USING VIRTUAL REALITY AS A HOME-BASED STROKE REHABILITATION APPROACH

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Prologue

Stroke is a central nervous system pathology that the World Health Organization (WHO) defines as "a clinical syndrome, of presumed vascular origin, typified by rapidly developing signs of focal or global disturbance of cerebral functions" [1]. The symptoms of stroke persist for more than 24 hours and might lead to death [1]. A stroke occurs when blood supply to the brain is interrupted, damaging affected brain areas. The resulting loss of brain function commonly implies serious cognitive, visual and motor complaints in those surviving a stroke [2]. With over 15 million occurrences each year, stroke constitutes one of the most important causes of death and disability [3] and can be said to be one of the most devastating diseases worldwide [4]. The concern over stroke becomes even more pressing if one considers the demographic changes that are currently leading to an ever higher quota of people aged 65+: Stroke is both most prevalent and most devastating in this age group. According to the WHO's European population projections, the number of new stroke events every year is estimated to increase from 1.1 million in 2000 to more than 1.5 million in 2050 solely due to demographic shifts towards older populations [5].

Given this shift, stroke rehabilitation should be a primary focus of attention in stroke research. The present doctoral thesis represents an effort to improve long-term stroke rehabilitation. Its main hypothesis is that home-based stroke rehabilitation programs specifically targeting balance have the potential to support recovery of locomotor function – one of the most important determinants of quality of life after stroke.

1.1 Stroke-induced motor deficits

Large research efforts are directed at the prevention of stroke. Here the primary focus is on lifestyle factors related to stroke risk. However, because the aforementioned demographic development is to a large extent given, stroke rehabilitation is an important line of attack as well. Although stroke causes a wide range of problems (e.g., pain, memory problems, speech impairments, loss of vision, altered level of consciousness), patients often express impaired locomotor function as a main cause of decreased quality of life. The loss of locomotor function is often caused by stroke-induced hemiparesis – a one-side partial loss of motor function [6-7]. It has been noticed that a large proportion of hemiparalized patients show diminished balance skills and a deviated walking pattern [8-10] involving reduced walking speed, cadence, stride length and an increased left-right asymmetry: so-called 'hemiparetic gait'. Not surprisingly, there is a great need in stroke rehabilitation to achieve a high level of walking skills aimed at regaining independence in walking. In this context balance, endurance, muscle strength and motor

coordination are key contributing factors affecting stroke patients' walking function [11-13]. Since good balance is widely considered as an indispensable prerequisite for normal walking [14-15], the focus on balance in rehabilitative interventions seems mandatory. Accordingly, a therapy program targeting balance should constitute a promising approach to improve walking – and hence quality of life – in stroke survivors.

A large literature body exists suggesting that the initial recovery period after stroke is the most sensitive phase in terms of motor deficit restoration [16-17]. Specifically, the first three months of rehabilitation seem critical for motor recovery after stroke [18]. Nevertheless, there is an increased awareness that meaningful improvements can still be achieved in the later phases of rehabilitation [18]. Consequently, stroke rehabilitation should not be restricted to only the initial period following stroke; it will have to be continued on a long-term basis. Since the treatment of stroke sufferers in hospitals or specialized rehabilitation units is expensive and hence places a large burden on the National Health Service, it is often not feasible to extend the length of stay in rehabilitation facilities. Consequently, for best recovery results, long-term and cost-effective (i.e., largely autonomous) rehabilitation is needed *after* patients are discharged from rehabilitation facilities.

In what follows, the development of a treatment approach that enables long-term rehabilitation for stroke patients discharged from hospitals or rehabilitation units will be presented. This doctoral thesis is based on research efforts within the project 'Rehabilitative Wayout In Responsive home Environments' (REWIRE) [19] funded by the European Commission under the FP7 framework. As such, the idea that stroke sufferers might benefit from an intensive home-therapy program using virtual reality (VR) formed the general framework for this doctoral thesis.

1.2 Virtual reality for rehabilitation

Because recent literature exposed a variety of benefits associated with the use of VR in health care, this technology has become a growing area within rehabilitation interventions [20-21]. A potent feature of VR is its great potential to create a wide variety of realistic scenarios adapted to patients' characteristics and needs. By simulating interactive environments, rehabilitation practice under controlled and safe conditions is provided. After all, a virtual environment can be controlled more easily than a real one, and any accidents will merely be virtual as well. Furthermore, VR seems to fare well in terms of motivating

patients for rehabilitation and better engaging them in the treatment plan [20, 22-25]. This will lead to improved continuity, which in turn positively impacts recovery [26].

The gaming industry has recently provided a set of modern low-cost, VR-based gaming consoles (i.e., the Nintendo Wii, the Sony PlayStation, and Microsoft X-box) that allow motion-controlled interactions with the system. By reliably tracking and responding to users' natural body movements, these commercially available gaming consoles have revolutionized the way videogames are played. Videogames have become more intuitive and, thereby, more accessible to a wider audience [27]. As such, they have become a source of inspiration for health care researchers and sparked the introduction of a novel gaming approach within rehabilitation interventions. In one study, the commercial VR gaming system Nintendo Wii Fit was used as a balance training tool for older adults [28]. The study included 12 *healthy* participants aged 53 to 91 years with a history of falls and reported improvements in balance following use of the Wii Fit system. The actual clinical effect induced by Wii Fit training in the presence of *pathologies*, however, remains speculative. A study by Deutsch et al. [29] suggested that VR-based approaches have great potential to positively affect rehabilitation. A 13-years-old patient diagnosed with cerebral palsy was included in this study. The training intervention consisted of playing commercially available games provided by the Nintendo Wii Fit sports software and resulted in positive therapy outcomes [29]. Similarly, a study performed by Flynn et al. [30] applied a low-cost commercially available gaming platform to promote the post-stroke recovery process. The study intervention included the PlayStation 2 Eyetoy software which consisted of 23 different videogames. Flynn et al. [30] reported that VR created an engaging and motivating therapy situation and, more importantly, that the gaming system beneficially impacted the recovery process and was able to reduce functional impairments stemming from stroke [30]. This study had one substantial limitation though: Based on participant's feedback, some of the PlayStation 2 Eyetoy games were perceived as too complex for the use by functionally impaired individuals [30]. Therefore, the authors emphasized the need for customization in order to optimally address therapeutic needs. This drawback is not surprising, given that the PlayStation 2 gaming system was (and is still being) developed for the leisure industry. In line with the result of Flynn et al. [30], several other studies highlighted that videogames designed for entertainment rather than therapeutic purposes are not perfectly suitable for the use in rehabilitation [3, 24, 31-32]. In all, there is clearly a place for VR-based systems in rehabilitation, but these systems must be tailored to the cognitive and physical constraints – as well as the treatment goals – of the target population.

Recently, the development of such tailored videogames has begun. For example, the VR-based Rehabilitation Gaming System (RGS) proposed by Cameirão et al. [33] focused on the treatment of upper extremity disorders following stroke. Likewise, the ongoing EU funded project FITREHAB [34] aims at developing a VR-based rehabilitation and training platform to provide a customized exercise program. Although this is definitely a welcome development, we feel that these pioneering studies suffer from a lack of tight cooperation between rehabilitation specialists and game developers. More concretely, since established game design principles were largely unheeded, rather boring and unattractive videogames resulted, which arguably lessened the aforementioned motivational merit of the gaming approach to rehabilitation. Importantly, rehabilitation games should not only be tailored to therapeutic goals in which both therapist and patient needs are explicitly considered, but also be based on fundamental game design principles making videogames fascinating and, thereby, rehabilitation more engaging.

1.3 Gentile's motor skill taxonomy for rehabilitation

Strong evidence exists that an effective therapy program in rehabilitation should be theory-based and guided by established motor learning principles [35-39]. Four such principles are *task-specificity* [40-42], *high repetition intensity* [43], *variable practice* [44-48] and *progression* [49-50], all of which promise an increased motor recovery effect and hence serve to ground a physical rehabilitation program theoretically. However, several researchers have recognized – and criticized – the absence of a *practical* framework within which such principled training programs can be developed. What is required is an adequate template to create a gradually progressing rehabilitation program including task-related and variable training exercises. Gentile's taxonomy – a classification system to differentiate motor skills [51] – provides just such a template and hence constitutes a practical tool for developing theory-based training programs. In the following, I will describe Gentile's taxonomy in more detail.

Gentile posits that any motor skill can be specified according to two general dimensions; namely the skill's *environmental context* and the skill's *function* [51-52]. She subsequently divides each of these two orthogonal dimensions (i.e., *environmental context* and *action function*) into four discrete levels so that they form a 4x4-table of 16 so-called skill categories (see Table 3.1, Chapter 3). This table of skill categories forms the basic framework of the taxonomy.

Within the first dimension (*environmental context*), the four levels are defined with two indicators: (a) *regulatory conditions* (i.e., relevant objects or people influencing a person's skill performance) and (b) *intertrial variability*. The regulatory conditions can either be stationary (*stationary regulatory conditions*)

or in motion (*in-motion regulatory conditions*) and these, hence, represent the first two levels of *environmental context*. Indicator (b) then further divides each of these levels according to whether or not these regulatory conditions vary from trial to trial: *intertrial variability* and *no intertrial variability*, respectively.

The second dimension (*action function*) also considers two indicators: (a) *body orientation* and (b) *object manipulation*. The term *body orientation* indicates whether a change in body location is required (*body transport*) or not (*body stability*) in order to perform a skill successfully. This indicator forms the first two levels of *action function*. Indicator (b) then further divides each of these levels according to whether or not the skill requires object manipulation: *object manipulation* and *no object manipulation*, respectively (see Table 3.1, Chapter 3).

Gentile's structured differentiation of 16 skill categories is simple yet accommodates all four training principles mentioned above: It ensures (1) *variable practice* because each of the 16 skill categories is characterized by unique features and (2) systematic *progression* because difficulty increases from the top left to lower right taxonomy corner. Furthermore, it allows for the flexible definition of (3) *task-specific* skill practice and (4) *high repetition intensity*. These favorable characteristics instigated the development of a virtual rehabilitation approach based on the taxonomy proposed by Gentile.

1.4 The instrumented Timed Up and Go test for rehabilitation efficacy assessment

Monitoring activities performed by individuals with chronic conditions (e.g., stroke) participating in home-based treatment programs has been considered a matter of paramount importance [53]. A valuable tool for the clinicians in disease management would be the use of wearable sensor technology to automate clinical testing procedures [53]. The patients could be able to perform the clinical testing procedures independently at home. This would make the regular assessment of the effectiveness of home-based rehabilitation interventions possible. Well-established tools for motor function assessment are, therefore, needed to optimize – for each individual patient – monitoring of the change process after stroke. One fundamental precondition of such a tool is the fulfillment of reliability and validity criteria. Moreover, in a training program focusing on regaining normal walking function, the assessment tool should detect balance and mobility impairments with high sensitivity so that intervention effectiveness can be adequately evaluated. The Timed Up and Go test (TUG) has been shown to meet all those criteria [54-57] and hence it comes at no surprise that it is one of the most frequently used motor function tests

in the stroke population [54, 58-59]. The TUG does, however, have the drawback of focusing only on the single outcome parameter 'time' needed to complete the entire test procedure [57, 60]. Furthermore, the TUG procedure is only considered as a whole and does not allow separate analysis of the subcomponents included in the test (i.e., sit-to-walk, gait, turning and turn-to-sit) [57, 60].

In order to overcome the limitations associated with the original test protocol, the TUG has been 'instrumented' in the sense that small inertial sensors are strategically placed on patients' bodies. By means of these sensors, many additional gait- and transition-related outcomes can be revealed [60]. Previous studies demonstrated that this so-called instrumented TUG (iTUG) is a reliable and valid gait analysis system in both healthy people and subjects with Parkinson's disease (PD). Although this clearly renders the iTUG a promising tool in clinical practice [57, 60], its reliability and validity as a balance and mobility assessment tool *in people with stroke-induced motor deficits* remains to be confirmed.

1.5 The aim and scope of this doctoral thesis

Overall, the present thesis attempts to develop and evaluate a treatment approach using VR for at-home rehabilitation following stroke. The thesis focuses on the development and testing of VR-based rehabilitation games targeting chronic stroke.

Chapter 2 offers the technical context by describing the main gaming functionalities that determine rehabilitation outcome. Specifically, it covers the development of an adaptive game engine system using specifically designed rehabilitation games based on Gentile's two-dimensional classification system of motor skills.

In **Chapter 3**, the focus is on the main clinical guidelines that contribute to positive motor recovery. It discusses Gentile's taxonomy as a promising framework for the development of virtual treatment programs that are consistent with primary motor learning principles. A program is presented that uses six basic rehabilitation games to generate 16 virtual rehabilitation scenarios that each represent one of Gentile's 16 skill categories. Finally, a formal procedure for guiding patients through the rehabilitation process is discussed.

Chapter 4 and 5 constitute the experimental section of this doctoral thesis.

Chapter 4 is based on a usability study in which novel rehabilitation games – developed in the context of the REWIRE project – were applied. The study aimed to investigate whether the VR-based approach

would be usable and effective in improving peoples' gait and balance. The methodological framework recommended by Campbell et al. [61] was used as a basis for this study. Accordingly, the study represents a preliminary exploratory phase (i.e., with untrained healthy elderly) of the large-scale REWIRE project that focuses on stroke patients.

Since, to our knowledge, no study used the sensor-based iTUG to measure functional recovery post-stroke, the study described in **Chapter 5** of this thesis served to investigate the iTUG's reliability and validity in people with stroke. This chapter provides the results of an experiment to assess the test-retest reliability and validity of gait- and transition-related metrics during iTUG performance. Fourteen stroke patients and 25 healthy controls were observed by one researcher in two measurement sessions. Outcome measures were the relative reliability (i.e., intraclass correlation coefficient (ICC)), the absolute reliability (i.e., standard error of measurement (SEM), limits of agreement (LOA) and smallest clinical detectable difference (SDD)) and the iTUG metrics' discriminatory capabilities between stroke patients and healthy controls.

Finally, **Chapter 6** provides a general discussion of the main results presented in this doctoral thesis. With respect to subsequent research studies in the framework of the REWIRE project, implications of the results and limitations are considered. Additionally, new research questions generated by the present results and general conclusions are presented.

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Computational intelligence and game design for effective at-home stroke rehabilitation

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Abstract

Objective: The aim of this article is to describe a game engine that has all the characteristics needed to support rehabilitation at home. The low-cost tracking devices recently introduced in the entertainment market allow measuring reliably at home, in real time, players' motion with a 'hands-free' approach. Such systems have also become a source of inspiration for researchers working in rehabilitation. Computer games appear suited to guide rehabilitation because of their ability to engage the users. However, commercial videogames and game engines lack the peculiar functionalities required in rehabilitation: Games should be adapted to each patient's functional status, and monitoring the patient's motion is mandatory to avoid maladaptation. Feedback on performance and progression of the exercises should be provided. Lastly, several tracking devices should be considered, according to the patient's pathology and rehabilitation aims.

Subjects and Methods: We have analyzed the needs of the clinicians and of the patients associated in performing rehabilitation at home, identifying the characteristics that the game engine should have.

Results: The result of this analysis has led us to develop the Intelligent Game Engine for Rehabilitation (IGER) system, which combines the principles upon which commercial games are designed with the needs of rehabilitation. IGER is heavily based on computational intelligence: Adaptation of the difficulty level of the exercise is carried out through a Bayesian framework from the observation of the patient's success rate. Monitoring is implemented in fuzzy systems and based on rules defined for the exercises by clinicians. Several devices can be attached to IGER through an input abstraction layer, like the Nintendo® (Kyoto, Japan) Wii™ Balance Board™, the Microsoft® (Redmond, WA) Kinect, the Falcon from Novint Technologies (Albuquerque, NM), or the Tyromotion (Graz, Austria) Tymo® plate balance board. IGER is complemented with videogames embedded in a specific taxonomy developed to support rehabilitation progression through time.

Conclusion: A few games aimed at postural rehabilitation have been designed and developed to test the functionalities of the IGER system. The preliminary results of tests on normal elderly people and patients with the supervision of clinicians have shown that the IGER system indeed does feature the characteristics required to support rehabilitation at home and that it is ready for clinical pilot testing at patients' homes.

2.1 Introduction

Novel tracking devices, like the Nintendo® (Kyoto, Japan) Wii[TM] and Balance Board[TM] and Microsoft® (Redmond, WA) Kinect, have made the interface with videogames more natural and intuitive, leading to the success of these devices and their associated games. The capability of measuring the players' movements has been early recognized as a major step forward in realizing cheap and reliable rehabilitation systems in which the patient can be guided through rehabilitation exercises by adequate videogames. Such capability has been explored in the rehabilitation field [1-3] and by recently funded European Commission projects [4-7].

However, it was soon recognized that the videogames developed for the entertainment market are not adequate for the pace and the goals of rehabilitation [8-10]: Their fast interaction, which can be barely matched to the patient's residual functional abilities, and the wealth of targets and distractors make usability low and may produce strain and anxiety. Thus, one hurdle facing the successful use of exercise videogames (or exergames) in older adults and functionally impaired population is that many off-the-shelf videogames are too complex for use by these groups [8]. Videogames must, therefore, be developed to take into consideration the cognitive and physical limitations of the population(s) for which they are intended. This is the reason why games explicitly dedicated to rehabilitation have been recently developed.

In addition, in the REWIRE [4] project, the need for developing game engines of a new generation, specifically targeted for rehabilitation purposes, has been clearly identified. Such engines should have a twofold goal: The first, common to all game engines, is to provide all functionalities for the gameplay, and the second, associated with their therapeutic role, is to provide real-time monitoring and advice to the patient. Rehabilitation game engines should (1) adapt the difficulty and the gameplay to the patients' abilities to avoid frustration and, most importantly, (2) should monitor maladaptation and wrong postures, as these would make rehabilitation more harmful than effective. The game engine should also be able (3) to give an adequate real-time feedback to the patient while exercising.

Another open problem when applying games in rehabilitation is the definition of a rehabilitation schedule based on important training principles (e.g., objective progression in the therapy, with an increasing level of difficulty mapped onto the rehabilitation plan and goals).

In the following, we discuss how these issues have been addressed inside the REWIRE platform. In particular, we illustrate the Intelligent Game Engine for Rehabilitation (IGER) system, developed

specifically to support rehabilitation through games, and how this can be integrated with the definition of an adequate taxonomy for rehabilitation progression through time inspired by the work of Gentile [11].

2.2 Materials and methods

The development of an effective game engine for rehabilitation has to be based on inputs from clinicians and patients. Several meetings have been organized to elicit such specifications. The key issue is that rehabilitation games cannot work as stand-alone applications but must be included into a broader structure involving patients, therapists, clinicians, hospitals, and institutions at the regional/national level. This is specifically the approach pursued inside the REWIRE project, recently funded by the European Commission. The REWIRE platform implements such a broad perspective by integrating three main hierarchical components: A hospital station (HS), a networking station (NS), and a patient station (PS), under the assumption that such a structure enables effective support of at-home rehabilitation.

The HS is used by clinicians to define and schedule the rehabilitation at home. It also monitors the patient's progression remotely and supports a virtual community of patients and clinicians that helps, educates, and motivates the patients. The NS is installed at the health provider site, at a regional level. It provides advanced data mining functionalities to discover patterns in rehabilitation treatments among hospitals and regions. The PS is installed at patients' homes and has at its core the IGER (Figure 2.1), which guides patients through their actual rehabilitation schedule using engaging and targeted videogames and monitors patients' movements and their correct execution of the exercises.

An additional hospital communication module of the station allows patients to interact with the clinicians at the hospital and to download the rehabilitation program and the configuration of the associated games. REWIRE contains also a lifestyle module that collects data on the patient's daily activity through a body sensor network that is used, along with environmental and physiological data, to tune the games' difficulty level, assess potential risks, and advise clinicians on the therapy.

Finally, a virtual community module, managed by the hospital, acts as a client of the patients' community and allows patients to interact with a peer group.
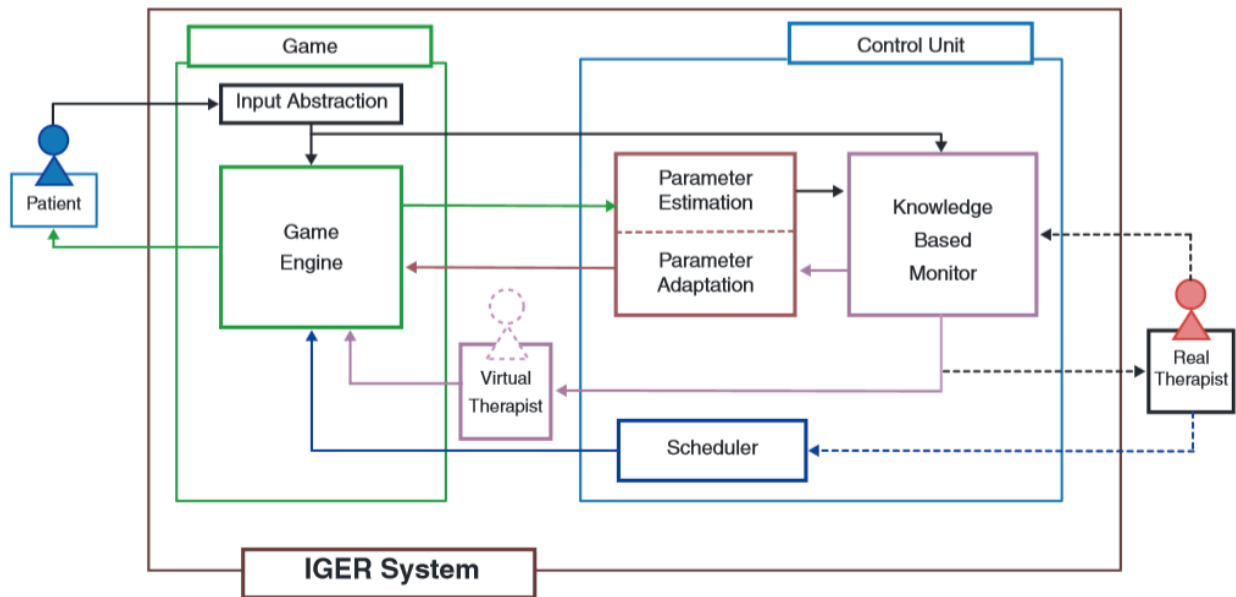
Figure 2.1: The Intelligent Game Engine for Rehabilitation (IGER) and its game and control modules. The connections with the patient and the therapist at the hospital and the virtual therapist, which provides real-time feedback to the patient, are highlighted.

Rehabilitation scheduling

Rehabilitation exercises are designed by therapists with specific goals, for example, (1) to increase or maintain mobility of the joints and surrounding soft tissues, (2) to develop coordination through control of individual muscles, (3) to increase muscular strength and endurance, or (4) to promote relaxation and relief of tension [12].

For each exercise, therapists define the correct way to perform it, and, in one-on-one sessions, they check that patients perform only correct movements and maintain correct postures so as to avoid maladaptation and, therefore, inadequate rehabilitation.

The variety of exercises is quite large and depends on the therapists' idiosyncrasies. Thus, it is difficult to map the therapists' rehabilitation exercises, their goals, and the mandatory posture/movement constraints to their implementation as videogames.

In our work, we guide the mapping between therapy and engaging videogames by using Gentile's taxonomy of motor skills [11], which identifies high-level features of rehabilitation routines and organizes them in a hierarchical structure (Figure 2.2).

Gentile's taxonomy [11] is a two-dimensional matrix that contains exercises with increasing complexity of the addressed functionality (from body stability to body movement) in its columns. In its rows are the

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conditions under which the exercises are executed, from simple static environments to time-varying situations with intertrial variability.

