CHAPTER 1

General introduction
Introduction

Falls are common events among older adults and different patient populations and may have deleterious consequences [1-5]. Approximately one third of the community-living people above 65 years of age fall each year [2, 6-8], and this fall risk is even higher in people with gait impairments after for example stroke or lower-limb amputation [1, 5]. Safe walking requires the ability to make step adjustments during walking in response to environmental demands. We should for example be able to avoid objects in our walkway, position our feet at selected safe foot placement locations and increase our walking speed to safely cross the street. This ability is often reduced in older adults and in people who have sustained a stroke or lower-limb amputation [9-20], as is reflected in the fact that falls frequently occur during walking, often in relation to environmental hazards [2-4, 21-24]. In addition, poor walking adaptability has been associated with fall risk in older adults [9, 25-27]. Hence, there seems to be a clear need for methods to assess and improve this important aspect of walking in fall-prone populations. This thesis focuses on the assessment and training of walking adaptability in people with a lower-limb amputation, people who had a stroke and older adults with a recent fall-related hip fracture. In this General introduction, I will first describe the risk factors and consequences of falling, followed by a section on walking adaptability and the description of an instrumented treadmill with projected environmental context for the assessment and training of walking adaptability.

Falls

Falls may lead to physical injuries such as fractures and soft-tissue injuries, but are also associated with inactivity, reduced participation and fear of falling [1-5, 22, 28-30]. In the Netherlands alone, falls among older adults yearly result in 80,000 emergency room visits, 40,000 hospital admissions and 2,645 deaths, culminating in an estimated yearly cost of 780M euro [31]. Falls thus place a major burden on individuals and the community at large. Many studies have tried to identify the risk factors for falling, which is often caused by a complex interaction between intrinsic and extrinsic risk factors [24]. Intrinsic risk factors associated with falling include gait and balance impairments, cognitive impairments, increased gait-related attentional demands, decreased muscle strength, impaired vision, and reduced executive function [2, 24, 32-36]. These intrinsic risk factors are age-related, but are also experienced after stroke or lower-limb amputation.
balance impairments, reduced activity of daily living, cognitive impairments and increased gait-related attentional demands are common [1, 14, 37-39]; all of these factors have been shown to be important determinants of fall risk after stroke [1]. Also people with a lower-limb amputation often experience one and usually more of the intrinsic risk factors for falling [40, 41]. Previous research in this population revealed an increased risk of falling with above-knee amputation, stump or prosthetic problems, back and joint pain and multiple problems with the non-affected leg [5]. Extrinsic factors related to falling include inadequate lightening, low seats and chairs and environmental hazards such as obstacles, curbs, stairs, uneven terrain and slippery surfaces [2, 3, 28]. Although these environmental hazards are important factors in the occurrence of falls [2, 3, 22-24, 28], fall prevention programs for older adults have mostly focused on different factors such as vitamin D supplementation, medication optimization, education, multi-factorial interventions, environmental home safety interventions and exercise interventions [42]. In addition, high-quality studies on fall prevention programs after stroke or lower-limb amputation are limited in general, implying that little evidence exists for their efficacy [43-47]. In older adults, beneficial effects for reducing fall risk and fall rate have only been established for exercise interventions and environmental home safety interventions [42]. These results underscore the importance of environmental hazards as risk factor for falls, but also the need to look into one’s ability to adjust walking to such environmental hazards as a possible determinant of one’s fall risk.

**Walking adaptability**

Walking adaptability is defined as the ability to adjust walking to environmental demands such as when walking over cluttered terrain or when avoiding obstacles. Most commonly, walking adaptability is evaluated in terms of obstacle avoidance during overground [13, 48-52] or treadmill walking [9, 11, 14-16]. Obstacle avoidance can further be broadly divided into anticipatory and reactive obstacle avoidance. Anticipatory obstacle avoidance refers to the avoidance of obstacles presented well before the actual obstacle crossing and allows for planned step adjustments during the approach and avoidance phase. Although older adults and people with a lower-limb amputation adopted slower and more cautious avoidance strategies for obstacles presented in an anticipatory manner, they were well able to successfully avoid such obstacles [10, 48-50]. After stroke, similar cautious
strategies for crossing anticipatory obstacles have been observed, albeit with more obstacle hits compared to healthy control participants [13, 53]. Impairments in obstacle avoidance are more pronounced when obstacles are suddenly presented, thereby reducing the available response time [9-11, 15, 16]. This so-called reactive obstacle avoidance requires rapid online step adjustments during the avoidance phase. Reactive obstacle avoidance is often evaluated on a treadmill [9, 11, 14-16, 25], where obstacles suddenly fall in front of one foot, and has been shown to be impaired in healthy older adults and people who had a stroke or lower-limb amputation [9, 11, 14-16]. In fact, obstacle avoidance performance has been shown to reduce with the available response time [9, 11, 15, 16], and has been associated with fall risk in older adults, particularly for short available response times [9, 25].

Other studies have evaluated walking adaptability using visually guided stepping to a sequence of targets, requiring adjustments on a step-to-step basis to accurately align the feet with stepping targets [17-20, 26, 27, 54]. Target stepping has been shown to be less accurate in older adults compared to young adults [17-20] and has been associated with executive function, gaze behavior and fall risk [17, 19, 26, 27]. In addition, a recent study in people after stroke showed that target stepping performance was significantly associated with lower-limb motor function and balance ability [54].

