develop biomedical products in a complex environment with multiple stakeholders [14]. The essential aspects of this approach are to perform an extensive problem analysis, create many ideas to increase the odds of having a good idea, and to postpone decisions in order to gain more knowledge and thus be able to make better decisions. The method starts with an analysis phase in which the problem is defined, the goals are set, a design assignment is formulated and the requirements that are to be fulfilled by the solution are specified. Based on these requirements many potential solutions are generated using brainstorm sessions. The best concept solutions are then worked out in more detail and finally a solution that best matches the requirements is selected, further developed and tested.
1.3 | FALLS IN OLDER ADULTS: PROBLEM ANALYSIS

1.3.1 | Balance and Postural control
In daily life older adults continually face situations challenging their balance. The simple act of reaching for a cup already disturbs balance, and adequate postural adjustments are required to prevent a fall [17,18]. The act of maintaining, achieving or restoring a state of balance during any posture or activity is generally referred to as 'postural control' or 'balance control' [17]. A more technical description often used to define postural control is the ability to maintain the center of gravity, which is the vertical projection of the center of mass on the ground, within manageable limits of the base of support [19,20], which is the area between all points of contact between the body and another surface [19,21].

Three intrinsic systems are essential for proper postural control: the sensory, motor and cognitive systems [22]. Three components of the sensory system that are of major importance for adequate postural control are vision, the vestibular system and the somatosensory system [19]. Vision is used to gain information about the surrounding environment, which is needed to plan locomotion, avoid obstacles and anticipate hazardous situations [19,22]. The vestibular system senses linear and angular accelerations of the head, information which is used to detect self-induced or externally induced perturbations [19,22,23]. The somatosensory system provides information about the position and velocity of individual body segments, as well as their contact with external objects [19,23]. The motor system corresponds with those part of the nervous system and muscles that are responsible for movement, and enables the body to plan and generate movements thereby enabling voluntary movements and automatic responses such as postural adjustments following external perturbations [22,24]. The role of the cognitive system in postural control primarily constitutes interpreting incoming sensory signals, remembering effective strategies to deal with a given situations and allocating attentional resources to (postural) tasks [22].

1.3.2 | Age-related deterioration of postural control
The sensory, motor and cognitive systems are subject to age-related deterioration. Vision for instance becomes progressively worse after the age of 50 [25]. The age-related physiological changes in the eyes have an effect on many eyesight characteristics such as acuity, contrast sensitivity, dark adaptation, accommodation and depth perception [26]. Information about the body orientation in space is further compromised due to a decline in somatosensory input including reduced peripheral sensation [27] and affected proprioception, which constitutes the position sense of body segments [28]. The third sensory channel that is affected by aging is the vestibular system. A decrease in the density of hairs cells already starts from the age of 30 and an estimated one third of the 70+ population has a vestibular impairment [29].

Age-related changes in the motor system result in slower neuromuscular contractile properties, reduced force control and muscle weakness [22,30,31]. Men lose between 54% and 89% of their muscle strength between the age of 25 and 75 in a linear fashion, and the muscle strength of women declines with 48-92% from the age of 41 [30]. Muscle power (the ability to generate force rapidly, or by definition: the energy output per unit of time [32]), which is considered more relevant than strength with regard to recovering from tripping and performing daily activities [22], decreases with 29% to 54% (depending on the muscle group) at age 65 in men, where the greatest loss is found in the lower body [33].
Age-related changes of the cognitive system that most likely affect postural control include deteriorated processes of attention, memory and intelligence [22]. Over the last decades research showed that postural tasks which were previously thought to be highly automated, in fact require attentional capacity [34,35]. The attentional load of postural tasks increase with age and older adults were found to allocate a greater proportion of their attentional capacity to upright stance and locomotion than young adults do [36-38]. Also, the task of postural recovery from an external perturbation is more attentionally demanding for older adults than for young adults [39].