With this taxonomy, it becomes easier to design and configure games for rehabilitation. In fact, any exercise for motor skill rehabilitation (proposed by any therapist) can be classified in one element of the taxonomy according to a progression in recovering functionality. At the same time, rehabilitative videogames can be developed by targeting one element of the taxonomy rather than a specific exercise proposed by a specific therapist, thus broadening the number of therapists and patients who might use it.

	Action Function			
	Body Stability		Body Transport	
Environmental ↓ Context	No Object Manipulation	Object Manipulation	No Object Manipulation	Object Manipulation
Stationary Regulatory Conditions and No Intertrial Variability	1A	1B	1C	1D
Stationary Regulatory Conditions and Intertrial Variability	2A	2B	2C	2D
In-Motion Regulatory Conditions and No Intertrial Variability	3A	3B	3C	3D
In-Motion Regulatory Conditions and Intertrial Variability	4A	4B	4C	

Figure 2.2: Gentile's taxonomy [11], with a possible mapping of exercises and a possible progression for balance and posture rehabilitation. The arrow indicates a possible progression of the patient and the possible mappings of the 'Fruit catcher' game described hereafter.

The IGER game engine

The IGER is the core component of the PS. It comprehends a game engine and a game control unit. The former provides all the basic gaming functionalities (input data, animation, collision detection, rendering, and game logic); the latter controls the game, and it has been developed to match the needs of games for rehabilitation:

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1. It schedules the games, chosen and configured according to the framework shown in Figure 2.2.
2. It adapts the game difficulty level to the actual patient's performance capacity, so that an adequate challenge level is maintained.
3. It supervises the gaming sessions and monitors whether or if the patient's movements comply with the specifications set by the therapist.
4. It displays a virtual therapist (VT) to advise and provide feedback to the patient on the therapy.

Games defined for rehabilitation have to be parametric. Specifically, games should be defined by parameters that can be regulated and adapted, depending on the level of game difficulty. Such parameters are initialized inside the hospital, where the clinician prescribes the therapy and are continuously adapted to each patient's progression. Such parameters can be, for instance, either the frequency of the obstacles and of the targets inside the game or the range of movements required to complete a game successfully. The control unit implements a real-time adaptation of the parameters through a Bayesian model [10]: The patient's performance is monitored, and the success rate is computed online. The parameters are then increased or decreased such that a certain success rate is maintained, where the amount of change is provided by the model.

The patient's movement is also used for monitoring. To this aim, a set of rules of correct execution is defined inside the HS. Such rules represent a knowledge base from the therapist's experience and are coded into logical propositions like, for instance, "do not bend the trunk" or "keep your feet slightly apart". Such rules are then fuzzyfied, defining a maximum range allowed for correct execution (e.g., maximum trunk bending allowed in 20°) and associating automatically intermediate ranges with the values in between (Figure 2.3). A visual interface, showing an avatar inside the game environment, helps the therapists in defining the constraints on the patient's motion.

At run-time the knowledge-based monitor inside the control unit (Figure 2.1) compares the movement of all the body segments with the rules defined inside the HS by the clinicians and raises an alarm level that can be graded: risky situation, bad movement, or wrong movement. If more than one constraint is violated, the most severe alarm level is raised, implicitly combining the fuzzy rules with the logical operator.
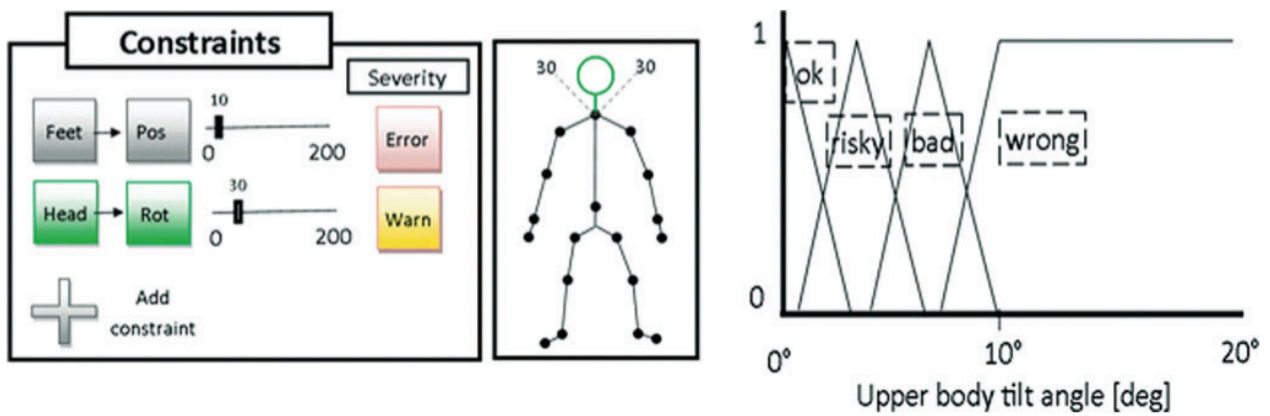
Figure 2.3: The graphical interface used to define the motion constraint inside the hospital station. The automatic fuzzyfication of a parameter on which a rule has been defined is shown.

The monitor supervises also the online adaptation process. Depending on the severity of the alarm raised, the monitor can stop increasing the game difficulty until the patient achieves a correct way of playing.

Once the alarm has been raised, the control unit has to give an adequate feedback to the patient. Inside the IGER we have implemented several methods to provide such feedback. The first method consists of displaying a visual feedback in the form of a text or an icon (e.g., a smiley face) and an audio feedback in the form of a warning sound (Figure 2.4d). The second method consists in showing a VT that can warn the patient that he or she is not doing the exercise correctly (Figure 2.4a). This is an avatar therapist; her face is animated through morphing expressions that are combined randomly to give her a variety of expressions, occasionally tilting the head or blinking the eyes. The three-dimensional model features also simplified lip syncing for a more realistic voice feedback, allowing playing back standard recorded audio messages while the lips of the three-dimensional model move reasonably. The second form of an avatar is a three-dimensional mascot (Figure 2.4b), similar to what Nintendo does with its Wii Balance Board avatar in the Wii Fit games. The third form of feedback is a video of a real therapist (Figure 2.4c), recorded and played back when needed.

In all cases, when the alarm rises to the wrong level, the game is paused, and the avatar inside the game shows the correct posture and movement superimposed on the patient's last movement on the screen to the patient.
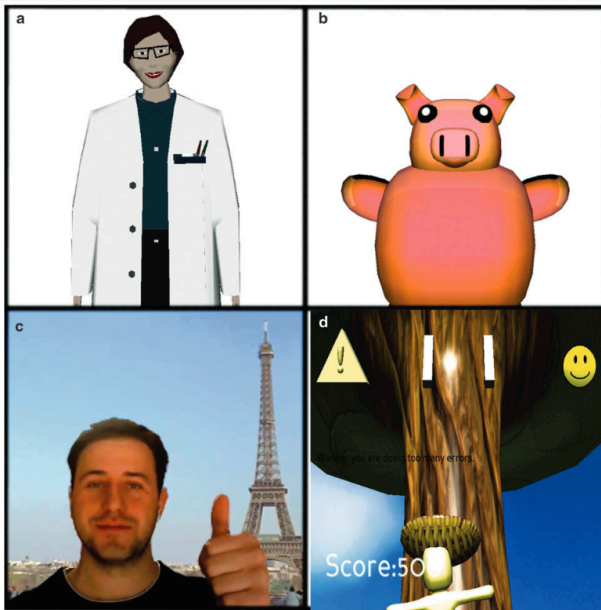
Figure 2.4: The feedback implemented inside the Intelligent Game Engine for Rehabilitation:
(a) a virtual therapist, (b) a mascot, (c) a real therapist, and (d) an icon (smiley face) shown inside the game.

Principles of game design

We have built through our framework a set of minigames, each designed according to the goals and the requirements of the underlying exercises and on the good game design practice [13-15]: Meaningful play, flow theory, and sense of presence have been all incorporated into the design.

Meaningful play states that each game action must have a direct and clearly distinguishable feedback as well as a reasonably lasting effect. This helps the patient in understanding what he or she can and cannot do. It was achieved here through a clear video-audio feedback of the success or failure of a patient's action, represented respectively with a '✓' green symbol displayed on the screen and a nice beep and a 'X' red symbol and an annoying beep.

The second basic principle is the theory of flow, which states that when the skills of the user are matched by the level of challenge posed by the game, the user enters a state of complete focus and immersion in which he or she loses track of time [14]. The patient's appropriate level of exercise difficulty is achieved inside IGER through an adaptation mechanism based on a Bayesian framework [10]. Scenarios and position of targets and distractors of each game are randomized, making the patient feel challenged by always different situations. Music matched to the game scenarios is played during the rehabilitation sessions. The scoring system reflects the rehabilitation nature of the games [8-10, 16]: No negative points are given, or no 'death' occurs, and an actual score value reflects the accuracy and/or speed of

execution of the movement. Former scores are shown along with the actual score to demonstrate improvement over time. All these elements contribute to create a flow experience that, in turn, contributes in focusing on the game. This hides the burden of therapeutic repetitive tasks and the difficulties arising from impairments, under the entertaining experience of a game. This is even more important when we consider that post-stroke patients often fall into depression [17].

The sense of presence is another strong point associated with IGER. As the avatar follows the patient's movements with no appreciable delays, the patient can feel that the avatar represents him- or herself inside the virtual environment and, therefore, the patient has a strong perception of being the actor in the game [18]. This is associated with the use of 'hands-free' tracking of motion, which does not require attaching any device to the patient, allowing the most natural interfacing with the games.

Games for rehabilitation

In our work, we aim to create a set of minigames built on clinically valid exercises and comprehending both monitoring and adaptability. We designed and realized several game concepts that address posture and balance rehabilitation. These games can be mapped on a set of exercises defined through Gentile's taxonomy [11] and share the same theme (in our case, the farm theme) to provide a continuity in gaming during the patient's rehabilitation process. To exemplify, we present here two of these minigames: 'Animal feeder' and 'Fruit catcher' (Figure 2.5), which highlight the flexibility of our approach and the monitoring and adaptation capabilities.
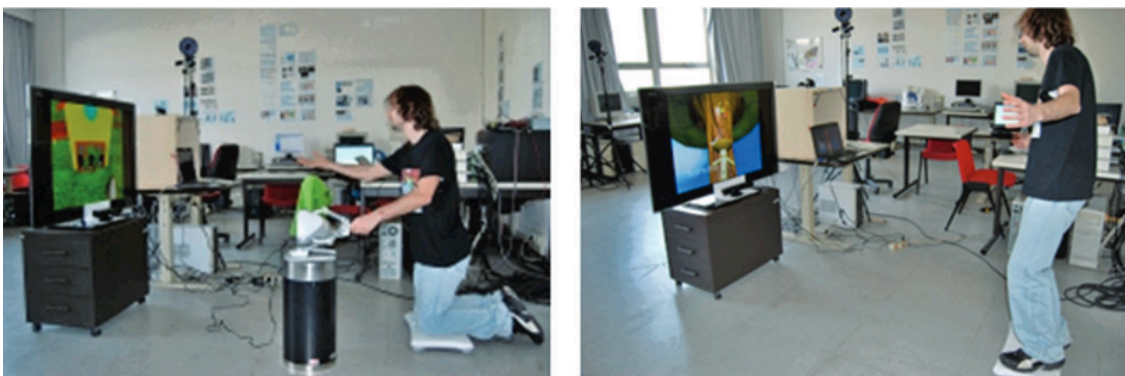
Figure 2.5: Two minigames of the patient station: (a) 'Animal feeder' and (b) 'Fruit catcher'.

The 'Animal feeder' minigame aims to train patients' balance by implementing a dual task. The exercise requires the patient to kneel in front of the display and to move the impaired arm to touch different targets, which are represented by three hungry cows that have to be fed. The cows keep requesting food

by mooing while opening their mouths (Figure 2.5a). The player controls a virtual hand in first-person view. He or she has first to collect some hay and then feed it to one of the hungry cows; when the cow has been fed, the player's score increases. If a cow remains hungry for too long, it groans, and the player's score decreases. In addition, a pitchfork positioned to the left of the player must be kept upright by the player with his or her other hand. If the player fails to do so, the pitchfork breaks, and the player's score decreases. 'Animal feeder' can be currently played with different devices. In particular, here the player's hand was tracked through a Kinect camera positioned above the display, while the pitchfork was controlled by Novint Technologies (Albuquerque, NM) Falcon® haptic device, which produces an elastic force to the patient's hand proportional to the hand displacement. Note that devices not used for gameplay can still be used for additional monitoring of the patient. For instance, Figure 2.5b shows how Nintendo's Balance Board is used to monitor the position of the foot center of pressure while performing a game. In this case, the oscillations do not affect the gameplay, but provide useful information in terms of a patient's balance capability.

The 'Fruit catcher' game (Figure 2.5b) is built on two different exercises. For the first exercise, the patient is required to shift his or her upper body to the left and to the right side, while keeping the feet still on the ground. For the second exercise, the patient must move laterally inside the minigame. In the basic concept of 'Fruit catcher', the player must catch fruits falling from the top of a tree. The player avatar stands below the tree with a virtual basket on its head and can move the body laterally to catch the fruits with the basket. The player's score increases when a fruit falls into the basket. The fruits fall from different heights and from different positions on the horizontal axis and at a different frequency. Like the 'Animal feeder' game, it can be played with different devices (e.g., the Nintendo Wii Balance Board or the Microsoft Kinect). The choice of the input device, in this case, depends also on the exercise rationale, showing an example of separation between game and exercise. When using the Nintendo Wii Balance Board, the player is constrained to keep the feet on the board. Thus, only the first exercise can be done in this way. When using the Microsoft Kinect, instead, the player can move freely around the play area. In this latter case, the exercise can be either of the two described above. In Figure 2.2, we can see where the two exercises are mapped over Gentile's taxonomy [11]. A possible progression inside the taxonomy is shown in Figure 2.2: The patient starts with an exercise classified as 1A, which belongs to the lowest classification, defining an easy exercise. In this case, using the 'Fruit catcher' game as an example, the patient may only have to stand still and not to move in order to not disturb the tree; otherwise, its fruits would fall down. As the patient progresses and improves strength and balance capability, the game may move toward the 1D box, adding both body transport (requiring the patient to move around) and object

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manipulation (adding the basket on the head and the requirement to catch fruits). Then, the patient may be presented with intertrial variability, moving the classification to 2D. At last, the patient may be required to meet birds flying around the virtual area and disturbing his or her focus, thus moving the classification toward 4D.

To accommodate such a variety of tracking devices, we have inserted an Input Abstraction Layer inside the IGER. Our prototype currently supports the Sony (Tokyo, Japan) PlayStation® PS3[TM] Eye camera, the Microsoft Kinect camera and its microphone array, the Wii Balance Board, or the Tyromotion (Graz, Austria) Tymo® plate and two haptic devices (the Omni® Phantom® [Sensable Technologies, Wilmington, MA] and the Novint Falcon). The input devices can be combined for additional control over game elements or for implementing dual tasks.

2.3 Discussion

Many authors have acknowledged the power of immersion associated with virtual reality and games in particular [19, 20]. This is referred to as presence; it would facilitate the rehabilitation sessions by providing a fun, interactive environment that challenges the skills of the player and immerses the player in a virtual world. Such an approach would limit the typical boredom and fatigue in traditional rehabilitation: The patient, while exercising, should feel like a player, focused on having fun while playing the game. To fully achieve this, games should be designed according to good games design principles to avoid coming up short in engaging the patients.

However, engaging games are not enough: Adaptation, monitoring, and real-time evaluation of the movements should be provided to the patient in real time. Such functionalities are not provided by commercial games, but are indeed incorporated inside the IGER system. In fact, (1) IGER allows configuring the game inside the HS, setting the parameters associated with the level of difficulty most adequate to the patient's functional status, and then it continuously adapts these parameters to the patient's performance to continuously challenge the patient at the proper level at any point during the rehabilitation process. (2) IGER allows the continuous monitoring of patients' actions and postures within the game engine, and it aims to enforce a correct execution of the rehabilitation movements. (3) IGER integrates a real-time feedback to the patient of his or her performance and of possible wrong movements, according to the rules set by the therapists.

Monitoring and real-time feedback have been designed to substitute for, although to a limited degree, the therapist. In one-on-one sessions, these functions are provided by the human therapist, who cannot

be present at home during rehabilitation. The monitoring role is achieved by the fuzzy monitor that implements the rule defined by the therapist him- or herself, mainly to avoid maladaptation. The rules operate in real time on the motion data and are downloaded from the HS at game configuration time.

The social aspects of rehabilitation are very important for patients and must be considered when designing a platform for home rehabilitation. For instance, in one-on-one sessions, the therapist is a major source of motivation for the patient [21], but this component is missing during home rehabilitation. To avoid isolation, which diminishes the appeal of a rehabilitation session, IGER provides an informative evaluation to the patient, besides displaying a balanced score that reflects performance on the actual exercise, by means of a VT that, through speech, evaluates the patient's performance of the exercise.

Given the importance of the issue, we have evaluated several feedback modalities. Icons (e.g., a smiley face) and sounds are especially useful because they provide immediate and easily understood feedback to the patient. Moreover, visual icons and sounds have a more immediate effect than the VT; they are less intrusive and less annoying when repeated often. For this reason, we use them for the simple and more frequent warnings.

The VT, because of its resemblance to a real therapist, allows the patient to feel the presence of a more serious character supervising his or her activity. The mascot, on the other hand, can be beneficial as a motivator because of its funny aspect and movements, enhancing the playful aspect of the application. The video is useful because of its realism and the presence of a real person, who could be preferred by the patient for a greater degree of empathy with the therapist. This implies a somehow stereotyped video style, as the amount of variability in the video appearance is much less than with mascots or three-dimensional models. We believe that there is not a single best feedback, but each patient will have his or her own preference, depending on personal idiosyncrasies.

The VT and the mascot can also be displayed between two games (exercises) of the same session to introduce the exercises and accompany the patient along his or her training period. In addition, they appear during the introduction of the game to explain its rules and during the course of the game, encouraging and motivating the players according to their performance. Lastly, they appear when the game is stopped because of wrong movements, explaining to the patient what went wrong and what the patient should do.

A proper game design and games specifically designed for therapeutic purposes are not sufficient. A complete rehabilitation program is required, and this can be defined only by a clinician. Besides the game engine, a clear definition of a rehabilitation path is required to support intensive prolonged rehabilitation processes. The therapist has still the fundamental role of the supervisor, although remotely from the hospital. The succession of games inside the rehabilitation program is customized by the therapist for each patient according to his or her impairments; the program is defined at the hospital, according to the rehabilitation goals set with the patient and the current position of the patient inside the taxonomy (Figure 2.2). The therapist can also fully configure each game, thus tailoring the underlying exercise to the patient's health status. For instance, the therapist can define, for each exercise, what input device should be used, how long the exercise should last, how far the targets can travel, and how fast they can move. Finally, the therapist has an important role concerning the definition of the knowledge base on which the rules monitor a patient's movements and his or her constraints are built upon. A personalized rehabilitation program can therefore be obtained.

2.4 Conclusion

This work is the result of a tight collaboration among game developers, human movement scientists, and physical therapists and aims at building engaging games that implement therapeutic exercises targeted to at-home rehabilitation. We designed the IGER platform to take up some of the therapist's functions during home rehabilitation. Although completely replacing the therapist's skill is beyond reach, the IGER system can make rehabilitation at home a viable option, especially if intertwined with periodic rehabilitation sessions at the reference hospital with the reference clinicians maintaining, therefore, a personal relationship that is presumably fundamental for prolonged rehabilitation.

Authors' contributions

NAB contributed to the conception and design of the manuscript, and writing the manuscript. MP and PLL have been involved in drafting the manuscript and critically revised the manuscript. SW made substantial contributions to conception and design of the manuscript, and participated in drafting the manuscript. EDdB participated in drafting the manuscript and revising it critically for important intellectual content. All authors read and approved the final manuscript.

Acknowledgments

Conflict of interest statement

No competing financial interests exist.

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3

Design considerations for a theory-driven exergame-based rehabilitation program to improve walking of persons with stroke

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Abstract

Virtual rehabilitation approaches for promoting motor recovery has attracted considerable attention in recent years. It appears to be a useful tool to provide beneficial and motivational rehabilitation conditions. Following a stroke, hemiparesis is one of the most disabling impairments and, therefore, many affected people often show substantial deficits in walking abilities. Hence, one of the major goals of stroke rehabilitation is to improve patients' gait characteristics and hence to regain their highest possible level of walking ability. Because previous studies indicate a relationship between walking and balance ability, this article proposes a stroke rehabilitation program that targets balance impairments to improve walking in stroke survivors. Most currently, available stroke rehabilitation programs lack a theory-driven, feasible template consistent with widely accepted motor learning principles and theories in rehabilitation. To address this hiatus, we explore the potential of a set of virtual reality games specifically developed for stroke rehabilitation and ordered according to an established two-dimensional motor skill classification taxonomy. We argue that the ensuing 'exergame'-based rehabilitation program warrants individually tailored balance progression in a learning environment that allows variable practice and hence optimizes the recovery of walking ability.

3.1 Introduction

Virtual reality technique can be combined with targeted exergames development with the aim to promote motor rehabilitation. Recently, a number of researchers have pointed to the potential of virtual reality applications in health care [6, 20, 28, 36, 47, 49] and hence sparked the introduction of this technology within rehabilitation medicine. The use of so-called 'exergames' – virtual reality games that involve physical exercise – has been proposed as a valuable instrument to encourage participation in rehabilitation and improve the adherence to therapy programs because of engaging the user [6, 12, 47]. For example, a study by Rizzo and Kim [47] demonstrated that virtual reality-based games reduce patients' dreariness and simultaneously increase their motivation for rehabilitation practice. Accordingly, virtual reality provides the capacity to simulate scenarios that are effective in attracting the performers' attention. Simulated circumstances can be used to elicit a thrilling ambience, whereas the patient can still perform movement and behaviors in a safe and controlled environment.

For best results in rehabilitation, videogames specifically designed for therapy should be used [5]. Because conventional videogames were primarily developed for entertainment purposes [62], most of these are not practical for rehabilitation [5]. One hurdle facing the successful use of exergames in rehabilitation is that many off-the-shelf videogames are too complex for use by functionally impaired persons or elderly people [12]. Videogames must therefore be developed to take into consideration the cognitive and physical limitations, as well as the interest sets, of the trainees [12]. To date, however, the vast majority of research has focused on games developed for the entertainment market which fails to adapt the gameplay according to patients' rehabilitation requirements [43].

FP7 is the short name for the 'Seventh Framework Programme for Research and Technological Development', the European Union's main instrument for funding research in Europe running from 2007 to 2013. FP7 is also designed to respond to Europe's employment needs, competitiveness, and quality of life [c.f. http://ec.europa.eu/research/fp7/index_en.cfm]. The research project 'Rehabilitative Wayout In Responsive home Environments' (REWIRE) [45], which is funded by FP7, aims to develop, integrate, and field test an innovative virtual reality-based rehabilitation platform for people with stroke. The platform should allow patients, discharged from the hospital, to continue intensive rehabilitation at home under remote monitoring by the hospital. The main idea is to combine off-the-shelf components (e.g., the tracking device Microsoft Kinect [30], the force plate Tymo [57]) in a robust and reliable way and render a system that can be used in the stroke patients' homes. In the context of the REWIRE project, the need has been recognized for exergames specifically targeted at walking rehabilitation [5].

When creating a virtual reality-based stroke treatment approach, the development of suitable exergames is undoubtedly an important requirement. There have been, to date, some studies that deal with the development of videogames adequate for therapy purposes. Based on specific game design principles, they intend to provide engaging and challenging treatment conditions to achieve a high level of motivation for rehabilitation practicing [1, 6, 7, 24, 33, 42, 58]. Moreover, it is important that the developed exergames are functionally integrated in a well-elaborated therapy program. On the one hand, the rehabilitation program should be aimed at appropriate rehabilitation goals. That is, it should be aimed at those goals that are considered to be essential for (and by) stroke victims. On the other hand, the rehabilitation program should be consistent with established training principles to successfully reach these goals. In this article, we describe how tailored exergames for stroke patients can be developed based on a theoretical framework. We will discuss key exergame design and training program content considerations for patients with stroke, which may be theoretically linked to impaired walking performance due to the stroke event.

3.2 Stroke-induced motor impairments and their treatment approach

In the United States of America[1], there are about 4.8 million survivors of stroke of whom about 1.1 million suffer lasting functional disabilities [14]. The specific disabilities caused by stroke vary greatly depending on the brain area that is damaged. Hemiparesis – a paralysis that characteristically affects an arm and leg on one side of the body – is one of the most common stroke-induced impairments [34] and often leads to a number of negative walking-related consequences. The typical 'hemiparetic gait' post-stroke is associated with a reduced walking velocity, cadence and stride length, with gait asymmetry, and with a prolonged double support and stance phase duration of both lower extremities [15, 26, 27, 44, 60]. It is for this reason that many stroke victims show marked deficits in walking abilities [50]. There is general agreement that an association exists between the degree of independent mobility and quality of life [46, 53, 55]. Consequently, a central goal of stroke rehabilitation should be to improve gait characteristics and to retrain the patient to the highest possible level of walking ability [16, 34]. The findings demonstrated by Vincent et al. [59] confirmed the importance of enhancing stroke patients' functional mobility through rehabilitation. Vincent and colleagues [59] set out to reveal rehabilitation needs from the perspective of four different parties involved in the stroke rehabilitation process (stroke patients, caregivers, health professionals, and healthcare managers) so as to better plan the post-stroke treatment service. According to patients' statements – which, in our view, should have high priority

when designing rehabilitation programs – continued rehabilitation should focus primarily on motor activities, such as walking. Patients' statements thus further highlight the importance of gait recovery.

Good balance skills are an important determinant of walking performance and impaired balance ability is assumed to be related to a decreased locomotor function [18, 61]. Considering that hemiparesis not only affects gait characteristics, but also often leads to diminished balance skills, a post-stroke rehabilitation program targeting deficits in static and dynamic balance may be an effective way to restore independent functional walking. In recent years, another factor contributing to walking recovery has been suggested: Several authors noted that task-related activities lead to greater improvements in post-stroke walking competency than non-task-related practices [13, 41, 48]. Specifically, they suggested that intervention protocols that include actual walking tasks improve walking skills to a greater extent than rehabilitation programs that do not. Additionally, there is robust evidence in the motor learning literature that the best outcomes in terms of long-term retention and transfer of skills are achieved when principles of motor learning are integrated into treatment protocols. In rehabilitation, it is widely accepted that more practice is better and that an intense structured therapy program with numerous repetitions of various, challenging tasks supports motor skill acquisition [38]. Specifically, two important elements in our consideration are the motor learning principles *variable practice* and *progression*. These principles are known to positively affect gait rehabilitation and, hence, should be considered in developing a rehabilitation program.

The literature to date has found that variable practice leads to better transfer and retention of motor skills than if a constant practice structure is used [22, 23, 31, 38, 51]. Instead of performing one task repeatedly and always in the same manner (constant practice), a specific task should be practiced differently throughout a treatment session by varying the conditions of practice (variable practice) [38]. Krakauer [31] – in his contribution published in the *Current Opinion in Neurology* – stated that variable practice is a fundamental principle in terms of retaining learning over time and that a consistent agreement in the literature exists indicating that varied practice is superior to repetitive identical tasks when it comes to motor learning. The principle of progression holds that motor learning and rehabilitation programs benefit from a continuous adaptation of task difficulty to increasing skill level [19]. For successful learning, an optimal challenging training situation should be given providing an appropriate task difficulty level according to individuals' capacities [17]. Furthermore, it can be hypothesized that the training effects will be enhanced when the locomotor practice gets combined with direct feedback; e.g., visual feedback. Visual feedback can be used to provide information about a

patient's movement or the result of a movement and is known to promote postural control and stability [2, 19, 25, 52, 61].

From the above, it follows that rehabilitation programs for stroke survivors are well-advised to train balance and walking skills by means of a variety of balance- and walking-specific exercises, the difficulty of which is progressively adapted to patients' skill level, in combination with direct visual feedback on performance.

Although previous studies have emphasized the importance of theory-based practice and rehabilitation [3, 11, 37, 56], there is still a lack of established concepts underlying the practical implementation of motor skill learning principles and theories in rehabilitation. A desirable template would be one that is simple and feasible and that facilitates the task-specific, progressive, and variable training of balance and walking skills. The motor skill taxonomy proposed by Gentile [21] seems to constitute just such a template for rehabilitation programs because it provides a two-dimensional basis for classifying a variety of motor skills. Based on the above, the aim of this article is to develop and describe a tailored exergame-based stroke rehabilitation program that is based on a theoretical framework.

3.3 Methods

Four prevalent classification systems exist for identifying common characteristics of motor skills. Three of these categorize motor skills according to one common characteristic of the skill and lead to one-dimension classification systems. In contrast, Gentile's taxonomy considers two general skill characteristics and offers, therefore, a broader concept leading to a two-dimensional classification system of motor skills. To highlight the high potential of Gentile's two-dimensional approach, it is worthwhile to focus at first on the one-dimensional classification systems and discus some of their limitations:

A description of these classification systems is given by Magill [35] (pp. 5–16). One one-dimension classification system differentiates skills depending on the sizes of the primary muscle groups required to produce an action (gross motor skills vs. fine motor skills). A second one-dimensional system considers the specificity of a movement's beginning and end points to categorize motor skills (continuous motor skills vs. discrete motor skills). The third one-dimension classification system makes a distinction according to the stability of the environmental context in which an action is being performed (open motor skills vs. closed motor skills) [35, 38]. These one-dimensional classification systems raise the

problem that they fail to capture the complexity of many motor skills [35] by only focusing on a single aspect of motor skills.

3.4 Gentile's motor skill taxonomy

Gentile presented a systematic classification system to categorize motor skills and movement according to two general dimensions of physical actions [32]. The first dimension, *environmental context*, refers to the environmental conditions to which the performer has to react in order to successfully perform a task. This dimension is characterized by two indicators: (a) *regulatory conditions* and (b) *intertrial variability*. The *regulatory conditions* indicate relevant environmental features that constrain movement execution and may either be stationary (*stationary regulatory conditions*) or moving (*in-motion regulatory conditions*). With the indicator *intertrial variability*, Gentile's taxonomy differentiates between regulatory conditions that change between trials (*intertrial variability*) and those that do not (*no intertrial variability*). The second dimension, *action function*, is also characterized by two indicators: (a) *body orientation* and (b) *object manipulation*. *Body orientation* indicates whether an action requires the performer to move from one location to another (*body transport*) or not (*body stability*). *Object manipulation* indicates whether an object has to be controlled during the action performance (*object manipulation*) or not (*no object manipulation*).

Through the interaction of the resulting four environmental context characteristics and four action function characteristics, Gentile defines 16 different motor skill categories that provide a comprehensive template to classify motor skills (Table 3.1). The taxonomy is a good means of becoming aware of the skill characteristics that make skills distinct from, as well as related to, other skills, and is an excellent guide for establishing practice or training routines [35].

According to Gentile, the easiest skill category can be found at the top left position (1A). Moving either rightward or downward in the table renders the skill category more difficult, so that the most difficult skill category can be found at the bottom right of the table (4D). For the action function dimension, this implies that body transport is more difficult than body stability and object manipulation more difficult than no object manipulation. Importantly, it also assumes a hierarchy in the action function characteristics: skills involving body transport but no object manipulation are more difficult than those involving object manipulations but not body transport. For the environmental context dimension, the same pattern of progression is assumed.

Thus, Gentile's taxonomy allows a systematic progression in difficulty of motor tasks and meets the demand of the motor learning principle *progression*. Moreover, each of the 16 categories is associated with unique features based on the two-dimensional approach and, consequently, the taxonomy involves task variations. Obviously, Gentile's classification system is consistent with the motor learning principle *variable practice*.

Table 3.1: Gentile's taxonomy of motor skills [35].

		Action Function			
		Body Stability		Body Transport	
Environmental Context		No Object Manipulation	Object Manipulation	No Object Manipulation	Object Manipulation
Stationary Regulatory Conditions	No Intertrial Variability	1A	1B	1C	1D
Stationary Regulatory Conditions	Intertrial Variability	2A	2B	2C	2D
In-Motion Regulatory Conditions	No Intertrial Variability	3A	3B	3C	3D
In-Motion Regulatory Conditions	Intertrial Variability	4A	4B	4C	4D

There are several reasons for assuming that this taxonomy provides a valuable tool for developing a theory-based rehabilitation program using virtual reality. Considering the explanations above, it is evident that Gentile's taxonomy is in accordance with the generally accepted motor learning principles *progression* and *variable practice*. The taxonomy provides a well-structured framework and the 4×4-

table can serve as a useful guide for preparing a systematically coherent motor learning concept in a simple manner. For implementing Gentile's taxonomy-based approach, exergames might demonstrate an optimal opportunity for providing beneficial treatment conditions. On the one hand, as we referred above, there is high potential for creating a motivating rehabilitation environment using virtual reality. On the other hand, the taxonomy seems suited for virtual reality applications where the environment, task complexity, and other contextual factors related to exercise performance can be manipulated. Exergame parameters can be easily modified and, thereby, adjusted to the demands of the taxonomy-included skill categories.

3.5 Gentile's taxonomy-based exergames to improve stroke patients' balance and walking skills

To provide a post-stroke rehabilitation program focused on improved balance skills in standing and walking in accordance with Gentile's framework, we designed six basic exergames. Based on these six basic exergames, we created 16 virtual reality scenarios, either by making game parameter modifications or by substituting another basic game. Each scenario corresponds to one of the 16 skill categories included in the taxonomy (Table 3.2).

In accordance with a phased iterative approach suggested by Campbell et al. [8], this paper demonstrates the theoretical phase – the first step – when developing and evaluating complex research-based interventions to improve health. Thus, a set of six basic exergames appears to be appropriate in the research process of designing an exergame-based stroke rehabilitation program. It keeps the number of games that have to be developed manageable and – with the same game being implemented across adjacent skill categories – it renders systematic progression more straightforward.

Table 3.2: Exergame scenarios corresponding to Gentile's skill categories.

		Action Function			
		Body Stability		Body Transport	
Environmental Context		No Object Manipulation	Object Manipulation	No Object Manipulation	Object Manipulation
Stationary Regulatory Conditions	No Intertrial Variability	1A Scarecrow	1B Blueberry Collector	1C Frog Jumping	1D Frog Jumping
	Intertrial Variability	2A Blueberry Collector	2B Blueberry Collector	2C Frog Jumping	2D Frog Jumping
In-Motion Regulatory Conditions	No Intertrial Variability	3A Tractor Driver	3B Fruit Catcher	3C Worm Hurdler	3D Worm Hurdler
	Intertrial Variability	4A Tractor Driver	4B Fruit Catcher	4C Worm Hurdler	4D Worm Hurdler

Below, we will briefly describe the content of each of the 16 skill categories.

1A

The first phase of the rehabilitation program focuses on the basic physical skill of standing quietly. In this exergame, the patient is represented as a scarecrow avatar and is required to maintain a cursor indicating the body's center of pressure (COP) within a predefined marked circle on a computer screen [39]. The exergame focuses on stance steadiness (sway) that demonstrates a relevant aspect related to an individual's balance ability [39]. Due to hemiparesis after stroke, patients often show an increased amount of postural sway [39].

1B

Whereas the game *Scarecrow* described for skill category 1A demands a centered and stable COP position, this game (called *Blueberry collector*) uses controlled COP displacements for successful performance. This exergame targets stroke patients' dynamic stability, because subjects with hemiparesis often suffer from reduced limits of stability [39]. The virtual environment represents a field of blueberries, which have to be collected by a virtual farmer. The farmer's moving is controlled by the patient's weight shifting tasks and, in this way, the blueberries can be gathered. Because the position of the berries in the field is fixed and unvarying between the different exergame trials, *stationary regulatory conditions* are given and *no intertrial variability*. To meet the requirement of *object manipulation*, a virtual basked filled with blueberries is placed on the farmer's head. In order to prevent berries from falling down, the patient must adopt an ideal upright body posture.

1C

Previous exercise interventions have shown that stepping exercises indicate an effective treatment method to improve postural stability and balance [9, 29, 40]. Accordingly, this exergame (called *Frog jumping*) requires the control of the COP displacements during stepping movements. The virtual environment represents a pond with several stones placed in it. By doing steps in a specific direction, the patient can control a frog jumping from one stone to another. A virtual arrow indicates which particular stone has to be targeted by the patient. In accordance with the taxonomy conditions, the position of each stone within the pond is fixed (*stationary regulatory conditions*) and the order of the targeted stones unchangeable from one exergame trial to the next (*no intertrial variability*).

1D

According to Gentile's taxonomy, the skill category 1D can be seen as a progression of 1C. Thus, the game *Frog jumping* described for 1C can be extended by integrating an *object manipulation* task. Specifically, in this game, the virtual frog is wearing a crown and it is the patient's task to perform stepping tasks with an upright body position in order to keep the virtual crown correctly positioned.

2A

The game *Blueberry collector* described above is not only adequate for skill category 1B, but also for category 2A by making small adaptations. On the one hand, the virtual basket on the farmer's head has to be removed to get the condition *no object manipulation*. On the other hand, because *intertrial variability* is required, the position of the berries varies within exergame trials.

2B

For skill category 2B, the exergame *Blueberry collector* for category 2A can be extended with an *object manipulation* task. Thus, the virtual farmer is balancing a basket on his head such as in the exergame described for skill category 1B.

2C

We use the game *Frog jumping* described for category 1C with the only modification of providing a random order of targeted stones – marked by the arrow – to realize *intertrial variability*. Consequently, each time when the game has been played, a unique step performance pattern is required by the patient.

2D

To meet the taxonomy requirements in skill category 2D, the game *Frog jumping* of category 2C can easily be adapted. The only modification that has to be done concerns the need for *object manipulation*. Hence, in this game, the frog is wearing a crown for which the patient has to control his or her position while playing the game.

3A

For skill category 3A, we created a game called *Tractor driver*. The exergame presents a moving tractor for which the driving speed is defaulted by the videogame. The direction of driving is controlled by the patient's weight shifting movements. When playing this exergame, the ability to move the COP in a standing posture without loss of balance (dynamic stability) is being trained [39]. Specifically, the purpose of this game is to fork up hay bales through directing the moving tractor from one hay bale to another. The hay bales are widely spread over the soil. Considering that the speed of the moving tractor is default and cannot be manipulated by the patient themselves, *in-motion regulatory conditions* are given. There is a fixed position of each hay bale unchangeable from one exergame trial to the next to ensure *no intertrial variability*.

3B

In this exergame (called *Fruit catcher*), the patient is represented as an avatar balancing a fruit basket on the head. Virtual apples are falling down from a tree (*in-motion regulatory conditions*) that should be caught by the basket. The patient has to perform target-oriented COP shifts to get an optimal avatar position and the apples are falling into the basket. This exergame focuses on dynamic stability due to controlled weight shifting movements to selected targets. For presenting *no intertrial variability*, the game parameters are always the same, even when the game is repeatedly played.

3C

According to Gentile's taxonomy, this exergame (called *Worm hurdler*) requires stepping tasks. Specifically, the patient represented as an avatar has to overstep a crawling worm coming closer alternately from the right and the left side (*in-motion regulatory conditions*). The parameters of the game are unchangeable and, thus, *no intertrial variability* is given.

3D

The exergame *Worm hurdler* described in 3C can easily be modified for skill category 3D. By integrating a virtual water jar that has to be balanced on the avatar's head, an *object manipulation* task is integrated. To avoid water spillage, the patient has to adopt an ideal upright body posture.

4A

For skill category 4A, we adapted the game *Tractor driver* described for category 3A by implementing *intertrial variability*. Specifically, to provide varying regulatory conditions, the hay bale positions change from one exergame trial to another.

4B

The exergame *Fruit catcher* described for skill category 3B needed a slight modification to meet the category requirements for 4B. In this game, there are not only falling apples which have to be caught, but various kinds of fruits. On the one hand, the fruits have different sizes and, on the other hand, different falling speeds. Obviously, *intertrial variability* is given.

4C

When playing the game *Worm hurdler* designed for category 3C, but with changing regulatory conditions between the exergame trials, *intertrial variability* is ensured. Accordingly, in this game, the worms are crawling with varying speeds and are coming either from the right or the left side in random order.

4D

For integrating an *object manipulation* task, the exergame *Worm hurdler* described for skill category 4C can be advanced by balancing a virtual water jar on the avatar's head. Consequently, while overstepping the randomly approaching crawling worms, the patient has to adopt an ideal upright body position ensuring that no water is spilling out (from the jar).

3.6 Practical application of the taxonomy-based rehabilitation program using exergames

When implementing a therapeutic program to improve stroke victims' motor skills, therapists must select exercises that are tailored to the demands of the individual patient. To achieve optimal outcomes

in rehabilitation, the activities should be matched to a patient's functional abilities and limitations. In a well-elaborated training plan, the (exercise) tasks which have to be performed should maintain an optimal challenge for the patient [7, 19]. Obviously, for providing a perfectly tuned exercise difficulty level at any point in time throughout the rehabilitation period, modifying the therapy plan is an essential need and an ongoing process. When a patient is making progress, more challenging tasks should be involved into the rehabilitation program. For selecting functionally appropriate activities during rehabilitation, we highlight the practical value of using Gentile's taxonomy. Based on the consideration that the taxonomy-based skill categories present a structure going from simple to complex motor tasks, we provide a formal procedure for guiding patients from the top left of the table to the bottom right. Closer inspection of Table 3.1 reveals that the taxonomy can be divided into seven difficulty levels. More specifically, starting from 1 of the 16 skill categories, a category-based progression in task difficulty can be achieved either through a horizontal shift to the right or a vertical shift downward. Accordingly, seven levels of difficulty can be distinguished which define a progressive increase of complexity in diagonal direction (Table 3.3).

Considering the allocation of the skill categories to one of the seven difficulty levels, Gentile's taxonomy offers a simple and easy-to-follow way for incorporating an ongoing progression into a rehabilitation process. Specifically, for selecting appropriate activities that provide rehabilitation at the optimal level of challenge, we propose the following procedure: A patient may only move up one level of difficulty when all skill categories within the current level are completed. For clarification, beginning with skill category 1A in difficulty level 1, the patient is required to move to the skill categories in difficulty level 2 (i.e., 1B and 2A) as soon as category 1A is successfully performed. Within level 2, patients and treating therapists are free to choose the order of execution of the belonging skill categories. Once a patient is capable to perform both skill categories 1B and 2A successfully, the next difficulty level 3 has to be incorporated into rehabilitation. This procedure can be continued until the patient finally achieves skill category 4D and, consequently, the highest level of difficulty (i.e., level 7). In this way, challenging situations are ensured at any point in time during rehabilitation and the patients are encouraged to exercise towards their functional limits. Following the procedure suggested to guide someone's therapy plan, one ensures that the selection of skill categories is constrained. Due to this constraint, a variation of both general dimensions defined by Gentile's taxonomy will be considered during the rehabilitation process. Accordingly, the procedure prevents a skill category-based progression only in one direction and includes the modification of both the environmental context and the action function characteristics.

Apart from these constraints, this approach also enables a certain degree of self-determination by therapy-involved actors. Within a specific level of difficulty, the performance order of the skill categories can be freely determined. This autonomy in decision-making increases the potential of tailoring the rehabilitation process to the demands of each individual patient and leaves freedom of choice to the treating therapists for the most adequate exercises that should currently be trained.

Table 3.3: Gentile's taxonomy of motor skills divided into seven levels of difficulty (ordered diagonally).

		Action Function			
		Body Stability		Body Transport	
Environmental Context		No Object Manipulation	Object Manipulation	No Object Manipulation	Object Manipulation
Stationary Regulatory Conditions	No Intertrial Variability	1A	1B	1C	1D
	Intertrial Variability	2A	2B	2C	2D
In-Motion Regulatory Conditions	No Intertrial Variability	3A	3B	3C	3D
	Intertrial Variability	4A	4B	4C	4D

3.7 Limitations and future directions

Using Gentile's taxonomy for designing a rehabilitation program that targets balance and walking deficits of stroke patients, an aspect must be considered critically. According to Gentile's framework, a horizontal shift to the right or a vertical shift downward within the taxonomy provides an increase of

task complexity. However, when we focus on a motor task such as standing still on one leg, a potential inconsistency in Gentile's approach emerges. Standing still on one leg can be categorized by the taxonomy dimension *body stability* that represents less complex tasks than motor skills that require *body transport* (e.g., walking). In our view, maintaining a one-leg stance position needs good balance skills. Therefore, this activity might be perceived by some stroke patients as an advanced motor task which challenges them more than a body transport activity. Furthermore, where this theoretical approach focused on the 'general stroke patient population', we are aware of the fact that different accompanying diseases and impairments; e.g., dizziness or muscle weakness due to stroke, may cause differences in how patients perceive tasks as being more or less difficult. It can be hypothesized that some patients have more difficulty maintaining a given posture without loss of balance whereas others experience performing a body transport task as more difficult. We think, however, that these potential differences may be resolved by clinicians that treat and monitor patients and decide, together with the patients and according their skill levels, how and when to progress through the taxonomy. It is clear to us that several pilot studies assessing feasibility and usability in several reference and subpopulations are needed as necessary next step in our program development process. Feasibility studies are comparative randomized trials designed to provide preliminary evidence on the clinical efficacy of a drug or intervention [54]. Usability evaluation is a way to ensure that interactive systems are adapted to the users and should be part of a fundamental step in the user-centered design process [4].

In this paper, we elucidate the theoretical basis for a theory-driven rehabilitation program to improve stroke sufferers' balance skills and walking capability using exergames. According to the framework proposed by Campbell et al. [8], investigating relevant theory prior to an exploratory trial is of great importance. Considering the theoretical knowledge gathered, an optimal study intervention design for pilot studies can be worked out that focus on the relevance and effectiveness of the rehabilitation program suggested. Depending on the usability and feasibility testing results obtained, refinements and extensions of the exergames can be made and the present set of six basic exergames may be extended to a maximum of 16 different exergames. Hence, a comprehensive and practical theory-driven stroke rehabilitation program based on Gentile's taxonomy can be achieved.

3.8 Conclusion

With stroke, the changes in the central nervous system and lifestyle may impair an individual's ability to regain and/or maintain certain levels of motor functioning. By using virtual reality, we might be able to

offer continued rehabilitation in an attractive and meaningful way. Specific targeted exergames have been designed that aim to minimize stroke-induced walking impairments. Considering the aim of presenting a well-elaborated training concept with a strong theoretical rationale, in this paper we demonstrate that Gentile's taxonomy presents a feasible template providing assistance for developing and implementing a theory-driven rehabilitation program. The motor skill taxonomy suggested by Gentile defines two general dimensions and structures a table that consists of 16 different skill categories (Table 3.1). On the one hand, based on these skill categories, the taxonomy provides variable training scenarios. Thus, a therapy program which meets the demand of the motor learning principle variable practice can be created. On the other hand, the taxonomy allows a systematic progression during the rehabilitation process. Accordingly, the motor learning principle of progression is explicitly considered. Due to the advantages of Gentile's two-dimensional approach, the taxonomy suits our purposes and was used as underlying framework to build up a post-stroke exergame rehabilitation program for enhancing balance and walking skills. Based on the literature reviewed here, clinical approaches to maintaining and improving physical functioning over longer time periods in persons with stroke may be combined with novel exergame-based approaches that sustain physical functioning.