1.3.3 | Effects of age-related deterioration of postural control
The age-related neuromuscular, sensory and cognitive changes in older adults have a detrimental effect on postural control. A larger proportion of attentional capacity is needed in older adults to perform postural tasks, which is caused on the one hand by impoverished sensory input and neuromuscular changes [40,41] and on the other hand by attentional allocation deficits, resulting from the age-related changes in cognitive functioning [34,39]. Adding a concurrent cognitive task to a postural task, also known as a dual task, further challenges balance [34]. A daily life situation where older adults could be at risk of falls due to the increased cognitive demands associated with postural dual tasks is for instance when walking while having a conversation [42,43].

Not only do the odds of ending up in a hazardous situation increase, the aging neuromuscular system also has more difficulties with producing an adequate response in these situations. The loss of muscle power and coordination in the legs reduces the ability to respond to incorrect weight shifts and perturbations [44,45]. The age-related neuromuscular changes also result in a decreased capacity of producing anticipatory postural adjustments (APAs) [46]. This recruitment of postural muscles prior to an expected perturbation, such as a weight shift, is used to minimize balance disturbances [47]. The affected APAs observed in older adults may put them at an increased risk of suffering falls [48-50]. As a result of the decreased ability of anticipating and responding to perturbations, older adults are less successful in recovering balance following trips than young adults are [51].

In summary, the age-related deterioration of the motor system, sensory system and cognition continually disturb balance, resulting in an increased risk of ending up in a hazardous situation and a decreased ability to effectively respond in such situations. These balance problems, which are experienced every day in daily life, ultimately lead to an increased risk of falling [52]. The problem analysis is summarized in Figure 1.1.
Increased fall risk

Environmental hazards and other external factors

Figure 1.1 | Analysis of problems. The scheme shows the causes and effects of fall incidents.

1.4 | GOAL ANALYSIS AND DESIGN ASSIGNMENT

1.4.1 | Goal Analysis

Figure 1.1 shows that the fundamental cause of falls is age-related deterioration of the sensory, motor and cognitive systems. Solving the fundamental problems would logically result in a decrease in fall incidence, as is shown in Figure 1.2. However, not all of these age-related problems can be solved and not all older adults suffer from all of these conditions to a similar extent. The underlying causes of increased fall risk differ per person; one might suffer more from neuromuscular changes, whereas another might have an increased fall risk primarily due to impoverished sensory input [18]. Moreover, the human body
is well able to compensate for defective systems and rely more strongly on intact systems [53]. People who experience reduced peripheral sensation for instance rely more on eyesight [54] and changes in neuromuscular functioning are compensated by adapting strategies to correcting postural sway [18]. Because of the variety in underlying causes of age-related deterioration of postural control and the extent to which systems that are lacking can be compensated, it was decided not to aim to directly improve the individual sensory, motor and cognitive systems, but rather aim to improve postural control as a whole. A solution that improves postural control logically results in a decrease in fall injuries (Figure 1.2).

**Figure 1.2 | Analysis of goals.** The scheme shows the effects of solving the fundamental problems identified in the problem analysis.
1.4.2 | Exercise for improving postural control
A plentitude of studies showed that postural control can be improved in older adults through training. Improving postural control through training is often referred to as ‘balance training’ or training ‘balance ability’. Recent review articles showed that group and home-based exercise programs improve postural control and reduce the risk of falls, and that key components of effective fall prevention training programs include balance training and muscle strengthening [21,55,56]. Review articles by Sherrington et al. and Howe et al. concluded that programs which included challenging balance exercises and a high dose of exercise (>50 hours over a trial period of three months) showed the largest effects on fall rate [21,57].

However, despite the large body of literature providing evidence for the beneficial effects of exercise-based programs on fall risk, older adults are reluctant to participate in these programs [58-60]. The willingness to train postural control is compromised by a broad variety of barriers, including poor health, the effort and cost of traveling, fear of falling, high costs and lack of motivation [61,62]. Many older people reject the idea that they are at risk of falling and will not participate in exercise programs [63]. An estimated 30% of the community dwelling older adults experience motivational barriers to exercise, such as being not interested in exercise or being bored [64,65]. The repetitive nature of traditional strength and balance training exercises was suggested as one of the underlying causes of the low uptake of exercising [66].