Authors' contributions

SW performed literature review and design considerations and contributed to writing the manuscript. RvdL performed design considerations and contributed to writing the manuscript. EDdB initiated the study, assisted in both literature review and design considerations and contributed to writing the manuscript. All authors read and approved the final manuscript.

The authors declare that the submitted paper, the data, and the results have not been published anywhere before.

Conflict of interest statement

Seline Wüest, Rolf van de Langenberg, and Eling D. de Bruin declare that they have no conflict of interest.

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4

Usability and effects of an exergame-based balance training program

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Abstract

Background: Post-stroke recovery benefits from structured, intense, challenging, and repetitive therapy. Exergames have emerged as promising to achieve sustained therapy practice and patient motivation. This study assessed the usability and effects of exergames on balance and gait.

Subjects and Methods: Sixteen elderly participants were provided with the study intervention based on five newly developed exergames. The participants were required to attend 36 training sessions; lasting for 20 minutes each. Adherence, attrition and acceptance were assessed together with (1) Berg Balance Scale, (2) 7-m Timed Up and Go, (3) Short Physical Performance Battery, (4) force platform stance tests, and (5) gait analysis.

Results: Thirteen participants completed the study (18.8 percent attrition), without missing a single training session (100 percent adherence). Participants showed high acceptance of the intervention. Only minor adaptations in the program were needed based on the users' feedback. No changes in center of pressure area during quiet stance on both stable and unstable surfaces and no changes of walking parameters were detected. Scores for the Berg Balance Scale (p = 0.007; r = 0.51), the 7-m Timed Up and Go (p = 0.002; r = 0.56), and the Short Physical Performance Battery (p = 0.013; r = 0.48) increased significantly with moderate to large effect sizes.

Conclusion: Participants evaluated the usability of the virtual reality training intervention positively. Results indicate that the intervention improves gait- and balance-related physical performance measures in untrained elderly. The present results warrant a clinical explorative study investigating the usability and effectiveness of the exergame-based program in stroke patients.

4.1 Introduction

Acute stroke rehabilitation services are limited – primarily because of cost constraints [1] – and many individuals return home with residual gait impairment [2]. The decision to discharge patients from further therapy is often justified with a 'plateau' in motor recovery [3]. However, further functional gains after acute rehabilitation are possible, even in the chronic stage [1, 4].

Following a stroke, approximately 80 percent of patients experience hemiparesis accompanied by considerable walking deficits [5]. The typical 'hemiplegic gait' post-stroke is associated with several negative consequences (e.g., gait asymmetry, reduced walking velocity, cadence, and stride length) [5-9]. Six months post-stroke, one-third of elderly stroke survivors are not able to walk independently [10].

An intense, structured therapy program offering numerous repetitions of various, challenging tasks improves motor skills [11]. For best recovery results, a rehabilitation program should be conducted regularly over an extended period of time. When patients find a treatment program enjoyable, their willingness to keep at it is increased. A high level of motivation should lead to high adherence and low attrition and hence positively affect treatment outcomes [12].

Virtual reality applications in health care have recently received considerable attention. Virtual reality can be used to provide engaging scenarios and improve adherence to therapy [13-17]. Videogames are most practical and effective in rehabilitation when they have been specifically designed for therapy purposes [18-20]. Given the importance of gait recovery post-stroke, games should be aimed towards walking recovery. An additional advantage of videogame-based programs is that they can be performed independently at home with minimal equipment [16].

The research project 'Rehabilitative Wayout In Responsive home Environments' (REWIRE) [21], funded by FP7, created such a rehabilitation program based on exergames. Exergames are defined as "any number of types of video games/multimedia interactions that require the game player to physically move in order to play" [22]. Five exergames have been developed in the context of the REWIRE project – by game developers in collaboration with human movement scientists and rehabilitation specialists. The process for game development within a theoretical framework has been described elsewhere [23]. The underlying exercises – specifically targeting balance and walking recovery – were designed to be performed independently at home and remotely monitored by healthcare professionals. Moreover, the rehabilitation program explicitly considered variable practice and individually tailored progression, hence keeping participants engaged and appropriately challenged [18, 23, 24].

In accordance with the phased iterative approach suggested by Campbell et al. [25], this article aims to evaluate (1) the usability of the rehabilitation program in terms of acceptance, adherence, and attrition and (2) the effect of the program on measures of balance and gait in untrained healthy elderly.

4.2 Subjects and methods

Study design

We assessed usability by means of a user-centered interaction design. The ETH Zurich Ethics Committee granted ethical approval (protocol number EK 2013-N-12). All participants were fully informed prior to participation and signed a consent form.

Participants

Usability and effects were assessed in an untrained elderly convenience sample, in which some balance and gait impairments can be assumed [26-30]. Sixteen participants were recruited in the city of Zurich, Switzerland, through contact persons of different institutions. Participants were included if they lived independently, were older than 64 years of age, were able to walk independently for 20 m, and had a Mini-Mental State Examination score of at least 22. Excluded were individuals with (1) acute or unstable chronic diseases, (2) rapidly progressing or terminal illnesses, (3) Alzheimer's disease or dementia, (4) other severe health problems, and/or (5) a recent head injury.

Intervention

The intervention program consisted of exergame-based balance training performed while standing directly on a force platform (Tymo plate by Tyromotion, Graz, Austria) [31] or on a compliant foam mat placed on top of this platform. The intervention was performed three times per week for a period of 12 weeks for a total of 36 sessions. Each one-on-one session was partitioned in three parts: 10 minutes training, 10 minutes break, and 10 minutes training. All participants were expected to complete all 36 sessions while being monitored by an instructor, who systematically observed them throughout the intervention. Participants were encouraged to 'think aloud' while operating the software and playing the exergames. Accordingly, any expressed comments from the participants related to their demands were documented by the instructor in writing to identify both problem areas and what people like. The aim of this procedure was to assess strengths and weaknesses of the exergame-based training program online

in a realistic setting. Consequently, based on participants' feedback, desired exergame adaptations could be carried out.

Exergames

A set of five exergames – four of them with different levels of difficulty (Table 4.1 gives details) – was used for the intervention. In each exergame, a therapist avatar provided real-time feedback. The exergames aimed to train quiet stance ('Scarecrow' [Figure 4.1]), mediolateral weight shifting ('Tractor driver' [Figure 4.2] and 'Fruit catcher' [Figure 4.3]), mediolateral weight shifting combined with single leg stance ('Worm hurdler' [Figure 4.4]), and mediolateral weight shifting combined with anteroposterior weight shifting ('Mix soup' [Figure 4.5]). A detailed description of the games can be found elsewhere [18, 23, 24].

Table 4.1: Exergame difficulty levels.

Scarecrow	Tractor driver	Fruit catcher	Worm hurdler	Mix soup
No difficulty level adaptation	Difficulty level adaptation: speed of the moving tractor	Difficulty level adaptation: fruit falling frequency & fruit falling range	Difficulty level adaptation: speed of the crawling worm	Difficulty level adaptation: life span of the bubbles

Primary outcomes

Acceptance of the training technology. An abridged version [32] of the technology acceptance model (TAM) questionnaire evaluated participants' perceived acceptance of the intervention post-training [33-35] (Figure 4.6).

Responses were recorded using a 7-point Likert scale ranging from 'strongly disagree' (rated as 1) to 'strongly agree' (rated as 7).

Attrition and adherence. For attrition, the number of participants lost during the intervention was recorded. For adherence, participants' engagement with the intervention was assessed. Adherence was calculated as the number of completed training sessions as a percentage of the maximal possible training sessions (i.e., 36).

Figure 4.1: Screenshot of the exergame 'Scarecrow'.

Figure 4.2: Screenshot of the exergame 'Tractor driver'.

Figure 4.3: Screenshot of the exergame 'Fruit catcher'.

Figure 4.4: Screenshot of the exergame 'Worm hurdler'.

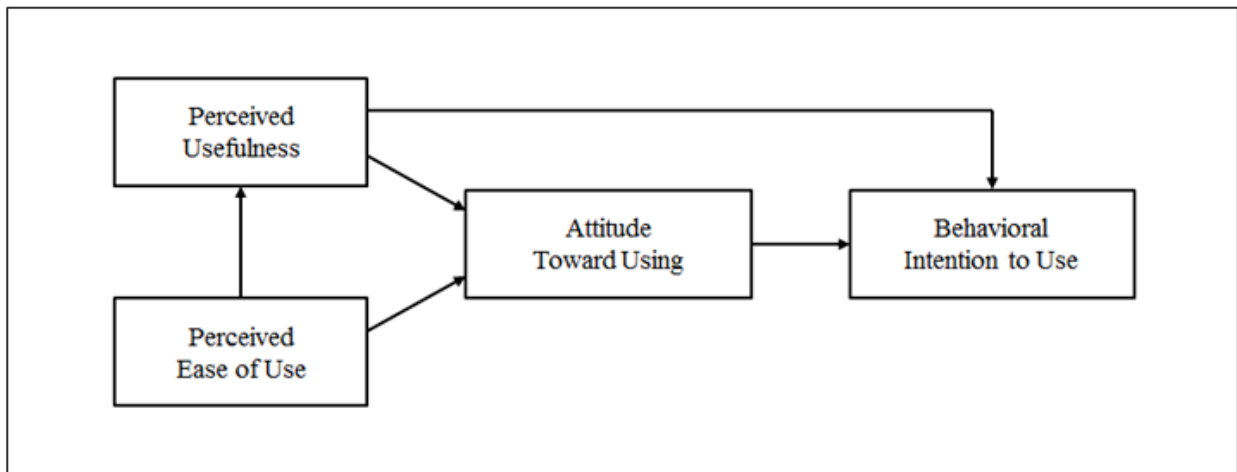**Figure 4.5:** Screenshot of the exergame 'Mix soup'.

Figure 4.6: Research model by Masrom [32].

Secondary outcomes

Berg Balance Scale. Balance ability while performing functional tasks was assessed with the Berg Balance Scale. This test consists of 14 mobility tasks that simulate common daily life activities and is reliable and valid in geriatrics [36]. By using a 5-point scale, ranging from 0 (most impaired balance) to 4 (normal balance), a person's functional capability can be defined for each test. The possible cumulative score ranges from 0 to 56 points.

Timed Up and Go. The Timed Up and Go [37, 38] requires participants to stand up from a sitting position, walk for 3 m, turn 180°, walk back 3 m, and turn to sit down again. We used an extended test version with a 7-m walking distance [39]. The test was repeated three times with 30-second breaks in between, and the total time to complete each trial was measured. The average time was used for further analysis.

Force platform. To measure postural balance control, participants stood quietly on a Kistler (Winterthur, Switzerland) force plate (type 9286B) under two different test conditions: (1) on a stable surface and (2) on an unstable surface (foam mat). Vertical ground reaction forces were collected at a frequency of 1000 Hz. In both conditions, participants were instructed to focus on a red cross displayed at eye level on a white wall at a distance of 30 cm. In each condition, three 20-second trials were performed with a 30-second break in between. For each trial, center of pressure (COP) area was quantified as the area of the smallest ellipse containing 95% of COP data points. Mean COP area was computed for each condition and used for statistical analysis.

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Short Physical Performance Battery. The Short Physical Performance Battery, composed of a balance test, a 3-m walking test, and a five-chair-rises test, resulted in scores between 0 (not able to complete the task) and 4 (good function) points per test. The sum of these scores represents the total Short Physical Performance Battery score. A higher score indicates better lower extremity function [40-42].

Gait analysis. Spatiotemporal gait parameters were assessed with the GAITRite® system (CIR Systems, Havertown, PA) consisting of an electronic walkway with gait analysis software. The active area of the walkway (i.e., the area equipped with pressure sensors) measures 7.3 m. To eliminate acceleration and deceleration effects on calculated gait parameters, the walkway contains an additional 2.5 m at the beginning and end of the active area. Participants were to walk over the electronic walkway at a self-selected comfortable walking speed. Three successful trials were collected, and the mean values of velocity (cm/second), cadence (steps/minute), step time (seconds), step length (cm), and swing time symmetry (ratio) were calculated. Gait symmetry was calculated from the following ratio [43]:

Symmetry ratio = swing time$_{\text{right side}}$/swing time$_{\text{left side}}$

Statistical analysis

All statistical analyses were performed using SPSS version 21.0 software (SPSS Inc., Chicago, IL). Secondary outcomes were only calculated and analyzed for participants who completed the intervention as per protocol. A Wilcoxon signed-rank test was used to compare pre- and post-test results. Results were deemed statistically significant at a *p*-value of ≤0.05. Effect size (*r*) was calculated as $r = Z/\sqrt{N}$, where *Z* represents the approximation of the observed difference in terms of the standard normal distribution and *N* is the total number of observations. Regarding effect size magnitude, *r* = 0.1 is considered a small, *r* = 0.3 a medium, and *r* = 0.5 a large effect [44].

4.3 Results

Primary outcomes

Sixteen participants were enrolled in the study, 13 of whom received the full allocated training program (Figure 4.7). Two participants dropped out because of injuries sustained outside the training, and one discontinued because of self-reported lack of time. All reasons were unrelated to the content of the training.
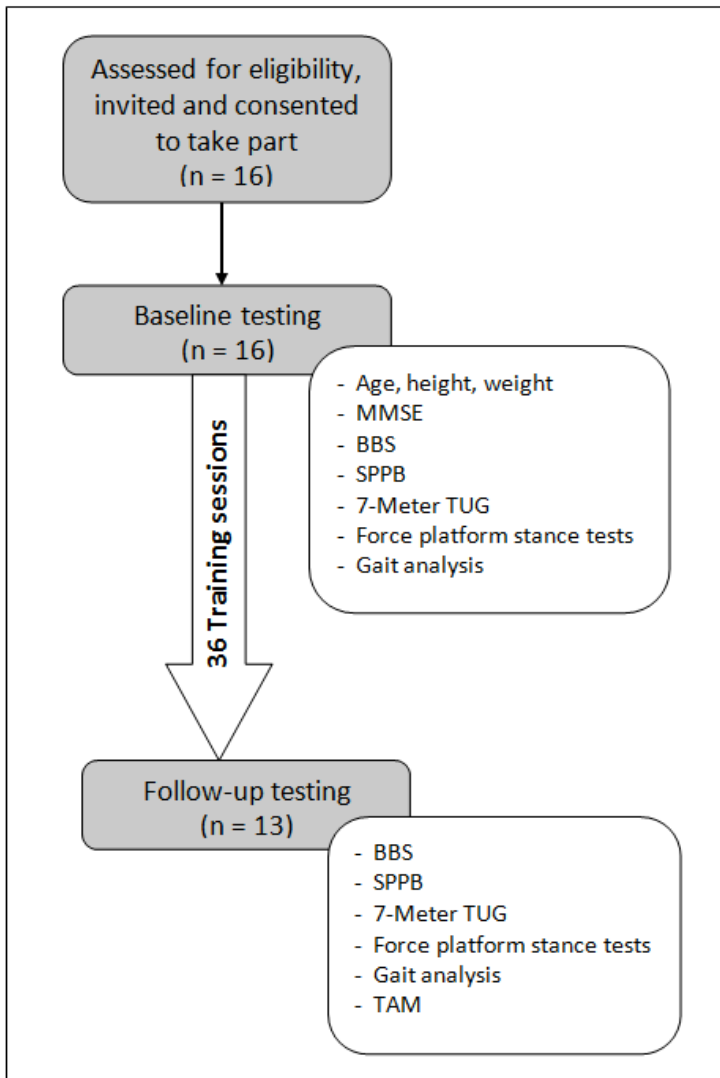
Figure 4.7: Study flowchart.
BBS, Berg Balance Scale; MMSE, Mini-Mental State Examination; n, sample size; SPPB, Short Physical Performance Battery; TAM, technology acceptance model; TUG, Timed Up and Go.

Table 4.2 presents completers' demographics and clinical characteristics. Adherence was 100 percent. None of the 13 participants suffered any adverse events during the intervention. The exergames were seen as easy to use and useful. The participants expressed a positive attitude toward using the exergames as well as an intention to continue using the games (Table 4.3).

Table 4.2: Completers' baseline characteristics.

Characteristics	Value
Number of participants	13
Age (years)	76.5 ± 5.4 (65-85)
Sex (female/male)	10/3
Height (cm)	163.6 ± 8.5 (152-177)
Weight (kg)	71.6 ± 9.7 (57.4-90.5)
MMSE (points)[a]	28.9 ± 1.6 (25-30)
Education	
College educated or higher	2
In a sitting position past profession	5
Health status	
≥2 self-reported chronic diseases	8
Feel pain daily	4
Estimated excellent/good health status	10
Estimated excellent/good balance ability	7

Data are number of subjects or mean ± standard deviation (range) values as indicated.
[a]The minimum score was 0, and the maximum score was 30 (a higher score indicates better cognitive functioning).
MMSE, Mini-Mental State Examination.

Table 4.3 presents the TAM items that were evaluated post-intervention.

During the intervention, participants reported some minor problems with using the games and progressing through the exercises. In response, the exergames were adapted online (Table 4.4 gives details) and subsequently re-assessed for usability.

Table 4.3: Evaluated technology acceptance model questionnaire items.

Item	Score
Perceived Ease of Use	5.9 ± 1.7 (1-7)
Perceived Usefulness	6.4 ± 1.0 (4-7)
Attitude Toward Using	6.5 ± 1.1 (2-7)
Behavioral Intention to Use	6.0 ± 1.3 (3-7)

Data are mean ± standard deviation (range) values.

Table 4.4: Description of the online exergame adaptations performed.

Scarecrow	Tractor driver	Fruit catcher	Worm hurdler	Mix soup
Added two difficulty levels to original three	Added two difficulty levels to original three	Added two difficulty levels to original three	Added two difficulty levels to original three	Added two difficulty levels to original three
Improved consistency of statements and scores provided by virtual therapist	Improved consistency of statements and scores provided by virtual therapist	Improved consistency of statements and scores provided by virtual therapist	Improved consistency of statements and scores provided by virtual therapist	Improved consistency of statements and scores provided by virtual therapist
	Added previously absent obstacles		Increased worm size and hence visibility	

Secondary outcomes

The results of the pre-and post-comparisons are presented in Table 4.5. Significant improvements in Berg Balance Scale, Timed Up and Go, and Short Physical Performance Battery scores were observed. Separate analyses of each of the three Short Physical Performance Battery components (standing balance, repeated chair rises, and gait speed) revealed that only standing balance changed. No significant changes were detected in (1) COP area during quiet stance and (2) any of the gait parameters (all p-values >0.1).

Table 4.5: Participants' baseline and post-intervention physical outcome measures.

	Mean ± standard deviation		p_{within}	r	Z
	Baseline	Post-intervention			
BBS (points)	51.7 ± 3.3	54.8 ± 1.4	0.007[a]	0.51[b]	2.590
7-m TUG (seconds)	19.8 ± 2.8	17.5 ± 2.4	0.002[a]	0.56[b]	2.830
COP area (mm^2)					
Stable surface	2.47 ± 1.64	4.43 ± 4.17	0.191	0.27	1.363
Unstable surface	10.42 ± 7.73	17.69 ± 18.54	0.414	0.17	0.874
SPPB (points)					
Total	9.9 ± 1.0	11.2 ± 0.8	0.013[a]	0.48[c]	2.436
Balance	3.1 ± 0.9	4.0 ± 0.0	0.008[a]	0.51[b]	2.585
Chair rises	3.2 ± 0.8	3.4 ± 0.7	0.375	0.26	1.342
Gait speed	3.7 ± 0.5	3.8 ± 0.6	1.000	0.07	0.378
Gait analysis					
Velocity (cm/second)	122.4 ± 17.3	128.4 ± 21.4	0.497	0.14	0.734
Cadence (steps/minute)	115.2 ± 8.7	119.1 ± 9.3	0.244	0.24	1.223
Step time (seconds)	0.52 ± 0.04	0.51 ± 0.04	0.273	0.23	1.153
Step length (cm)	63.6 ± 6.0	64.4 ± 6.9	0.542	0.13	0.664
Swing time symmetry (ratio)	0.99 ± 0.03	1.00 ± 0.04	0.127	0.31[c]	1.572

[a]Significant within-group differences pre-post (p_{within} ≤0.05) calculated with Wilcoxon signed-rank test.
For effect size r, r = 0.1 indicates a small effect, [c]r = 0.3 indicates a medium effect, and [b]r = 0.5 indicates a large effect.
BBS, Berg Balance Scale; COP, center of pressure; p_{within}, p-value for within-group comparisons; SPPB, Short Physical Performance Battery; TUG, Timed Up and Go; Z, approximation of the observed difference in terms of the standard normal distribution.

4.4 Discussion

This study assessed – in untrained elderly – (1) the usability of the program in terms of acceptance, adherence, and attrition and (2) the effect of the program on balance and gait. The findings revealed a high level of acceptance with concomitant high adherence rates. High scores for each of the four TAM items were found. On average, participants found the exergames easy to use, clear, and understandable without requiring much mental effort to operate. Perceived Usefulness results showed that the exergames were perceived as a useful means to increase training effectiveness, productivity, and performance. Moreover, there was a broad consensus in terms of Attitude Toward Using: All participants expressed a positive attitude towards the program. In addition, Behavioral Intention to Use results showed that participants liked the idea of continuing their use of exergames on a regular basis. The high acceptance rate obtained in the current study seems at odds with a previous study by Laver et al. [45] that revealed skepticism about the use of commercially available videogames in geriatric rehabilitation. A likely explanation may be found in game design: Where Laver et al. [45] used an off-the-shelf system without patient-specific adaptations, the exergames used in this study were specifically designed and developed for rehabilitation and were adapted to the cognitive and physical limitations of functionally impaired persons or elderly. This explanation is in line with Cameirão et al. [46], who found high acceptance of a gaming system specifically designed to treat post-stroke motor deficits, and with Lewis et al. [4], who demonstrated positive results for newly developed exergames aimed to improve stroke patients' arm function. Our findings also corroborate the high acceptance rates of specifically designed exergames found by Backlund et al. [47].

Thirteen of the 16 participants (81 percent) completed the full allocated training program and attended the retesting assessments. Considering the median rate for attrition in falls prevention interventions in community settings for clinical trials [48], a 10 percent attrition rate can be deemed acceptable. In our study, we achieved a slightly higher rate. It should be noted, however, that the reasons for discontinuation of the intervention were unrelated to the intervention. In contrast to the somewhat low attrition rate, adherence was 100 percent across the 36 training sessions. This perfect adherence is in line with the high acceptance revealed by the TAM survey. The high adherence and acceptance rates in the present study may be related to the online adaptations of the training intervention: The exergames were subjected to several online adaptations based on participants' feedback during the training period, which might have positively impacted both usability and effectiveness.

We expected the exergames to improve participants' balance and gait. The intervention had a positive effect on clinical measures of balance. This is in line with a study by Lai et al. [49] that reported similar results through a 6-week interactive videogame-based intervention. Although body sway during quiet stance did not change significantly, both standing on a stable and unstable surface yielded *larger* average COP areas in the post-test compared with the pre-test. Given that better balance is usually associated with *smaller* COP areas, this trend is surprising. Although speculative, it might nonetheless constitute a positive intervention effect: Note that four of the five exergames trained effective control rather than minimization of COP movement. Given that – to be precise – postural stability likewise requires effective control of COP (in order to minimize center of mass movement) rather than its minimization, COP might not be the best indicator of postural stability, particularly in the present study [50]. Measurements of center of mass movements (e.g., during walking) would have given a better insight into the actual participants' dynamic postural balance control.

The absence of gait-related effects in this study constitutes a confirmation of results by Szturm et al. [51], who also examined an exergame-based intervention with goal-directed weight shifting tasks and found no significant improvement in spatiotemporal gait parameters. Hence, exercises with a stationary base of support do not seem to present the most effective way to improve walking in untrained elderly.

However, the absence of significant effects on gait might also be related to the low power of testing together with the rather high level of walking function in our sample. Effect sizes were medium or close to medium and – with a preferred gait speed between 1.0 and 1.4 m/second – our participants should be classified as normal walkers [52]. A logical next step would therefore be to apply the present intervention to community-dwelling chronic stroke populations that exhibit mildly abnormal (0.6–1.0 m/second) or seriously abnormal gait speed (below 0.6 m/second) and re-assess intervention effects on gait in this actual target population [52]. Given that gait speed is an important factor related to community walking in stroke patients, which in turn is strongly determined by balance [53], it seems likely that our exergames – which explicitly target this skill – will improve walking in chronic patients.

Future work

We performed an 'a priori power analysis' to determine the minimum sample size for such a future trial [54]. Specifically, we assessed the requirements for a randomized controlled study with an experimental group (receiving exergame-based therapy and usual stroke rehabilitation) and a control group (receiving usual stroke rehabilitation only). Assuming an effect size of $r = 0.30$ (based on our observed value for gait symmetry), acceptable type I and II error probabilities (0.05 and 0.20, respectively) may be obtained with

a minimum sample of 12 participants per group for a two-group pre- and post-test design. To account for attrition, initial sample size should be increased to 15 participants per group.

Limitations

Some limitations of this study should be discussed. First, this study featured a rather small sample of healthy untrained elderly, which resulted in limited statistical power for gait analysis. The validity of using elderly persons to test the usability may be questioned. However, (1) the primary focus of this study was on usability, where a sample of five participants is sufficient for detecting 80 percent of the usability problems [55], and (2) untrained elderly normally show both balance and gait impairments, which should render them an adequate population for assessing effectiveness as well. Second, the study may suffer from volunteer bias: It can be hypothesized that our volunteer participants were more interested in technology than the average elderly, which might explain in part their positive attitude toward the intervention. Both these limitations would not apply in a controlled trial with stroke patients, which – in combination with the promising results of the present study – highlights the need for such a trial. A third limitation concerns the gender distribution in our sample, with women outnumbering men. However, sex disparity in stroke prevalence persists, with women being more affected then men [56]. This makes it important to especially test acceptance and feasibility in women.

4.5 Conclusion

Small-scale interventions focusing on usability represent an important stage when developing complex theory-based interventions to improve health [25]. Usability studies provide invaluable results for information technology developers and rehabilitation specialists using innovative systems and might be highly relevant for furthering the development of new emerging virtual reality-based rehabilitation. Our results corroborate previous findings in showing that virtual training approaches for performing balance training have great potential. Specifically, this study demonstrates that the exergame-based intervention was perceived as usable and had a positive effect on both standing balance and daily life tasks.

Authors' contributions

SW contributed to the conception of the work, the acquisition, analysis and interpretation of data, and writing the manuscript. NAB, MP, and RM contributed to the development of the software and exergames. RvdL assisted in the acquisition of data and contributed to the analysis and interpretation of data and to writing the manuscript. EDdB initiated the study, assisted in the acquisition of data, and contributed to writing the manuscript. All authors read and approved the final manuscript.

Conflict of interest statement

No competing financial interests exist.

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5

Reliability and validity of the inertial sensor-based Timed Up and Go test in post-stroke individuals

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Abstract

The instrumented Timed Up and Go test (iTUG) has the potential for playing an important role in providing clinically useful information regarding an individuals' balance and mobility that cannot be derived from the original single-outcome TUG protocol. The purpose of this study was to determine the reliability and validity of the iTUG using body-fixed inertial sensors in people affected by stroke. For test-retest reliability analysis, 14 individuals with stroke and 25 healthy elderly were assessed. For validity analysis, an age-matched comparison of 12 stroke patients and 12 healthy controls was performed. Out of the 14 computed iTUG metrics, the majority showed excellent test-retest reliability expressed by high intraclass correlation coefficients (ICCs range 0.431-0.994) together with low standard error of measurement (SEM and SEM%, respectively) and smallest detectable difference (SDD and SDD%, respectively) values. Bland and Altman plots demonstrated good agreement between two repeated measurements. Significant differences between stroke patients and healthy controls were found in nine of 14 iTUG parameters analyzed. Consequently, these results warrant the future application of the inertial sensor-based iTUG test for the assessment of physical deficits post-stroke in longitudinal study designs.

5.1 Introduction

After a stroke, many individuals suffer from hemiparesis which often leads to an impaired walking pattern with altered gait characteristics [1-7]. Specifically, the hemiplegic gait is typically associated with a reduced gait speed [1-3, 5, 8], cadence [2, 5, 8], stride length [2, 8] and an increased left-right asymmetry during walking [1, 3, 9] when compared to healthy, age-matched controls. Furthermore, it is often characterized by an increased stance phase duration [2]. Hemiparesis not only leads to gait impairments, but may also affect balance and postural transfers (i.e., changing position from sitting to standing, and vice versa) further impeding the patients' mobility and independence [6, 10-12]. It is therefore a central goal of stroke rehabilitation to improve the patient's independence and functional capacity by improving his or her mobility [13].

The Timed Up and Go test (TUG) is often used to evaluate balance and mobility in stroke patients [14], with good reliability and validity [15-17]. The TUG requires a person to rise from a chair, walk a distance of 3 meters at a self-paced comfortable speed, turn around, and return to the chair to sit down again. The total time for completion is recorded and used as measure of mobility. However, although the TUG is commonly used to evaluate mobility post-stroke, it has some drawbacks. First, it only uses the outcome parameter 'time' and fails to detect other balance- and mobility-related parameters [18-19]. Second, although it consists of a number of consecutive tasks it does not allow analyzing these separately [18-19]. Recently, several researchers instrumented the TUG in an effort to overcome some of the drawbacks. For example, Vernon et al. [20] used a Microsoft Kinect camera-based TUG method for analyzing the specific subcomponents of the test. Furthermore, Zampieri et al. [19] revealed the potential benefit of an instrumented TUG (iTUG) system using wearable inertial sensors while assessing individuals with Parkinson's disease (PD). While 10 of the 21 gait and postural transition parameters that were identifiable with the iTUG showed significant differences between PD and healthy controls, the total test performance time was not diverging. Obviously, the iTUG seemed to exhibit a greater sensitivity than the conventional TUG test in terms of mobility deficit detection in PD [18].

The recent use of body-fixed sensors suggests that they could serve as a tool for analyzing measures of physical functioning of patients [21-22]. It could potentially deliver more detailed and clinically relevant information on a stroke patient's gait and mobility than the conventional TUG, which only reports the time to complete the task. To the best of our knowledge, no study exists applying an inertial sensor-based iTUG system in people affected by stroke. To be clinically useful, an assessment procedure must

have a small measurement error to detect a real change and must be able to distinguish between subpopulations; e.g., stroke patients in various stages and healthy controls. A test-retest difference in a patient with a value smaller than the standard error of the measurement (SEM) is likely to be the result of 'measurement noise' and is unlikely to be detected reliably in practice; a difference greater than the smallest real difference is highly likely (with 95% confidence) to be a real difference [23-25]. Another example of these statistics is the smallest detectable difference (SDD) [24, 26]. The present study was conducted to assess the reliability and validity of inertial sensor-based iTUG metrics in stroke patients and age-matched healthy control elderly.

5.2 Methods

Study design

The study was designed as an observational study where all participants were tested by the same observer. Ethical approval for this study was granted by the local ETH Zurich Ethics Committee (protocol number EK 2012-N-32) and the cantonal Ethics Committee of the Canton of St. Gallen (protocol number EKSG 12/002/1B). Prior to participation, all participants were fully informed about the complete research protocol and requested to sign a consent form.

Participants

Participants were recruited on a voluntary basis through researchers from the Institute of Human Movement Sciences and Sport at ETH Zurich, Switzerland, and by contacting physicians and therapists from the Rehabilitation Center Valens, Switzerland. There were two groups of participants: 1) fourteen patients at any stage after ischemic or hemorrhagic stroke aged over 18 years. Participants were excluded from the study if any known comorbid disabilities other than stroke were present (e.g., musculoskeletal illness, cardiovascular disorders or other neurologic diseases) that might have affected performance in the test procedures; 2) twenty-five healthy by self-report control participants aged over 65 years who had no history of neurological, cardiovascular or musculoskeletal pathologies. To be eligible for the study, individuals had to be able to walk unassisted for at least 15 meters. The use of one crutch for walking was accepted for inclusion. Individuals who were not able to give informed consent were excluded.

Apparatus

In total, eight body-fixed devices (Physilog®, GaitUp, CH) were placed on participants' body: the sensor configuration described in the iTUG procedure by Salarian et al. [18] – one on each wrist, one on each shank, and one on the trunk – was complemented with one device on each foot and one on the back (L3) for further analysis. The sensor located on patient's back was taped using hypoallergenic breathable straps to ensure firm attachment to the skin. Every other sensor devices were firmly affixed to the patient using elastic straps.

The devices recorded to an on-board memory card the signals from a calibrated inertial sensor (3D-accelerometer and 3D-gyroscope) at 500 Hz [27]. Before any processing, the inertial signals, sampled synchronously across devices, were resampled by software (Matlab 2014a, Mathworks, USA) at 200 Hz as described in the original iTUG study [18].

Measurement protocol

Each patient was first equipped with the wearable sensor set. Then, in accordance with Salarian et al. [18], we used an extended iTUG test version with a 7-meter walking distance. Thereby, more gait cycles were recorded than when using the original TUG test protocol. All participants completed the testing session either in a gait laboratory of the Institute of Human Movement Sciences and Sport at ETH Zurich, Switzerland, or in suitable locations at the Rehabilitation Center Valens, Switzerland.

The testing session included the following procedure: Initially, each participant was equipped with a set of sensors. Once the sensors had been attached on the appropriate participants' body positions, they performed the first iTUG measurement session composed of three repeated iTUG trials (measurement session 1). Between each trial, a 30-second rest period was applied. After completing the three iTUG trials, the participants were instructed to relax for 15 minutes while removing the sensors from their body. Then, the sensors were reattached to participants' body and the same protocol repeated (measurement session 2). Each testing session was recorded with a video camera allowing researchers later inspection if necessary.

In order to get sufficient information about the assessment tool's reliability and validity characteristics, we identified 1) the relative reliability by using the intraclass correlation coefficient (ICC), 2) the absolute reliability to identify a real improvement by calculating a) the standard error of measurement (SEM) for groups of subjects, b) the limits of agreement (LOA) for a single person and c) the smallest clinical detectable difference (SDD) which also reveals the limits for the real change for a single person and 3)

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the discriminatory capabilities on the iTUG metrics by comparing stroke patients to healthy age-matched controls.

Data analysis

Based on algorithms described elsewhere [18-19, 28-29], different parameters of gait and postural transition during iTUG performance were measured:

- iTUG total duration (sec): Total duration of the iTUG trial in seconds

Sit-to-walk metrics

- Sit-to-walk duration (sec): Duration of the sit-to-walk transition in seconds

- Peak sit-to-walk velocity (deg/sec): Maximum angular trunk velocity in degrees per second during the sit-to-walk transition

Gait metrics

- Gait cadence (steps/min): Walking cadence in number of steps per minute; normalized to participants' height

- Gait stance phase (%): Stance phase as a percentage of gait cycle time

- Gait limp phase (%): Difference between initial and terminal double support phase as a percentage of gait cycle time

- Gait velocity (m/sec): Walking speed in meters per second; normalized to participants' height

- Gait stride length (m): Distance in meters between two consecutive foot falls at the moments of initial contact; normalized to participants' height

- Gait peak swing velocity (deg/sec): Maximum angular shank velocity in degrees per second during one stride

- Gait asymmetry: Symmetry ratio related to the swing phase performed by each leg; calculated with the formula = |1-((limb with lower value)/(limb with higher value))|

Turning metrics

- Turning duration (sec): Duration of 180° turn in seconds

- Peak turning velocity (deg/sec): Maximum angular trunk velocity in degrees per second while turning

Turn-to-sit metrics

- Turn-to-sit duration (sec): Duration of the turn-to-sit transition in seconds

- Peak turn-to-sit velocity (deg/sec): Maximum angular trunk velocity in degrees per second during the turn-to-sit transition

The reliability and validity assessments apply to the iTUG measured for three times and averaged values as opposed to the original TUG where a single measure after a practice trial is taken as the outcome. For data analysis, the mean value of the iTUG total duration across the three iTUG trials performed in measurement session 1 and measurement session 2, respectively, was used. The median of the metrics of the straight walking gait, the transitions and turns across the three iTUG trials performed in measurement session 1 and measurement session 2, respectively, was used to eliminate possible outliers. Except of the parameter 'gait asymmetry' which is based on the swing phase performed by each leg, the average value of both legs was used.

Statistical analysis

Descriptive statistical analysis was carried out to describe the study population. The one-sample Kolmogorov-Smirnov test, skewness and kurtosis were used to test normality of the data. The primary test-retest reliability calculations were based on the entire study population. A reliability subanalysis only including the stroke patients was performed separately. The reliability subanalysis incorporated the five gait iTUG metrics 'cadence', 'stance phase', 'velocity', 'stride length' and 'asymmetry'. For assessing differences between stroke patients and healthy elderly (age-matched), two groups were created (stroke & healthy control) and compared with the paired t-test or the non-parametric equivalent where appropriate. All statistical analyses were performed using SPSS version 21.0 software (SPSS Inc., Chicago, IL). The critical α-level was set at $p \leq 0.05$.

Reliability

Several statistical methods of assessing test-retest reliability were performed. Heteroscedasticity was tested by calculating the square value of Pearson's correlation coefficient (r^2) between the absolute difference and the mean of each pair of measurements. If values of r^2 are greater than 0.1, then the data are heteroscedastic [30]. The ICC with the 95% confidence interval (CI) was used as an estimate of relative reliability [30]. The ICC is commonly used to determine the consistency or reproducibility between repeated measurements and to assess the SEM [31]. In this article, the $ICC_{1,k}$ one-way analysis of variance (ANOVA) was considered for the following reasons: The same device and same participants tested by the sole rater were used for assessing test-retest reliability. Furthermore, the two

measurement sessions performed during the study were separated by a time period of only 15 minutes. Therefore, we assumed that participants' gait pattern would not have changed over this time.

The interpretation of the ICC values was according to Shrout and Fleiss [32] in which values of >0.75 indicate excellent reliability, 0.75-0.40 fair to good reliability and <0.40 poor reliability. Since the ICC score depends greatly on the range of values in the analyzed sample [30] and is not able to provide information about the accuracy for a specific individual, the SEM and the SDD for each parameter were calculated. The SEM indicates a real improvement in the group of individuals and was assessed using: *SEM = SD√(1-ICC),* in which *SD* represents the sample standard deviation [30]. The SDD can be used as an indicator for assessing real change beyond measurement error in a single person. It was derived from the SEM through: *1.96 x √2 x SEM* [26]. The SEM and SDD can be expressed as a percentage which are independent of the units of measurement and, therefore, suitable to compare the amount of random error between measurement parameters: *SEM% = ((SEM/mean of the two measurements)*100)* and *SDD% = ((SDD/mean of the two measurements)*100)*. Discrepancies between the measurements were also investigated by performing Bland and Altman's 95% LOA analysis. It expresses the degree of error proportional to the mean. The Bland and Altman method includes a scatter plot providing information about the degree of error (*measurement 1 – measurement 2*) proportional to the mean of the two measurements with 95% LOA (*mean difference ± 1.96 x SD of the difference*) [24, 33-34].

Validity

The paired *t*-test and the Wilcoxon signed-rank test were performed to examine differences between stroke patients and the age-matched healthy controls, depending on normality of data. Group mean values of the iTUG metrics are expressed as *mean ± SD*. Effect sizes are presented as Pearson's correlation coefficient (*r*) which can be calculated from the *t*-statistics converted into *r*-statistics by the formula $r = t^2/(t^2+df)$ or from the *Z* value using the equation $r = Z/\sqrt{N}$ [35]. *df* represents the degrees of freedom, *Z* the approximation of the observed difference in terms of the standard normal distribution and *N* the total number of observations. The effect size magnitude of *r* = 0.1 indicates a small, *r* = 0.3 a medium and *r* = 0.5 a large effect [35]. The results of the first measurement session were used for analysis. Since the gait parameters walking speed, stride length and cadence are related to someone's body height, these parameters were normalized to height (actual parameter value/height) [36].

5.3 Results

A total of 39 participants were enrolled in the study, whereof 25 were healthy elderly. The characteristics of this study population are described in Table 5.1. Since the two groups differed in mean age, an age-matched comparison of 12 stroke patients and 12 age-matched healthy controls was performed for validity analysis. The characteristics of those participants are presented in Table 5.2.

Reliability

Out of the 14 analyzed iTUG metrics, the ICCs of 12 variables showed excellent test-retest reliability ($ICC_{1,k}$ = 0.855-0.994). Only the two sit-to-walk parameters 'duration' and 'peak sit-to-walk velocity' reported a lower relative reliability coefficient ($ICC_{1,k}$ = 0.431 and $ICC_{1,k}$ = 0.674). The ICC values with corresponding 95% CI are reported together with the SEM and SEM%, the SDD and SDD%, and the 95% LOA in Table 5.3. Values of r^2 based on the absolute differences between measurement session 1 and measurement session 2 and the mean value of both measurement sessions were for all iTUG parameters below 0.1 indicating no evidence of heteroscedasticity. Bland and Altman plots graphically support homoscedasticity in all iTUG variables analyzed (Figures 5.1-5.14). Eleven of the 14 analyzed iTUG parameters showed low SEM and SEM% values (ranging from SEM% = 0.220 to 7.109%), and low SDD and SDD% values (ranging from SDD% = 0.659 to 19.706%). High SEM and SEM% values (ranging from SEM% = 15.819 to 20.600%), and high SDD and SDD% values (ranging from SDD% = 43.848 to 57.134%) were found for both sit-to-walk parameters and for the gait parameter related to the limp phase.

The reliability subanalysis of the gait iTUG metrics 'cadence', 'stance phase', 'velocity', 'stride length' and 'asymmetry' revealed similar results to those based on the entire study population (Table 5.4): For all five iTUG metrics measured, excellent test-retest reliability ($ICC_{1,k}$ = 0.958-0.991) with concomitant low SEM and SEM% (ranging from SEM% = 0.431 to 2.701%), and low SDD and SDD% values (ranging from SDD% = 1.292 to 7.481%) were found.

Table 5.1: Demographic data of the entire study population.

Characteristics	Stroke patients	Healthy elderly	Total	*p*-value	*r*-value
Number of participants	14	25	39		
Age (years), mean ± SD (range)	64.7 ± 9.2 (47-76)	76.0 ± 5.7 (66-86)	72.0 ± 9.0 (47-86)	<0.001[a]	0.381[c]
Sex (female/male)	2/12	17/8	19/20		
Height (cm), mean ± SD (range)	175.4 ± 6.0 (166-186)	167.7 ± 9.2 (152-189)	170.4 ± 8.9 (152-189)	0.008[a]	0.174
Weight (kg), mean ± SD (range)	82.0 ± 15.1 (62.5-114.0)	73.4 ± 12.4 (50.4-101.10)	76.5 ± 13.9 (50.4-114.0)	0.061	0.092
BMI (kg/m^2), mean ± SD (range)	26.6 ± 4.1 (21.1-35.2)	26.0 ± 3.1 (19.0-30.4)	26.2 ± 3.5 (19.0-35.2)	0.907	0.019
Walking assistance, n (%)	5 (35.7%)	0 (0.0%)	5 (12.8%)		
Affected side (right/left)	8/6	-	-		

p-value for between-groups comparison, [a]Significant between-group differences ($p_{between}$ ≤0.05) calculated with independent *t*-test and Mann-Whitney *U*-test.
r-value, effect size, calculated according to $r = Z/\sqrt{N}$ and $r = t^2/(t^2+df)$, *r* = 0.1: small effect, [c]*r* = 0.3: medium effect, [b]*r* = 0.5: large effect.
BMI, Body mass index; SD, standard deviation.

Table 5.2: Demographic data of the age-matched study population.

Characteristics	Stroke patients	Healthy elderly	Total	*p*-value	*r*-value
Number of participants	12	12	24		
Age (years), mean ± SD (range)	67.5 ± 6.2 (57-76)	71.2 ± 3.0 (66-76)	69.3 ± 5.1 (57-76)	0.078	0.134
Sex (female/male)	0/12	9/3	9/15		
Height (cm), mean ± SD (range)	176.4 ± 5.7 (168-186)	168.9 ± 9.5 (157-189)	172.7 ± 8.6 (157-189)	0.029[a]	0.200
Weight (kg), mean ± SD (range)	85.2 ± 14.0 (70.0-114.0)	75.3 ± 12.4 (60.2-101.10)	80.3 ± 13.9 (60.2-114.0)	0.082	0.131
BMI (kg/m^2), mean ± SD (range)	27.3 ± 4.0 (22.6-35.2)	26.3 ± 2.6 (21.7-30.4)	26.8 ± 3.3 (21.6-35.2)	0.452	0.026
Walking assistance, n (%)	5 (41.7%)	0 (0.0%)	5 (20.8%)		
Affected side (right/left)	7/5	-	-		

p-value for between-groups comparison, [a]Significant between-group differences ($p_{between}$ ≤0.05) calculated with independent *t*-test and Mann-Whitney *U*-test.

r-value, effect size, calculated according to $r = Z/\sqrt{N}$ and $r = t^2/(t^2+df)$, *r* = 0.1: small effect, [c]*r* = 0.3: medium effect, [b]*r* = 0.5: large effect.

BMI, Body mass index; SD, standard deviation.