1.4.3 | Design assignment
Developing an effective training program for improving postural control, which achieves high adherence rates is not trivial. Recent advances in (information) technology, further discussed in chapter 2, enable new paradigms for training postural control, which potentially might take down some of the barriers experienced when improving postural control through exercise training programs. The approach chosen in the current project was to develop an exercise videogame (exergame) to train postural control. This project was initiated by the SPRINT research institute and the University Medical Center Groningen [67].

The design assignment of the thesis is subject to a number of demarcations. First the target group was defined as community dwelling older adults who can independently walk without walking aids, but already are at increased fall risk due to a deterioration of postural control. The target group was not defined by age, as deterioration of postural control is not caused directly by high age. Very frail older adults were excluded, because the act of training postural control might put this group at risk of falls already. A second demarcation is that the product developed in this project is a technological invention, which is tested in a small group of older adults. To make a technological invention a successful product, it should be accompanied with a social innovation, which is generally defined as a novel mechanism that increases the welfare of the individuals who adopt it compared with the status quo [68]. The concept of training postural control using the chosen approach (exergaming) is new to most elderly, therefore a strategy is needed to ensure uptake of this new training paradigm among the target group.
1.4.4 | Exergames for balance training

Exergames, a portmanteau of exercise and videogames, are videogames that combine play and exercise [69]. The goals set in exergames can only be achieved through bodily movements displayed by the user. The game hardware measures these movements and then rewards the user based on this sensor input. The first exercise videogames were developed in the late 80’s. In 1988 Nintendo (Kyoto, Japan) launched the NES Power Pad system (Nintendo, Kyoto, Japan), a floor mat game controller with twelve pressure-sensitive circles that came with games in which players had to run, jump or make music by pressing the circles with their feet [69]. Konami (Tokyo, Japan) in 1998 used this principle to develop Dance Dance Revolution, a dance simulator game that is again played by pressing pressure-sensitive pads with the feet. Although these games primarily focused on the entertainment sector, potential health benefits were already suggested by the developers. The Power Pad for instance was in the United States briefly sold as ‘Family Fun Fitness’ and dance dance revolution got media attention as a tool for losing weight [70].

Rapid advances in computer processing power and sensor technology led in 2006 to the development of the Nintendo Wii (Nintendo, Kyoto, Japan), which measures the player’s movements using a wireless hand-held controller. This controller allows the user to play for instance virtual tennis, by making movements with the arms and upper body that are similar to movements made by actual tennis players. As an additional Wii controller, Nintendo developed the Wii balance board, a force plate used to control skiing, yoga and other games in which balance plays an important role. The Nintendo Wii was launched as a consumer product and focuses primarily on recreational entertainment for children and adolescents. Nintendo did however sell several games that focused on improving health, such as ‘Wii sports’, in which the player could track weight loss and was given a ‘Wii Age’, which was used as an indicator for physical fitness [71]. In 2010 Microsoft developed the Kinect (Microsoft, Redmond, USA), a camera system that enabled players to play videogames that are controlled without a traditional game controller. Instead the body itself became the controller. Kinect adventures (Microsoft, Redmond, USA), a commercial Kinect game, for instance allows players to hit virtual balls by moving the arms, or to control a raft on a river by taking steps.

Although exergames were primarily developed for commercial use, research groups became interested in using these games as clinical tools for rehabilitation. They developed non-commercial exergames for specific training objectives, such as rehabilitation after stroke [72]. Over the last decade both commercial and non-commercial exergames have been examined for their potential health benefits in a broad variety of patient populations, such as people with stroke [73,74], Parkinson’s disease [75], obesity [76], and multiple sclerosis [77]. In general, these studies report that the effects of exergames are positive, yet weak, but that the potential of exergames is large [73-77].