Table 5.3: Reliability of the iTUG metrics based on the entire study population (stroke patients and healthy elderly).

iTUG metrics	$ICC_{1,k}$	CI 95% for $ICC_{1,k}$	SEM	CI 95% for SEM	SDD	SEM%	SDD%	LALB	LAUB
iTUG total duration (sec)	0.935	0.876-0.966	1.487	±2.914	4.122	6.435	17.838	-12.865	9.997
Sit-to-walk metrics									
Sit-to-walk duration (sec)	0.431	-0.079-0.701	0.346	±0.679	0.960	15.908	44.138	-0.900	0.858
Peak sit-to-walk velocity (deg/sec)	0.674	0.382-0.828	12.923	±25.330	35.821	15.819	43.848	-38.700	50.025
Gait metrics									
Gait cadence (steps/min)	0.985	0.971-0.992	0.487	±0.955	1.350	0.453	1.257	-7.142	8.432
Gait stance phase (%)	0.947	0.900-0.972	0.317	±0.622	0.880	0.516	1.434	-3.003	2.400
Gait limp phase (%)	0.855	0.725-0.924	0.680	±1.334	1.886	20.600	57.134	-4.007	2.997
Gait velocity (m/sec)	0.991	0.982-0.995	0.006	±0.011	0.016	0.470	1.302	-0.114	0.126
Gait stride length (m)	0.994	0.989-0.997	0.003	±0.006	0.009	0.220	0.659	-0.077	0.083
Gait peak swing velocity (deg/sec)	0.988	0.977-0.993	1.618	±3.172	4.486	0.466	1.293	-28.105	29.807
Gait asymmetry	0.963	0.930-0.981	0.666	±1.305	1.846	6.777	18.783	-7.617	5.951
Turning metrics									
Turning duration (sec)	0.985	0.972-0.992	0.064	±0.126	0.178	1.914	5.323	-1.209	0.845
Peak turning velocity (deg/sec)	0.905	0.820-0.950	8.057	±15.791	22.332	5.502	15.251	-48.866	53.599
Turn-to-sit metrics									
Turn-to-sit duration (sec)	0.951	0.908-0.974	0.242	±0.474	0.670	5.549	15.363	-2.200	2.079
Peak turn-to-sit velocity (deg/sec)	0.862	0.739-0.928	6.461	±12.664	17.909	7.109	19.706	-29.150	39.030

$ICC_{1,k}$, intraclass correlation coefficient (one-way analysis); CI 95%, confidence interval 95%; SEM, standard error of measurement; SDD, smallest detectable difference; LALB, limits of agreement lower boundary; LAUB, limits of agreement upper boundary.
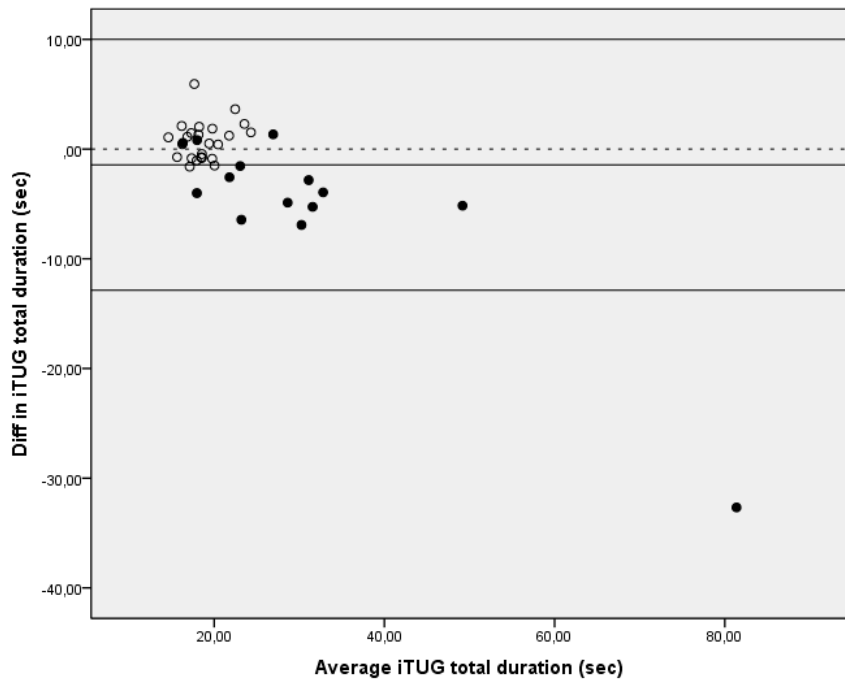
Figure 5.1: Bland and Altman plot of iTUG total duration. Closed circles = stroke patients, open circles = healthy elderly.
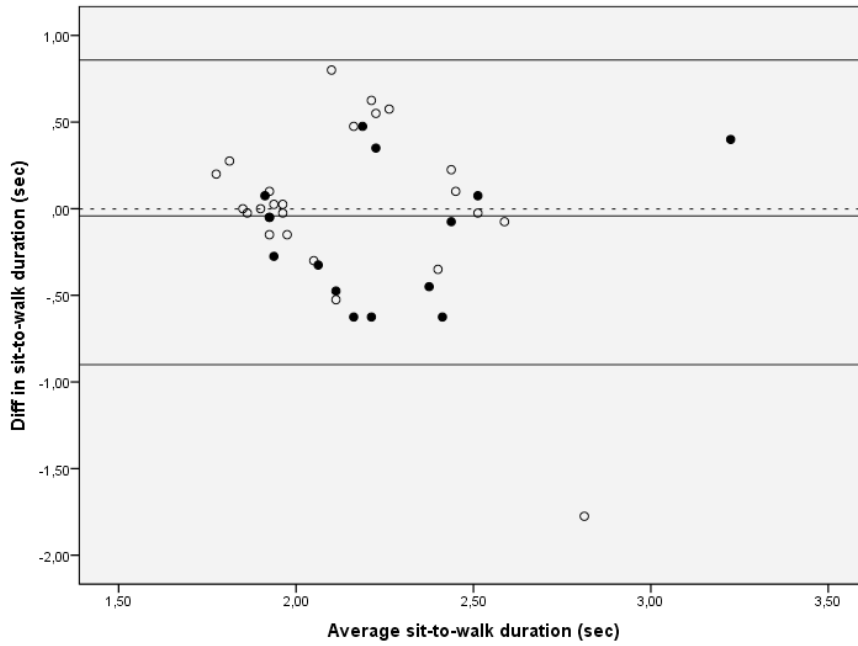

Figure 5.2: Bland and Altman plot of sit-to-walk duration. Closed circles = stroke patients, open circles = healthy elderly.
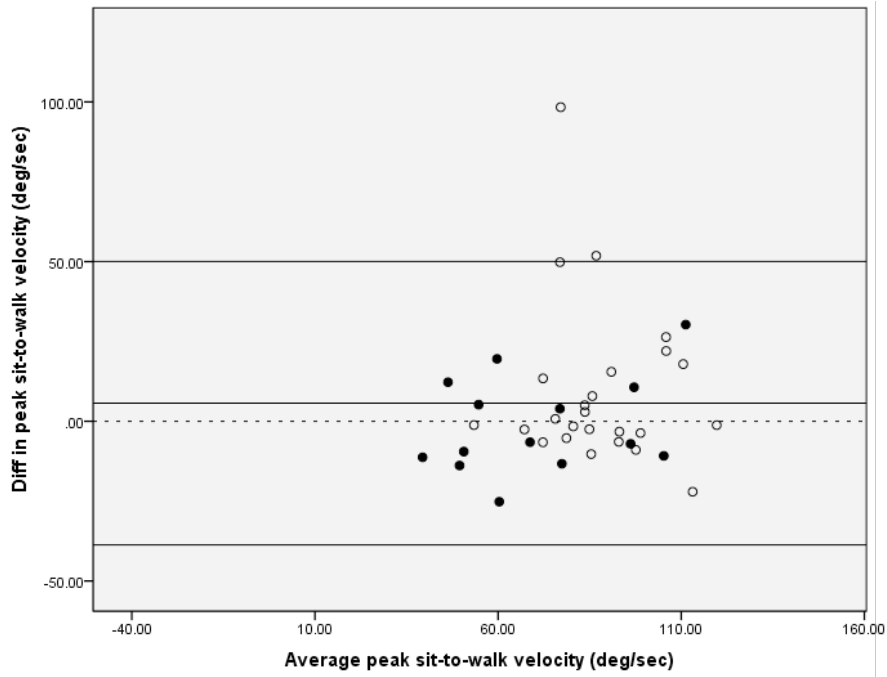
Figure 5.3: Bland and Altman plot of sit-to-walk velocity. Closed circles = stroke patients, open circles = healthy elderly.
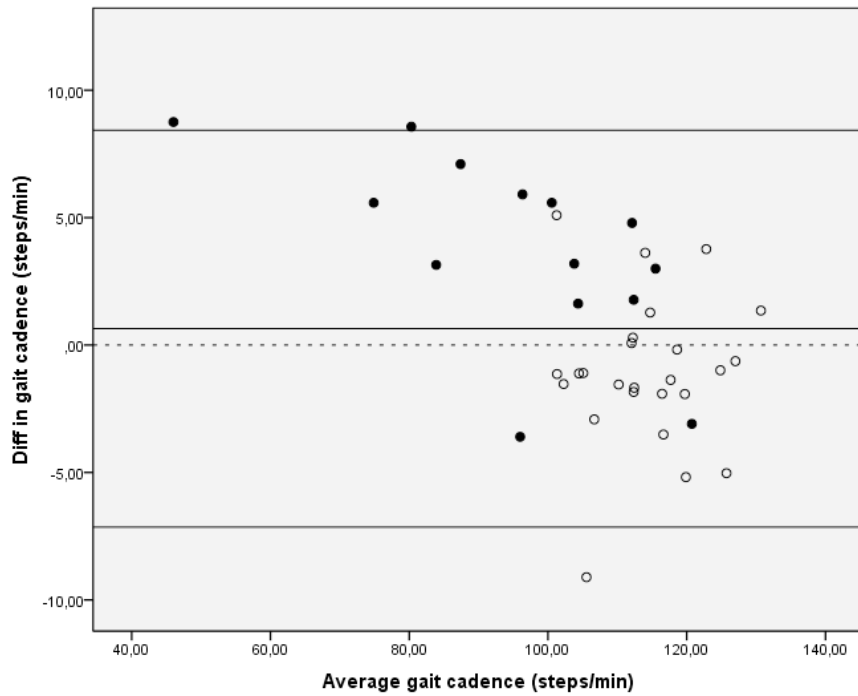

Figure 5.4: Bland and Altman plot of gait cadence (not normalized data). Closed circles = stroke patients, open circles = healthy elderly.
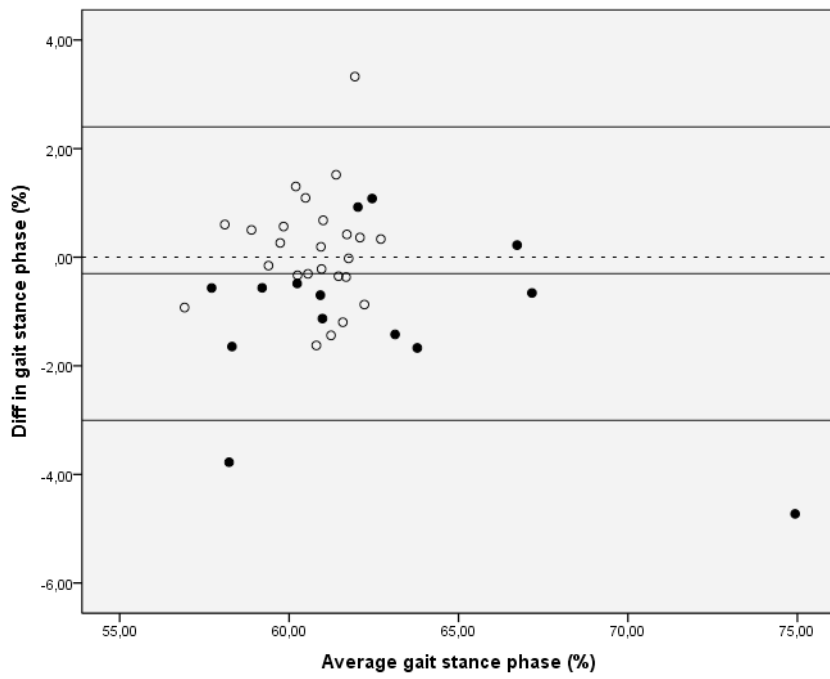
Figure 5.5: Bland and Altman plot of gait stance phase. Closed circles = stroke patients, open circles = healthy elderly.
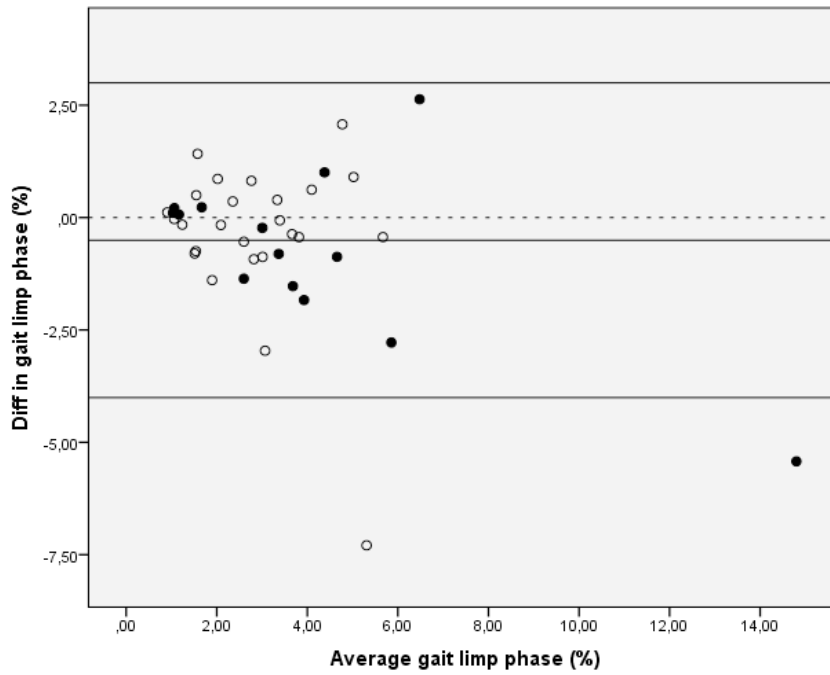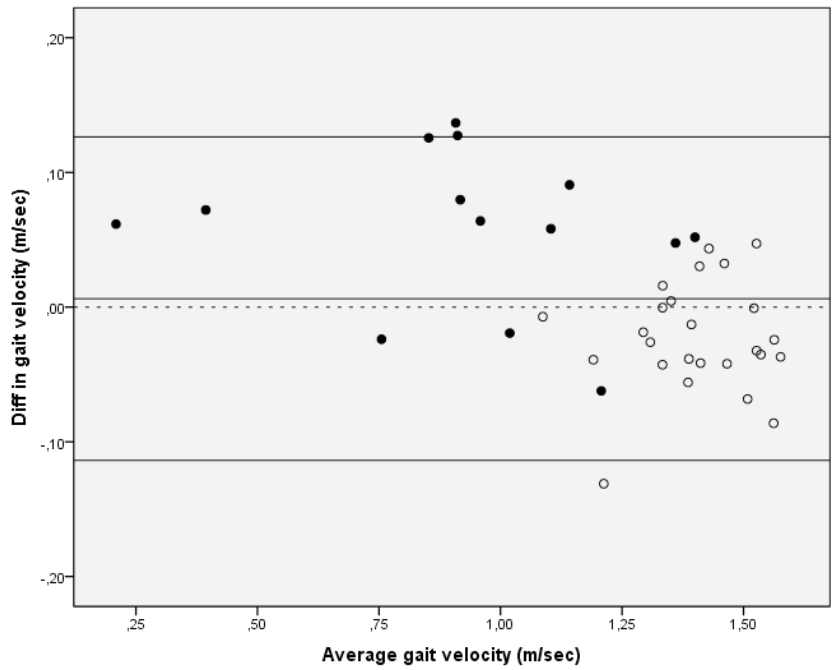

Figure 5.6: Bland and Altman plot of gait limp phase. Closed circles = stroke patients, open circles = healthy elderly.

Figure 5.7: Bland and Altman plot of gait velocity (not normalized data). Closed circles = stroke patients, open circles = healthy elderly.

Figure 5.8: Bland and Altman plot of gait stride length (not normalized data). Closed circles = stroke patients, open circles = healthy elderly.

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Figure 5.9: Bland and Altman plot of gait peak swing velocity. Closed circles = stroke patients, open circles = healthy elderly.
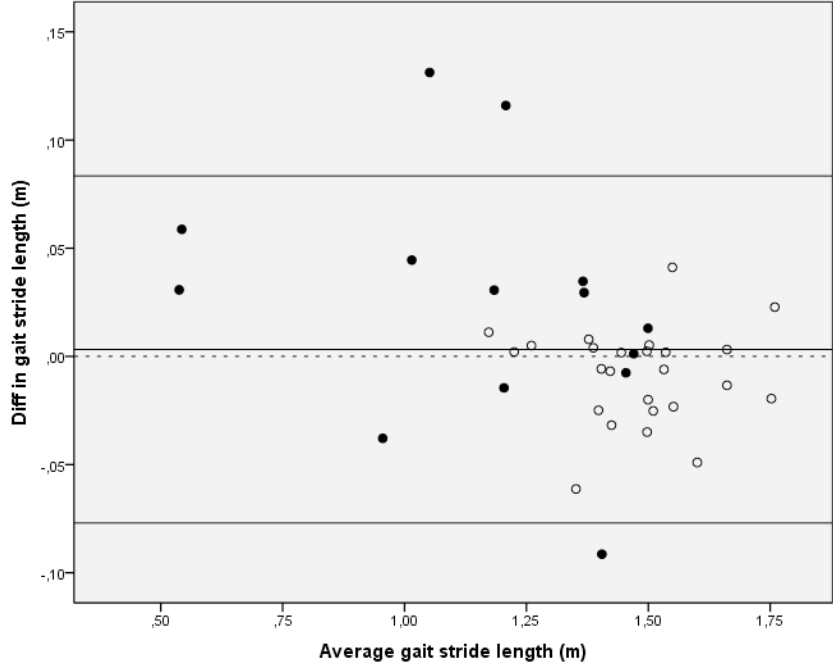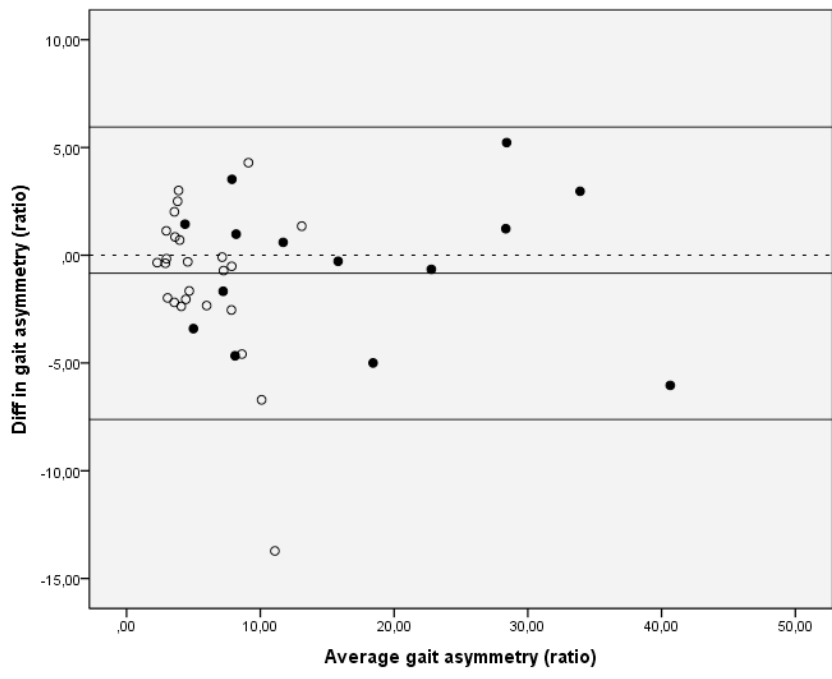

Figure 5.10: Bland and Altman plot of gait asymmetry. Closed circles = stroke patients, open circles = healthy elderly.

Figure 5.11: Bland and Altman plot of turning duration. Closed circles = stroke patients, open circles = healthy elderly.
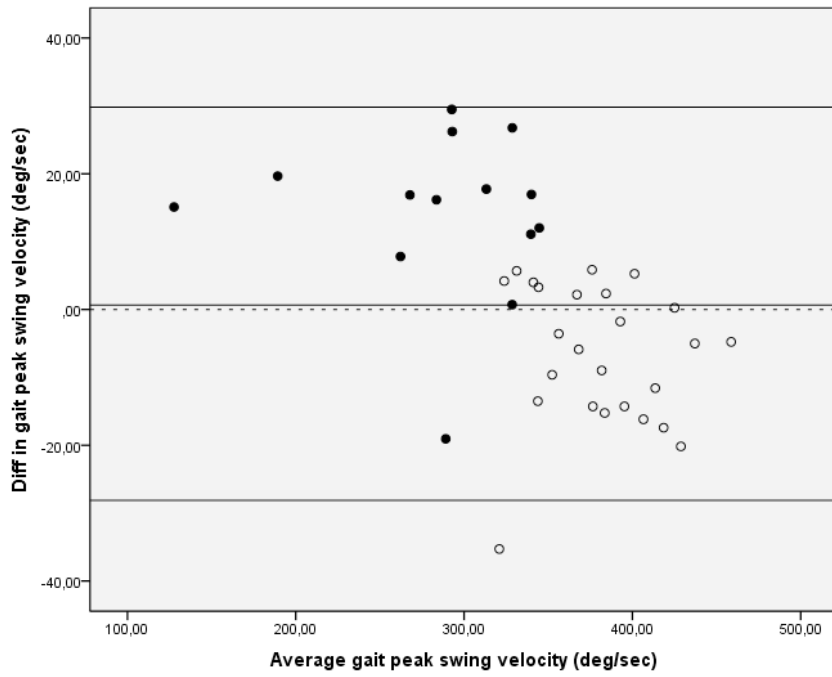

Figure 5.12: Bland and Altman plot of peak turning velocity. Closed circles = stroke patients, open circles = healthy elderly.

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Figure 5.13: Bland and Altman plot of turn-to-sit duration. Closed circles = stroke patients, open circles = healthy elderly.
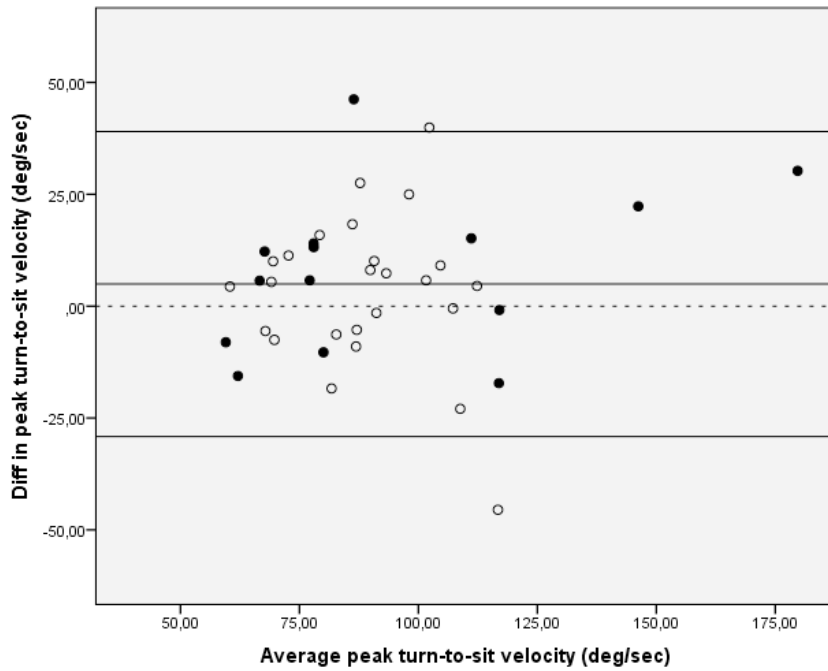
Figure 5.14: Bland and Altman plot of peak turn-to-sit velocity. Closed circles = stroke patients, open circles = healthy elderly.
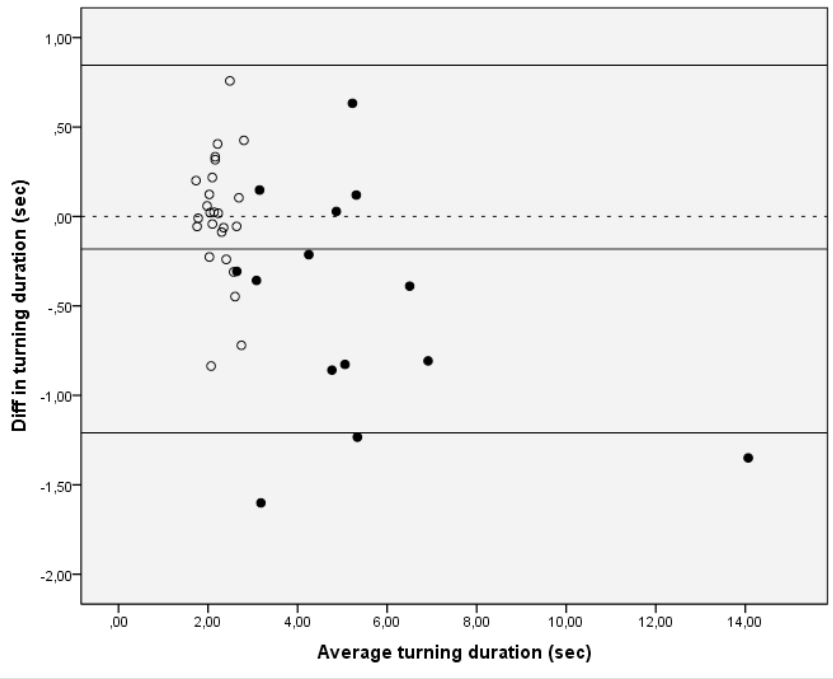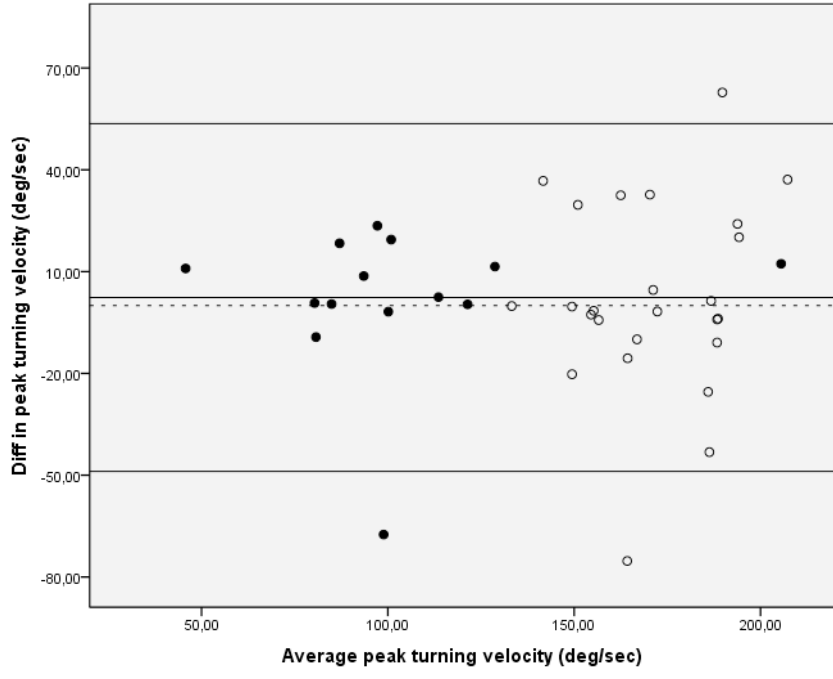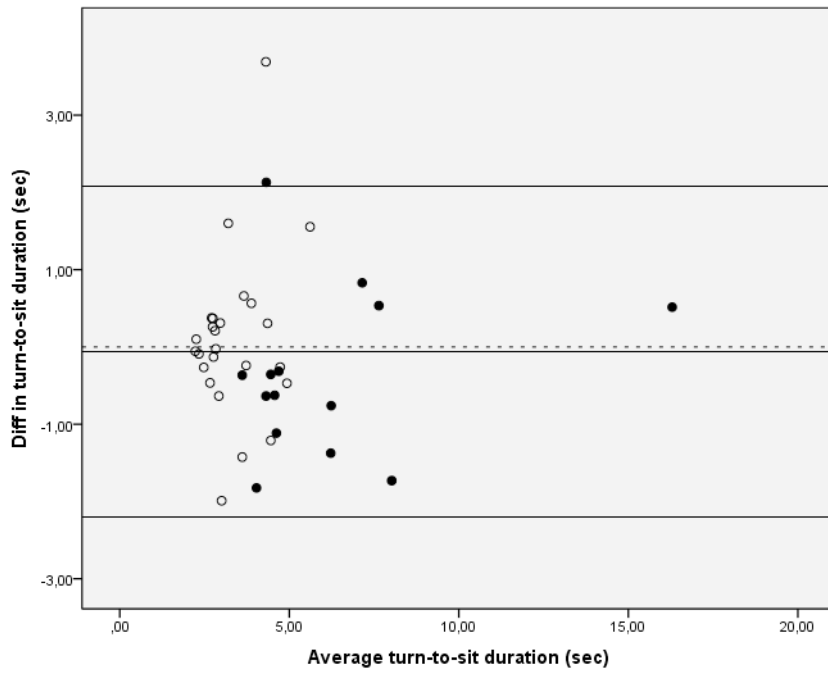
Table 5.4: Reliability of the iTUG metrics based on the stroke patients.

iTUG metrics	$ICC_{1,k}$	CI 95% for $ICC_{1,k}$	SEM	CI 95% for SEM	SDD	SEM%	SDD%	LALB	LAUB
Gait metrics									
Gait cadence (steps/min)	0.983	0.948-0.994	0.488	±0.957	1.354	0.512	1.421	-3.603	11.081
Gait stance phase (%)	0.958	0.873-0.986	0.327	±0.641	0.907	0.522	1.448	-4.198	2.059
Gait velocity (m/sec)	0.985	0.955-0.995	0.007	±0.014	0.020	0.746	2.131	-0.057	0.173
Gait stride length (m)	0.991	0.973-0.997	0.005	±0.011	0.015	0.431	1.292	-0.087	0.136
Gait asymmetry	0.981	0.942-0.994	0.464	±0.910	1.285	2.701	7.481	-6.810	6.078

$ICC_{1,k}$, intraclass correlation coefficient (one-way analysis); CI 95%, confidence interval 95%; SEM, standard error of measurement; SDD, smallest detectable difference; LALB, limits of agreement lower boundary; LAUB, limits of agreement upper boundary.

Validity

The results of the validity analysis are presented in Table 5.5. Considering the total time duration needed for iTUG completion, there was a statistically significant difference between the two groups. The stroke patients required more time to compete the iTUG test compared to the age-matched healthy controls. Among the 13 computed iTUG subcomponent parameters, eight showed significant between-group differences.

5.4 Discussion

This study was performed to analyze inertial sensor-based iTUG metrics regarding 1) test-retest reliability in a group composed of stroke patients and healthy elderly and 2) the ability to discriminate between individuals with stroke and age-matched healthy controls. The present study revealed that all but two of the computed iTUG metrics reached ICCs above 0.75, which indicates excellent relative reliability. Both variables that did not achieve excellent relative reliability values were related to the iTUG subcomponent 'sit-to-walk'. Comparable results found in this study were reported by Salarian et al. [18], who performed the inertial sensor-based iTUG in patients suffering PD and healthy participants. Three, out of the four major iTUG subcomponents 'sit-to-stand', 'steady-state gait', 'turning' and 'turn-to-sit' showed good to excellent reliability for most of their contributing metrics [18]. In line with our findings, the parameters 'cadence' and 'stance phase' have pointed out as one of the most reliable iTUG variables with ICCs greater than 0.90. Regarding the subcomponents 'turning' and 'turn-to-sit', there was consensus that the parameter 'duration' seems to be the most reliable. Moreover, in accordance to our study, Salarian et al. [18] revealed the sit-to-stand subcomponent as least reliable part of the iTUG test.

Beside high ICCs, a measurement tool should exhibit small measurement errors and be able to identify real changes in the group and in single individuals [37]. The absolute reliability analysis performed in this study corroborates the good relative reliability of the inertial sensor-based iTUG metrics. Specifically, small SEM and SEM% values together with small SDD and SDD% values were found in 11 of the total computed 14 iTUG parameters. Those low values indicate good precision of the measurement tool.

Except for a few outliers, most of the difference values between the two repeated measurements were lying within the 95% LOA in the Bland and Altman plots and were well distributed around zero (dashed zero line in Figures 5.1-5.14) demonstrating good agreement between the data of repeated measurements (Figures 5.1-5.14).

Table 5.5: Differences between the groups for the iTUG metrics.

iTUG metrics	Stroke patients	Healthy elderly	Mean diff ± SD	CI 95% for mean diff	*p*-value	*r*-value
iTUG total duration (sec)	27.66 ± 12.73	18.19 ± 1.84	9.477 ± 11.860	1.941-17.013	0.002[a]	0.577[b]
Sit-to-walk metrics						
Sit-to-walk duration (sec)	2.17 ± 0.47	2.10 ± 0.29	0.073 ± 0.570	-0.289-0.435	0.945	0.021
Peak sit-to-walk velocity (deg/sec)	69.77 ± 26.48	97.81 ± 20.33	28.043 ± 34.812	5.925-50.162	0.018[a]	0.414[c]
Gait metrics						
Gait cadence (steps/min)	54.6 ± 10.9	68.9 ± 7.4	14.278 ± 12.801	6.144-22.411	0.005[a]	0.544[b]
Gait stance phase (%)	62.20 ± 4.19	61.01 ± 1.39	1.187 ± 4.809	-1.868-4.243	0.850	0.048
Gait limp phase (%)	3.64 ± 2.87	2.80 ± 1.86	0.841 ± 3.981	-1.689-3.370	0.850	0.048
Gait velocity (m/sec)	0.57 ± 0.17	0.85 ± 0.06	0.282 ± 0.192	0.160-0.404	0.001[a]	0.609[b]
Gait stride length (m)	0.69 ± 0.16	0.88 ± 0.05	0.187 ± 0.184	0.070-0.303	0.002[a]	0.577[b]
Gait peak swing velocity (deg/sec)	297.56 ± 59.24	391.38 ± 34.43	93.824 ± 80.058	42.957-144.690	0.001[a]	0.609[b]
Gait asymmetry	15.60 ± 11.28	6.42 ± 3.39	9.179 ± 13.655	0.503-17.854	0.092	0.352[c]
Turning metrics						
Turning duration (sec)	5.15 ± 2.83	2.16 ± 0.35	2.994 ± 2.776	1.230-4.757	<0.001[a]	0.624[b]
Peak turning velocity (deg/sec)	95.34 ± 24.47	180.13 ± 28.44	84.788 ± 36.971	61.297-108.278	<0.001[a]	0.852[b]
Turn-to-sit metrics						
Turn-to-sit duration (sec)	5.98 ± 3.63	3.17 ± 1.19	2.812 ± 2.758	1.060-4.564	<0.001[a]	0.625[b]
Peak turn-to-sit velocity (deg/sec)	97.51 ± 36.81	88.71 ± 19.42	8.804 ± 37.729	-15.168-32.776	0.733	0.080

p-value for between-groups comparison, [a]Significant between-group differences ($p_{between}$ ≤0.05) calculated with paired *t*-test and Wilcoxon signed-rank test.

r-value, effect size, calculated according to $r = Z/\sqrt{N}$ and $r = t^2/(t^2+df)$, $r = 0.1$: small effect, [c]$r = 0.3$: medium effect, [b]$r = 0.5$: large effect.

Mean diff, mean difference = (mean of the group with the higher value)-(mean of the group with the lower value); SD, standard deviation of the difference; CI 95%, confidence interval 95%.

On average the patients improved between the first and the second measurement (Bland and Altman plots in Figures 5.1-5.14). This is likely a learning effect between the first and second measurement. Performing an initial test trial prior to the actual measurement may have prevented this learning effect.

Several studies described the typical 'hemiplegic gait' post-stroke with a decreased walking velocity, cadence and stride length [1-3, 5, 8]. Moreover, an increase in stance phase duration and left-right asymmetry seems to be a characteristic feature of stroke patients' gait [1-3, 9]. Accordingly, in this study, those five iTUG metrics were highlighted by a separate reliability analysis where the group 'stroke patients' were separated from the healthy elderly controls (Table 5.4). The subanalysis showed similar relative test-retest reliability values as found in the entire study population. Specifically, excellent ICCs above 0.75 were achieved. Furthermore, all five iTUG metrics in the subanalysis demonstrated good absolute test-retest reliability expressed by small SEM and SEM% values together with small SDD and SDD% values. These findings warrant further investigations of the iTUG in larger samples of stroke survivors and, thus, further exploring the clinical relevance of the system.

In clinical settings, the assessment of mobility and balance in stroke survivors is important for several reasons; e.g., to accurately perform a diagnosis, to plan the treatment method for each individual patient and to adequately evaluate the rehabilitation effectiveness. The iTUG system has the potential for playing an important role in providing clinically useful information by objectively assessing a stroke patient's balance and mobility. This highlights its potential relevance for application in clinical practice.

Out of the 14 analyzed iTUG metrics, nine showed a significant difference between stroke patients and healthy controls (Table 5.5). Among the variables which were significantly different between the two groups, all demonstrated high effect size values close to 0.50 and larger. In contrast, smaller effect sizes ranging from 0.021 to 0.352 were measured for those five parameters which did not differ between the two groups. Specifically, there were no significant differences in the duration required for completing the iTUG subcomponent 'sit-to-walk', in the percentage values related to 'stance phase' and 'limp phase' of gait cycle time during steady-state gait, in the left-right gait asymmetry, and in the maximum angular trunk velocity during turn-to-sit transition.

From previous studies we have indication that stroke leads to walking- and balance-related limitations and negatively affects patients' functional mobility. Research by Ng and Hui-Chan [15] indicates that there was a significant difference between chronic stroke patients and healthy elderly of the duration it took for TUG test performance. In line with our study, the stroke patients needed more time to finish the

TUG procedure. Furthermore, significant higher values for walking speed, cadence and step length in favor of the healthy individuals were found. Regarding the variable 'stance time', Ng and Hui-Chan [15] revealed a discrepancy between the two groups, but only when the outcome based on stroke patients' unaffected side was considered. In our study, no separate body-side related analysis was done and, therefore, no specific information regarding the paretic and non-paretic side available. Hence, we recommend that this should be part of future studies. Olney and Richards [38] stated an increase of the stance phase proportion within the gait cycle in stroke patients. In the present study, however, no significant difference was found between stroke patients and age-matched healthy controls. The inconsistency between the studies may be related to differences in stroke characteristics and severity.

Gait symmetry represents an indicator of normal walking [39]. Since stroke often results in unilateral symptoms contralateral to the infarct, normalization of gait symmetry may be an indicator for recovery of gait. For gait symmetry evaluation, various metrics can be considered. According to literature, the most common symmetry metrics used for gait assessment are swing time, single support time, pelvic and/or trunk movement, and ground reaction forces [39-40]. Patterson et al. [40] concluded that the parameter 'swing time' is suitable to analyze gait symmetry post-stroke and, therefore, highly recommended. Hence, this study focused on the gait variable 'swing phase' for symmetry measure. Our results of the gait symmetry evaluation are, however, at odds with the findings revealed by Patterson et al. [40]. Patterson et al. [40] reported a more asymmetric gait pattern in stroke patients when compared with healthy individuals. In the current study, no significant asymmetry difference was found. Nonetheless, the effect size for gait asymmetry exceeded the 0.30 level and showed, consequently, a medium effect. One possible reason for this might be the rather small sample of stroke survivors with insufficient between-subjects variance. Future studies should, therefore, repeat our study design in larger samples of stroke patients in different post-stroke recovery phases.

Another interesting parameter to be considered for gait analysis of stroke patients is arm swing. Indication exists that the asymmetries frequently seen in gait parameters post-stroke also affect upper body movements resulting in asymmetric arm swing patterns [41]. The hemiparetic gait of stroke patients is often associated with an adducted arm with no or limited arm swing on the affected side. A normalization of the arm swing on the affected side might be a parameter for recovery of normal gait. Zampieri et al. [19] identified the iTUG parameter 'peak arm swing velocity' as one of the most sensitive

deficits in early PD. It might be that the parameter 'arm swing' is also of clinical relevance post-stroke. Future research is warranted that includes arm swing parameters as outcome variable.

5.5 Limitations

Some limitations of this study should be considered. A first limitation is the lack of detailed information regarding the severity, type and anatomical lesion location(s) of the stroke. Further studies are needed that focus on specific subgroups in the stroke population (e.g., sub-acute or chronic patients, first-ever or recurrent stroke) to substantiate our findings of the inertial sensor-based iTUG application in clinical settings. Moreover, the pertinence of using elderly to test the iTUG may be questioned. However, untrained elderly normally show both balance and gait impairments [42-46], which should render them an adequate population for assessing reliability as well. The gender distribution in our sample may be another limitation with a difference between the stroke patients and the age-matched healthy controls with respect to sex: All the stroke patients were males whereas only three of 12 healthy controls were males. This may be a source of bias confounding the results. Furthermore, sex disparity in stroke prevalence persists with women being more affected then men [47] making it important to especially test reliability in women in future studies. A further limitation of this study is the small sample size in relation to reliability studies. An adequate sample size for the assessment of the agreement parameter, based on a general guideline by Altman [48], is lying around at least 50. The sample size of 14 stroke survivors and 25 healthy elderly individuals we used is, however, a realistic group size to find first estimates for the assumed relation between stroke and functionally important tasks as measured with the iTUG and results in preliminary data as a basis for further examinations including larger samples. Furthermore, the reliability subanalysis has to be interpreted with caution: Other than the data used for the primary reliability analysis based on the entire study population, the subanalysis data were not checked for heteroscedasticity.

5.6 Conclusion

Excellent test-retest reliability was found for most of the iTUG metrics measured and the inertial sensor-based iTUG is able to distinguish stroke patients from healthy controls. These findings suggest that the inertial sensor-based iTUG measures are useful to assess functional mobility in stroke patients. However, the study should be repeated with a larger group of patients to investigate its discriminatory capabilities between different subgroups of stroke patients.

Authors' contributions

SW contributed to the conception of the work, to the acquisition, analysis and interpretation of data, and to writing the manuscript. FM contributed to the development of the iTUG software, assisted in the acquisition and analysis of data. KA contributed to the conception of the work and the development of the iTUG software. RG assisted in the acquisition and analysis of data in the clinical setting and critically revised the manuscript. EDdB initiated the study, assisted in the acquisition of data, and contributed to writing and critically revising the manuscript. All authors read and approved the final manuscript.

Conflict of interest statement

The authors declare that they have no competing financial interests.

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6

Epilogue

The number of stroke patients increases year after year [1]. Moreover, there is an increased awareness that stroke patients benefit strongly from a rehabilitation program that well exceeds the critical first three months after stroke [2]. Clearly, the need for a long-term approach to stroke rehabilitation for an ever larger number of stroke patients cannot be realized by cost-intensive inpatient care alone. Autonomous home-based rehabilitation programs are required. Interactive rehabilitation games represent a promising tool to support intensive and prolonged home-based stroke rehabilitation.

Accordingly, the overarching theme of this doctoral thesis was home-based long-term stroke rehabilitation using rehabilitation games specifically designed for this purpose. First, this thesis described the Intelligent Game Engine for Rehabilitation (IGER) – a game engine designed for building rehabilitation games that are functional, accessible and entertaining. Second, it discussed the two-dimensional taxonomy framework suggested by Gentile as a template for providing beneficial virtual reality (VR)-based rehabilitation circumstances in accordance with established motor learning principles. Third, it presented an intervention study following a user-centered interaction design methodology. This study assessed the usability and effects of a 12-week rehabilitation program based on the newly developed rehabilitation games and organized according Gentile's taxonomy.

In order to quantify intervention effects, a reliable method for measuring stroke victims' physical functioning is needed. To this end, this thesis evaluated an instrumented version of the Timed Up and Go test (TUG) abbreviated as iTUG. Specifically, it was evaluated whether the iTUG using wearable inertial sensors represents a reliable and valid assessment tool for mobility deficit detection post-stroke.

In this epilogue, I will (1) detail the main findings of the thesis (2) outline methodological issues and (3) provide directions for future research.

6.1. Computational intelligence and game design for effective at-home stroke rehabilitation (Chapter 2)

VR technique was hypothesized to offer a broad spectrum of advantages for providing beneficial treatment conditions in clinical practice. It is not surprising, therefore, that interactive videogames available for the entertainment market found their way into the field of health care and influenced the direction of research in this area. However, to date, the majority of games applied in health care lacked the features needed to support rehabilitation at home. In our view, the following features must be ensured: First, a flexible adaptation of the game challenge level according to patient's actual status of functional abilities is required. A proper level of exercise difficulty ensures that the rehabilitation

exercise is neither perceived as too easy and boring nor as too difficult and frustrating. This helps to keep individuals' training motivation high. Second, continuous monitoring of the patient is needed to be able to correct harmful posture and bad movements. Third, and related, given the absence of clinicians and therapists in patients' home environments, automatic real-time patient feedback is of great importance. The patient can then be warned upon incorrect movement execution or gameplay, thereby ensuring patient safety. Moreover, the feedback feature can also serve as a motivational tool.

In order to achieve pleasurable gameplay experiences, it is important to explicitly consider game design principles widely applied in games developed for the leisure industry. Three such principles are meaningful play, flow theory and sense of presence. The principle of meaningful play refers to the link between a player's particular action and its consequences within the game. By providing direct and clear feedback, this link is ensured and the player understands the game's internal logic and feels in control of game events [3]. Furthermore, according to the theory of flow, it has been found that by appropriately adapting the challenge and complexity of a videogame to a patient's cognitive and physical capabilities, the player will achieve a high level of focus and feel truly present in the virtual world. This could even reach a stage in which patients forget that they are performing therapeutic exercises [4]. Moreover, there is evidence that the player's real body movements should be tracked and integrated in the game in real time; i.e., well-synchronized with the game's virtual environment. Thereby, the player gets an enhanced sense of autonomy and regards him- or herself as being the actor [5]. We assume that rehabilitation games that meet these requirements are more successful at motivating patients for treatment practice than those who do not.

In order to optimize home-based rehabilitation, games should not be treated as stand-alone components. There is a need for overarching system architecture to connect relevant parties contributing to successful rehabilitation outcomes. Specifically, the rehabilitation games must be integrated into a broader structure comprised of patients, rehabilitation specialists, hospitals and health providers. Within the REWIRE project, three main components make up a multi-layered structure: (1) the patient station (PS), (2) the hospital station (HS) and (3) the networking station (NS). The PS – installed in the patient's home – includes four modules that enable the following tasks: hospital communication for downloading game configurations, data collection of patients' daily life activities, patient community for interacting with peers and guidance of the rehabilitation process based on the IGER. The IGER system represents the core component of the PS allowing game configurability and flexibility, feedback realization, real-time adaptation and monitoring [4]. Its functioning is based on a game engine and a game control unit. The HS – conceived as a web application – is a therapy management tool used at

hospital. It generates a virtual community between persons involved in the rehabilitation process (e.g., patients, therapists, clinicians) to support patients' therapy practice. Additionally, the HS enables insight into patients' rehabilitation outcomes as well as the specification and monitoring of treatment sessions. The NS – installed at a regional level at the health provider site – is responsible for data mining. This station reveals features and trends of rehabilitation treatment and allows a comparison of, e.g., different hospitals, geographic regions and socio-economic groupings.

The structure and characteristics described here are likely to ensure a motivating, safe and well-supervised rehabilitation environment and hence render long-term home-based rehabilitation feasible. However, a set of targeted videogames embedded in overarching system architecture – although necessary – is not yet sufficient for providing a comprehensive approach to rehabilitation. The videogames must be embedded in a structured, theory-based therapy program so that continuous progress across all relevant dimensions of motor function is ensured.

6.2. Design considerations for a theory-driven exergame-based rehabilitation program to improve walking of persons with stroke (Chapter 3)

In the context of this doctoral thesis, Gentile's taxonomy was considered as a therapy program template. **Chapter 3** explained how Gentile's taxonomy constitutes a practical template, which allows the development of a therapy program according to the motor learning principles *variable practice* and *progression*. Concretely, based on a 4x4-table (see Table 3.1, Chapter 3), 16 different categories to classify motor skills are characterized. Each skill category is defined by unique features through two general dimensions (i.e., *environmental context* and *action function*). Due to the positioning of the 16 skill categories within the taxonomy, a systematic progression in task difficulty could be performed in a structured and simple manner. Gentile's taxonomy allows VR rehabilitation scenarios to be efficiently created. Since the beginning of the 1990s, evidence has accumulated that virtual environments are able to facilitate the acquisition of motor skills [6]. Consequently, VR has begun to be applied as a potential tool for motor rehabilitation. A key advantage of this technology is the possibility of tailoring the environmental conditions for therapy purposes. Furthermore, numerous studies emphasize that VR provides engaging treatment situations and, thereby, enhances patients' motivation for rehabilitation practice. This, in turn, might lead to better clinical outcomes [7]. Accordingly, we developed six exergames and used them to create 16 virtual rehabilitation scenarios organized in accordance with Gentile's taxonomy.