One of the main advantages of exergames often reported is that exergames add a ‘fun’ component to a training program, thereby increasing motivation to train [66,78,79]. Betker et al. for instance showed that a series of custom made exergames based on weight shifts was considered attractive, motivational and an improvement to conventional exercise regimes [80]. Other characteristics of exergames that are often considered advantageous include the possibility of training both motor and cognitive skills while exercising, playing together with or against other players, the possibility of training at home rather than in a center-based setting, and the relatively low costs of exergame systems [81-83]. Exergames however hold more interesting characteristics that might further benefit training outcome and adherence.
Exergames for instance can provide a training environment with performance requirements and changing game-contexts, thereby accomplishing effective training programs, which include challenging and variable exercises with a large number of repetitions [84]. In this training environment the focus of attention of the player is directed towards the outcome of the movements in the game environment, rather than to the bodily movements themselves. This so-called external focus of attention enhances the learning of motor skills [85]. Moreover, directing the focus of attention to the outcome of a movement in a game task closely resembles daily life, where balance is always embedded in tasks, such as reaching for a cup. While performing goal-directed tasks in a game environment, exergames can provide objective feedback to the user about his motor performance, playing frequency etc. [84]. Many studies have shown the beneficial effects of feedback for the purpose of balance training [86,87]. In exergames feedback can be operationalized for instance by rewarding a correctly executed movement with more in-game success such a higher speed or a better score [88]. When improving physical functioning a player can be more successful in the game.

An interesting feature of exergames is the possibility of capturing movement data while the user is performing the training exercises. When training postural control using an exergame, the bodily movements executed by the user to perform the in-game exercises, are captured using sensors [69]. The readout of the sensors is used to control the game, but could also be stored on a storage medium. These captured movement data hold information about the postural control of a user during a specified exergame challenge. Since the game challenges balance, and success in the game is dependent on balance ability, it can be assumed that the physical functioning of the user is reflected in the movements displayed while playing the exergame. These movement data can be continually captured during gameplay and we hypothesize that the postural control of the individual player can be assessed using these captured movement data. Quantification of postural control during gameplay opens many new exergaming possibilities, including monitoring the progression of a player and adjusting gameplay to his individual needs.

1.4.5 | Aims
The aim of the current dissertation is to develop an exergame that enables older adults to train postural control at home in a fun and motivating manner. More specifically, the dissertation aims to provide insight into the current state of art of exergames for balance training, evaluate the accuracy of exergame hardware, propose algorithms for assessment of postural control, develop an exergame and test a prototype of the exergame developed in the current project in a group of healthy older adults.
1.5 | OUTLINE OF THE DISSERTATION

The current dissertation describes the development and testing of an exergame that enables older adults to train postural control, from defining the problem and requirements to testing the prototype. Chapter 2, ‘Exergaming for balance training of elderly: state of the art and future developments,’ provides a review of the current state of art of exergames for training postural control in older adults. The chapter also discusses the caveats in current ‘off-the-shelf’ exergames and different methodological approaches for measuring balance during gameplay. Chapter 3, ‘User requirements,’ deals with the requirements that have to be fulfilled by the exergame, which were studied using the ‘Users as Designers’ approach. Chapter 4, ‘Suitability of Kinect for measuring whole body movement patterns during exergaming,’ evaluates the accuracy of the sensor that was selected for capturing movement data, thereby controlling the exergame. In Chapter 5, ‘Quantifying postural control during exergaming using multivariate whole-body movement data: A self-organizing maps approach,’ we evaluated the use of self-organizing maps, an artificial neural network, for assessment of postural control using the movement data captured with Kinect.

After exploring the requirements a prototype of the exergame was developed. The resulting prototype of the exergame is described in Chapter 6, ‘An exergame for balance training in older adults.’ The prototype was then tested for a period of six weeks in a group of ten older adults. This study is described in Chapter 7, ‘Exergames for unsupervised balance training at home: a pilot study in healthy older adults.’ Finally, Chapter 8 discusses the findings of the studies and provides directions for further development of the prototype.
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General introduction