The 16 scenarios organized thus accommodate the description of seven levels of task difficulty, which are ordered along the diagonal of the 4x4-taxonomy (see Table 3.3, Chapter 3). Based on this structure, we presented a formal procedure for defining meaningful therapy plans. Concretely, rehabilitation starts with skill category 1A in the upper left corner of the taxonomy, which represents difficulty level 1. Difficulty may be increased either by a vertical shift to the adjacent row (skill category 1B), or a horizontal shift to the adjacent column (skill category 2A). Hence, skill categories 1B and 2A together form difficulty level 2. From either of the two skill categories in difficulty level 2, we can obtain difficulty level 3 by again shifting either horizontally or vertically. When continuing this process, we end up in skill category 4D, which represents the seventh and final difficulty level in the taxonomy. Importantly, the procedure proposed is not limited to skill category-based shifts in only one direction yet involves both horizontal and vertical shifts and hence a modification of both *environmental context* and *action function*. Additionally, persons involved in the therapy may freely choose the order in which skill categories in the same difficulty level are traversed, thus allowing the therapy program to be tweaked to each patient's individual rehabilitation requirements. Due to these advantages, Gentile's taxonomy constitutes a valuable template for the systematic development of coherent VR-based rehabilitation programs to improve post-stroke motor deficits. Future exploratory studies are needed with focus on usability and feasibility of rehabilitation interventions based on Gentile's taxonomy using VR.

6.3. Usability and effects of an exergame-based balance training program (Chapter 4)

Hemiparesis is regarded as a major impairment of stroke patients which results in an impaired walking pattern and diminished balance skills. Intact walking abilities are, however, central for the preservation of autonomous mobility and the achievement of a high quality of life [8]. Intensive therapy sessions performed repeatedly over a prolonged period of time have been proven to guarantee a good level of motor recovery post-stroke [9]. Previous studies were able to demonstrate that one of the best predictors of successful rehabilitation outcome was a high level of motivation. High motivation corresponds to high adherence and low attrition and contributes to optimal functional recovery from stroke [10]. Unfortunately, however, stroke patients often perceive therapeutic interventions based on usual rehabilitation exercises as monotonous and boring and their motivation for rehabilitation practice is correspondingly low. Because VR represents a promising tool for turning boring rehabilitation exercises into entertaining ones, videogames could be a good tool to promote long-term rehabilitation via increased motivation.

With this in mind, we designed an intervention program based on a set of five rehabilitation games designed within the REWIRE project. The program aimed to reduce stroke-induced walking and balance impairments. **Chapter 4** reports a pilot project in which the program is applied in healthy elderly. In line with the phased iterative approach proposed by Campbell et al. [11], the pilot project represents a discrete exploratory phase, which is to be followed by a prospective study with stroke patients. Specifically, the pilot project focused on usability and effectiveness of the exergame-based program. The training sessions were performed three sessions per week for 12 weeks for a grand total of 36 sessions. Thirteen of the 16 enrolled participants completed the study intervention (18.8 percent attrition) with a remarkable adherence rate of 100 percent. Furthermore, based on participants' feedback, a high level of training technology acceptance was expressed and few modifications of the rehabilitation games were suggested. After the intervention, no significant changes were found in center of pressure (COP) area during quite stance and in walking parameters. However, the Berg Balance Scale (p = 0.007; r = 0.51), the 7-m Timed Up and Go test (p = 0.002; r = 0.56) and the Short Physical Performance Battery (p = 0.013; r = 0.48) showed significant improvement with moderate to large effect sizes. Obviously, the study results suggest that the exergame-based intervention was perceived as usable and able to influence gait- and balance-related physical performance measures positively. In next research steps, it would be interesting to evaluate the intervention presented here on stroke survivors, first performed in clinical settings and thereafter in patients' homes.

6.4. Reliability and validity of the inertial sensor-based Timed Up and Go test in post-stroke individuals (Chapter 5)

For evaluating and tailoring a stroke treatment program to the patients' specific requirements, an accurate assessment of physical functioning is of great relevance. The instrumented version of the TUG based on wearable inertial sensors resulted in improved discriminative capabilities for balance and mobility evaluation compared to the original test protocol [12]. Yet the iTUG has only been used – invariably with positive results – in healthy elderly and patients with Parkinson's disease (PD). Hence, although validity and reliability have never been tested in stroke patients, it can be hypothesized that the iTUG might also be a useful tool for testing balance and mobility limitations in this population.

The study presented in **Chapter 5** analyzed iTUG-based gait and transition metrics in terms of test-retest reliability and its ability to discriminate between individuals with stroke and age-matched healthy elderly controls. To investigate test-retest reliability, a repeated-measures design was used composed of two

measurement sessions with a 15-minute break in between. Within each measurement session, the iTUG was repeated three times with a 30-second break in between. One observer tested a mixed study population including both stroke patients (n = 14) and healthy elderly (n = 25). To examine the discriminatory capabilities of the iTUG metrics, an age-matched group of 12 patients and 12 healthy individuals was created by random selection.

The following 14 iTUG metrics were analyzed: *iTUG total duration*, *sit-to-walk duration*, *peak sit-to-walk velocity*, *gait cadence*, *gait stance phase*, *gait limp phase*, *gait velocity*, *gait stride length*, *gait peak swing velocity*, *gait asymmetry*, *turning duration*, *peak turning velocity*, *turn-to-sit duration* and *peak turn-to-sit velocity*. The sit-to-walk metrics 'duration' and 'peak sit-to-walk velocity' showed fair to good relative test-retest reliability; all other metrics showed excellent relative reliability. The high relative reliability was corroborated by small 'standard error of measurement' and 'smallest detectable difference' values found in 11 out of 14 iTUG metrics. Additionally, the iTUG parameters were revealed to be in a good agreement in Bland and Altman plots, with most of the data lying close to the mean difference within narrow limits of agreement. The analysis of validity indicates that the inertial sensor-based iTUG represents a valid assessment method allowing a distinction between stroke patients and healthy elderly. Concretely, out of the 14 analyzed iTUG metrics, nine showed a significant difference between the two groups with large effect sizes. A future study could use a pre- and post-design to explore whether the iTUG represents a valuable tool for efficacy assessment of home-based stroke rehabilitation.

6.5. Methodological issues

The results of the studies reported in this doctoral thesis (**Chapters 2-5**) should be interpreted within the context of the methodological limitations outlined below.

This thesis shows a strong focus on balance and largely disregards the importance of muscular strength. Previous stroke studies have shown that – besides balance deficits – muscle weakness seems to be a relevant contributing factor for impaired walking function [13-14]. Muscle weakness is recognized as a frequent negative consequence of stroke and as a limiting factor of gait performance [13, 15-16]. Therefore, the ideal stroke rehabilitation intervention should include strength training in addition to balance training.

In addition to the motor deficits that are the main focus of this thesis, cognitive deficits, which negatively affect both independence and quality of life [17-18], are also common after stroke. Although no

generalized and unitary profile of cognitive problems after stroke currently exists, it is now thought that stroke often has a great negative impact on patients' executive functioning [17-19]. Executive functioning stands for cognitive abilities associated with goal-directed self-regulatory behavior including response inhibition, planning, working memory, task switching, and attention. Earlier studies highlight that executive functioning is related to walking performance in both healthy and cognitively impaired older adults and in patients suffering from neurological diseases (e.g., stroke) [20-21]. A substantial literature demonstrates positive effects on cognitive functioning post-stroke caused by an intervention program that emphasized various aspects of executive functions (e.g., planning, strategy, decision-making, and learning) besides physical and social activities [19]. Obviously, a rehabilitation program including an enriched environment and a focus on both physical activities and executive functioning may effectively promote both motor performance and brain function [22]. Based on my own experiences with VR gathered during the REWIRE project, VR has great potential to these conditions and hence to effectively promote both cognitive and motor functioning. However, in my view, the current REWIRE rehabilitation games, with their strong focus on balance, should be developed further in order to become more cognitively challenging. Specifically, structured cognitive stimuli such as response inhibition, attention, dual tasks and decision-making opportunities should be included in the future to more effectively train executive functioning and, hence, more effectively improve walking performance.

The study presented in **Chapter 4** aimed at the improvement of individuals' balance and walking competency. The intervention was based on a set of five rehabilitation games which required, for successful game-playing, postural control and stability while standing on a COP sensing force platform (i.e., Tymo plate by Tyromotion, Graz, Austria [23]). Interestingly, the intervention did not result in significant changes of walking parameters. As I already noted previously, it is well established that, in order to successfully master a motor skill (e.g., walking), task-specific practice is paramount [24]. Hence, stepping exercises might have been more effective for improving walking function than exercises with a stationary base of support. Unfortunately, stepping movements cannot be performed safely in the existing setup, since the Tymo platform is too small (32 x 51 cm). Another interacting device is required if stepping is to be included in gameplay. The Microsoft Kinect (Microsoft, Redmond, WA) motion sensing camera [25] – a commercially available body motion tracking device – may be such a device. In my view, stroke rehabilitation guided by Gentile's taxonomy should harness the advantages of both the Tymo plate and a device like the Microsoft Kinect: When, according to the taxonomy, an exercise requires body stability, using the Tymo plate is preferable as it provides information about patients' COP movements (and hence their stability), even if both feet are stationary. When body transport is required, walking-

related stepping movements should be performed and tracked by using a device like the Microsoft Kinect.

6.6. Clinical implications and future directions

The fundamental idea of the REWIRE project and likewise of this doctoral thesis is to develop an innovative VR-based rehabilitation platform, which allows patients to continue intensive home rehabilitation under remote monitoring after being discharged from hospital. Such a home-based rehabilitation approach is required because, as the number of stroke victims continues to increase, the cost-intensive rehabilitation services in specialized stroke units or hospitals will pose an ever increasing burden to the National Health Service. Therefore, there is a pressure to shorten the duration of stroke rehabilitation in specialized centers and replace it by more cost-extensive – yet effective – home-based rehabilitation. The recently launched Tymo force plate and Microsoft Kinect camera open new possibilities for providing this important service. Given the low cost and small footprint of such novel types of hardware, they have the potential to offer stroke patients a highly motivating and customizable VR-based rehabilitation program within the comforts of their own homes. With the system architecture developed in the REWIRE project (i.e., the PS, the HS and the NS; see **Chapter 2**) the patient is always under supervision by clinicians and connected with other patients. Hence, professional supervision and customization of the rehabilitation process, positive peer pressure and a sense of community combine to create an optimal rehabilitation environment. Particularly the positive effects of both VR and the sense of community on motivation might be crucial. After all, for best recovery results, discharged stroke patients should practice rehabilitation exercises on a regular basis for many months on end, which is well-nigh impossible without motivating exercises and the presence of a community of peers. The high acceptance towards the REWIRE rehabilitation games presented in **Chapter 4** shows that the newly developed games are indeed motivating. This positive result warrants a subsequent clinical explorative study using this intervention approach with actual stroke patients.

In our study only five balance games were used. This set of exercises should be expanded to include the aforementioned strength and cognitive elements. It might even be a good idea to generate a set of games that allows the development of two parallel taxonomies: one focusing on balance, and another focusing on muscular strength. All exercises – and hence both taxonomies – should include a pronounced cognitive element to provide a multifaceted complex challenge that will not only challenge balance or strength, but also patients' executive functioning.

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In further clinical trials, I also recommend using the iTUG to replace the traditional TUG test for the objective assessment of motor functions. The iTUG provides a more comprehensive insight into the effects of a training intervention to improve gait and mobility. The study offered in **Chapter 5** used a gait analysis system for iTUG metrics assessment based on eight inertial sensors. However, for clinical practice, a smaller number of sensors is preferable, if this does not significantly affects measurement accuracy. A smaller number of sensors would reduce the time needed to attach the sensors and reduce the system's weight thereby enhancing wearing comfort. Based on previous studies [26-31], I propose six inertial sensors located as follows: One sensor on each wrist (to assess upper limb movement), one sensor on each tibia plate mid-shank (to assess gait pattern), one sensor on the mid-thoracic spine (to assess body posture) and one sensor on the sacrum (i.e., near the center of mass, to accurately assess balance). This proposal for a reduced number of sensors for the iTUG should be tested in future experiments. Aiming the development of instrumented assessment procedures that can be performed independently at patients' homes, reducing the number of sensors might be of great relevance. One can assume that only a system designed for easy self-application avoids frustration induced by the inability to use it. Further effort should be directed towards usability evaluation of the independent use of the iTUG by patients.

In a next research step, the effect of the exergame-based intervention on patients' physical functioning should be analyzed. Before concluding that the intervention truly represents a therapeutic advance, an RCT including stroke patients should ideally be performed. The proposed study would compare two groups: one experimental group, which performs the game intervention in addition to conventional physical therapy and one control group, which only performs conventional physical therapy for a total of 36 training sessions. The main outcome measures would be pre- and post-test results of relevant walking-related parameters.

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Summary / Zusammenfassung

Summary

Stroke is considered as one of the main causes of acquired adult disability. In the majority of cases, stroke causes hemiparesis and, hence, diminished balance and walking ability. Locomotor function deficits are often considered by stroke patients as a primary reason for decreased quality of life. Therefore, recovery of walking is a major focus in almost all rehabilitation efforts for stroke victims. Stroke rehabilitation in hospitals or specialized rehabilitation units is expensive. As the number of stroke patients continues to increase, there is a pressure to reduce the treatment duration in specialized stroke facilities. Home-based stroke rehabilitation represents a less costly approach and, therefore, a promising tool to support rehabilitation on a long-term basis.

Indications exist that virtual reality technology has the potential to promote motor recovery in rehabilitation. However, videogames that have been originally developed for the leisure industry are not optimally suited for therapeutic purposes. Specific gaming functionalities (i.e., game difficulty level adaptation, continuous monitoring of the patient, real-time feedback) needed for providing beneficial rehabilitation situations for intensive home-based therapy rehabilitation are lacking. Moreover, for creating motivating rehabilitation games, it is crucial to explicitly consider game design principles (i.e., meaningful play, flow theory and sense of presence). These game design principles might be largely responsible for eliciting attractive gameplay scenarios which, in turn, are presumably fundamental for prolonged rehabilitation adherence. All those gaming characteristics, described in more detail in **Chapter 2,** are considered to provide beneficial and engaging rehabilitation conditions in a safe and controlled environment.

Rehabilitation games must be embedded in a well-elaborated therapy program so that continuous motor function progress becomes possible. However, to date, no simple and feasible concept is available that facilitates the development of a therapy program consistent with widely accepted motor learning principles and theories. Specifically, there is a need for an adequate template which allows the development of a gradually progressing therapy program including task-specific and variable exercises. In this doctoral thesis, Gentile's taxonomy, described in more detail in **Chapter 3**, was considered as such a template. It demonstrates a classification system that categorizes motor skills based on a 4x4-table according to two basic dimensions (i.e., *environmental context* and *action function*). Concretely, 16 categories to classify motor skills are defined; each of those described by unique features. The 16 skill

categories are positioned in such a way that seven levels of difficulty are distinguishable. This structure allows a skill category-based progression and challenging rehabilitation situations at any point in time during rehabilitation.

Virtual reality has been shown to be a valuable and flexible technology for tailoring rehabilitation exercises based on Gentile's taxonomy.

Given the importance of walking recovery post-stroke, the research question dealt with in **Chapter 4** was whether the virtual reality-based approach would be usable and effective in improving individuals' gait and balance. In order to provide preliminary results, a pilot project was applied in healthy elderly and the usability tested. The study included a tri-weekly balance training program performed for 12 weeks. The first objective of the study was to determine the usability of the intervention based on newly developed interactive rehabilitation games. The findings revealed a high level of acceptance and a good adherence rate and, furthermore, that the participants' perceived the virtual reality-based treatment program as usable and motivating. The second objective was to evaluate the effectiveness of the intervention. The results of the pre- and post-comparisons revealed statistically significant changes in the Berg Balance Scale, the 7-m Timed Up and Go test and the Short Physical Performance Battery. It is therefore concluded that the virtual reality-based intervention positively influenced gait- and balance-related physical performance measures.

For adequately evaluating the effectiveness of a rehabilitation program and tailoring the treatment method to the patients' individual requirements, an accurate assessment of physical functioning is of great importance. The study presented in **Chapter 5** evaluated an instrumented method of the Timed Up and Go test (iTUG) using inertial sensors. The purpose of this study was to estimate the test-retest reliability and validity of iTUG-based gait and transition metrics in stroke patients and healthy elderly. The results revealed that the majority of the iTUG metrics measured showed excellent test-retest reliability. Moreover, the iTUG has shown to be able to distinguish stroke patients from healthy age-matched elderly controls.

The present doctoral thesis emphasizes that virtual reality technology has great potential to provide beneficial conditions for home rehabilitation. However, it is not entirely settled whether the virtual reality-based rehabilitation approach can be practically implemented in patients' home environments and easily be used independently by stroke-affected individuals. Furthermore, its actual clinical effect on

motor performance (e.g., walking) among stroke victims is still uncertain. These open questions provide an incentive for further research to foster the development of effective at-home rehabilitation following stroke.

Zusammenfassung

Der Schlaganfall gilt als eine der Hauptursachen einer erworbenen Behinderung im Erwachsenenalter. Nach einem Schlaganfall kommt es in den meisten Fällen zu einer Hemiparese und einhergehend zu einer verminderten Gleichgewichts- und Gehfähigkeit. Eine beeinträchtigte Fortbewegungsfunktion nehmen die betroffenen Menschen häufig als eine der wichtigsten Gründe für eine Einbusse an Lebensqualität wahr. Die Wiederherstellung und Verbesserung der Gehfähigkeit hat deswegen in der Schlaganfallrehabilitation eine hohe Priorität. Die Rehabilitation in spezialisierten Zentren ist jedoch mit hohen Behandlungskosten verbunden. Da die Zahl an Schlaganfallpatienten stetig ansteigt, erhöht sich der Druck nach einer Einschränkung der Behandlungsdauer in spezialisierten Einrichtungen. Ein Rehabilitationsprogramm für zu Hause stellt eine kostensparende Möglichkeit für eine Therapie auf langfristiger Basis dar. Sie gewinnt deshalb zunehmend an Bedeutung.

Hinweise existieren, dass durch die Verwendung von virtueller Realität die motorische Rehabilitation begünstigt werden kann. Zu anerkennen ist aber, dass sich Videogames aus der Unterhaltungsbranche für den therapeutischen Einsatz nicht optimal eignen. Es fehlt ihnen an spezifischen Eigenschaften (Anpassung der Schwierigkeitsstufe, Monitoring des Patienten, Feedback-Funktion), um optimale Rehabilitationsbedingungen für zu Hause zu gewährleisten. Des Weiteren ist entscheidend, dass die Videogames nach bewährten Game-Design-Richtlinien ('meaningful play', 'flow theory', 'sense of presence') konzipiert sind. Es wird angenommen, dass durch die Berücksichtigung der Game-Design-Richtlinien faszinierende Szenarien geschaffen werden, was eine langfristige Aufrechterhaltung der Rehabilitation unterstützt. All diese Charakteristiken (beschrieben in **Kapitel 2**) werden als wichtig erachtet, um förderliche und spannende Rehabilitationsbedingungen in einer sicheren und kontrollierten Umgebung zu ermöglichen.

Videogames sollen für den therapeutischen Gebrauch in ein gut ausgearbeitetes Therapieprogramm eingebettet sein, um möglichst optimale Fortschritte zu erreichen. Bis heute konnte sich noch kein Konzept etablieren, welches die Ausarbeitung eines Therapieprogramms – übereinstimmend mit motorischen Lernprinzipien und Theorien – unterstützt. Entsprechend ist ein Konzept erwünscht, um ein progressives Rehabilitationsprogramm zu definieren, das sich durch aufgabenspezifische und variable Übungen auszeichnet. In der vorliegenden Doktorarbeit wird Gentile's Taxonomie (beschrieben in **Kapitel 3**) als ein dafür sich eignendes Konzept beurteilt. Gentile's Taxonomie beschreibt ein

Klassifikationssystem, basierend auf einer 4x4-Tabelle, um motorische Fertigkeiten zu kategorisieren. Es werden zwei grundlegende Dimensionen berücksichtigt: *Anforderungen der Umwelt* und *Funktion der Aktion*. Die beiden Dimensionen sind jeweils in zwei Komponenten unterteilt, so dass sich eine Taxonomie mit 16 Kategorien ergibt. Jede dieser 16 Kategorien weist einen spezifischen motorischen Fertigkeitscharakter auf und grenzt sich dadurch von den anderen ab. Die Taxonomie vermag deshalb variable Übungen zu bieten. Die Anordnung der 16 Kategorien ermöglicht eine Einteilung gemäss derer Komplexität, woraus sieben Schwierigkeitsstufen resultieren. Es bietet sich ein strukturierter Rehabilitationsverlauf von einfachen zu schwierigen Übungen.

Durch die Verwendung von virtueller Realität lassen sich Rehabilitationsübungen entsprechend der Taxonomie von Gentile definieren.

Angesichts der Bedeutung, die Gehfunktion von Schlaganfallpatienten zu optimieren, wurde in **Kapitel 4** die Benutzbarkeit und der Effekt eines virtuell-realitätsbasierten Rehabilitationsprogramms zur Förderung der Gleichgewichts- und Gehfähigkeit untersucht. In einer Pilotstudie absolvierten gesunde Senioren dreimal pro Woche ein Gleichgewichtstraining über eine Zeitspanne von 12 Wochen. Das primäre Ziel der Studie war, die Benutzbarkeit der virtuell-realitätsbasierten Intervention zu ermitteln, welche den Einsatz von neu entwickelten interaktiven Videogames gewährte. Die Resultate zeigten eine hohe Akzeptanz und Adhärenz. Zudem wurde erkannt, dass die Probanden die virtuell-realitätsbasierte Intervention als benutzbar und motivierend beurteilten. Des Weiteren verfolgte die Studie das Ziel, die Effektivität der Intervention zu erfassen. Ein Prä- und Post-Vergleich ergab signifikante Veränderungen hinsichtlich folgenden Tests: ‚Berg Balance Scale‘, ‚7-m Timed Up and Go‘ und ‚Short Physical Performance Battery‘. Diese Ergebnisse lassen den Schluss zu, dass die virtuell-realitätsbasierte Intervention einen positiven Effekt auf Gleichgewichts- und Gehfähigkeits-bestimmende Parameter bewirkt.

Die Effektivitätsbestimmung und Anpassung eines Rehabilitationsprogramms an individuelle Erfordernisse bedarf präzise Messmethoden. In der Studie (präsentiert in **Kapitel 5**) wurde eine instrumentalisierte Methode des ‚Timed Up and Go‘-Tests (iTUG) unter Verwendung von Inertialsensoren evaluiert. Das Ziel der Studie war, die Zuverlässigkeit und die Validität von iTUG-Parametern bei Schlaganfallpatienten und gesunden Senioren zu untersuchen. Die Ergebnisse dieser Studie verdeutlichen eine hohe Zuverlässigkeit für die Mehrheit der erhobenen iTUG-Parameter. Zudem

zeigte sich der iTUG als fähige Methode, um Schlaganfallpatienten von gesunden, gleichaltrigen Senioren zu unterscheiden.

Die vorliegende Doktorarbeit unterstreicht das grosse Potential, welches die Verwendung von virtueller Realität hinsichtlich förderlicher Massnahmen einer Rehabilitation für zu Hause aufweist. Es ist allerdings noch unklar, ob sich die virtuell-realitätsbasierte Methode praktisch zu Hause umsetzen lässt und sich für die selbstständige Durchführung durch Schlaganfallpatienten eignet. Zudem ist die klinische Wirksamkeit hinsichtlich motorischer Leistungsfähigkeiten (z.B. der Gehfähigkeit) bei Schlaganfallpatienten noch ungewiss. Diese offenen Fragen stellen eine Legitimation für weitere Forschung dar, um die Entwicklung von effektiven Schlaganfall-Rehabilitationsmassnahmen für zu Hause voran zu treiben.

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