Apart from these laboratory studies on obstacle avoidance and target stepping performance, the assessment of walking adaptability has received relatively little attention and there is currently no gold standard for the clinical assessment of walking adaptability [55]. This is likely due to the fact that walking adaptability is a complex and multifaceted construct that involves for example obstacle avoidance and target stepping, but also walking on uneven surfaces, walking under different ambient conditions, turning and walking speed modulations [55]. Standard assessments of walking have mostly evaluated walking in flat and uncluttered environments, which requires little to no interaction with the environment and, hence, does not represent the more complex circumstances that are typical of everyday walking [55]. Moreover, they ignore the attentional demands of walking, while these comprise an important aspect of safe walking and have been related to fall risk as well [56-58]. The attentional demands of walking are elevated in older adults and after stroke in particular [38, 58-61], especially when walking adjustments are required [14, 60, 61]. This may cause problems when attention has to be paid to a secondary task such as attending to traffic lights or having a conversation [14, 60].
Although there is currently no comprehensive assessment of walking adaptability, it is clear that walking adaptability is reduced in different populations [9-20], and is associated with increased attentional demands [14, 60, 61] and fall risk [9, 25-27]. The ability to adjust walking in response to environmental demands therefore seems to be an essential part of both the assessment and intervention of walking ability and fall risk, which is consistent with previous recommendations to include the complex and hazardous situations encountered during everyday walking in fall prevention programs [1, 16, 45, 62]. Few studies have focused on interventions integrating exercises of walking adaptability. Nevertheless, these studies have reported promising results in different populations prone to falling, showing improved obstacle avoidance performance [25, 63-67] and reduced fall incidence [25, 63, 67]. In addition, a recent systematic review in older adults showed that step training in response to environmental challenges was effective in reducing fall rate and fall risk by approximately 50% [62]. Walking adaptability may thus improve with practice, which might result in a reduced risk of falling.

The C-Mill for training and assessing walking adaptability

The C-Mill is an instrumented treadmill which was developed specifically to practice step adjustments relative to environmental context during walking [68]. Environmental context such as obstacles and targets is projected on the belt’s surface to elicit step adjustments during walking (Figure 1.1), mimicking the task-specific step adjustments required for safe community ambulation in a cluttered environment. A large force platform embedded in the treadmill is used for the real-time determination of gait events and gait characteristics [69], as well as the estimation of future footfall instants and locations. The instrumented treadmill thus allows for various individual-tailored exercises of walking adaptability in a movement-dependent manner, while providing direct feedback on the successfulness of the interactions with the projected context. The C-Mill allows for (at least) four modes of eliciting step responses. First, a sequence of stepping targets can be projected on the belt’s surface to target accurate foot placement during walking (Figure 1.1A). The stepping targets approach the individual with the belt speed and are attuned to the individuals current gait pattern. This visually guided stepping to a sequence of targets can be made more challenging by introducing irregularly spaced stepping targets and targets that unexpectedly change into
Figure 1.1 The C-Mill is a 3-m long instrumented treadmill augmented with projected visual context to elicit step adjustments during walking. A) A sequence of regularly or irregularly spaced stepping targets, B) obstacle avoidance, C) speeding up and slowing down by following a moving walking area, and D) walking adaptability game in which targets should be stepped on and obstacles should be avoided. By using an embedded force platform, performance can be monitored and directly fed back to the patient.

obstacles. Second, obstacles that approach the individual with the speed of the treadmill can be projected on the belt’s surface such that step adjustments are required in order to successfully avoid the obstacle (Figure 1.1B). In other words, the obstacle would be stepped on when walking is not adjusted. The difficulty of obstacle avoidance can be manipulated by changing the size of the obstacle and the available response time. Besides visually guided stepping to a sequence of targets and obstacle avoidance, the C-Mill also allows for practicing speed-related walking adjustments (Figure 1.1C). These are elicited by projecting a walking area that moves over the treadmill surface in anterior-posterior direction. Walking should be accelerated or decelerated relative to the constant belt speed to stay in the moving walking area, which can accelerate to different degrees to alter the level of difficulty. Finally, walking adaptability games consisting of a combination of interactive obstacles and stepping targets can be performed, which require not only
walking adjustments but also quick and appropriate decision making as to how to respond to the presented context (Figure 1.1D). By combining those different modes of eliciting step responses, the C-Mill allows for the practice of task-specific step adjustments during treadmill walking relative to projected visual context in a safe and controlled environment. Hence, adaptability treadmill training aims to practice the complex and challenging situations encountered during everyday walking, rather than walking in simple and uncluttered environments. C-Mill adaptability treadmill training further targets great amounts of movement practice as an important factor for effective rehabilitation by the use of a treadmill [70-72]. Treadmill walking is widely used in different patient populations and is generally deemed to evoke a greater number of gait cycles practiced per treatment session compared to overground gait training [73-79]. It is therefore expected that adaptability treadmill training evokes a great(er) amount of movement practice, which may contribute to its efficacy in improving walking adaptability and reducing fall risk.

The use of the C-Mill provides not only potential for training walking adaptability but also for its assessment. Using the C-Mill, various types of walking adjustments can be triggered in a well-controlled manner, with and without time pressure. Each step is measured directly in relation to the projected visual context without the need for markers, which means that no valuable (therapy) time is lost to data processing or marker placement. The C-Mill thus seems promising for both the training and assessment of walking adaptability and warrants studies to examine its usability, validity and efficacy in those regards.

**Aim and outline of this thesis**

The aim of this thesis was to examine the usability, validity and efficacy of the C-Mill for the assessment and training of walking adaptability. Collectively, the studies in question provide an encompassing evaluation of the efficacy of adaptability treadmill training with different patient groups and diverse methods to assess the efficacy using a comprehensive set of clinical and laboratory outcome measures associated with walking, walking adaptability and fall risk. The validity of the assumptions underlying adaptability treadmill training (i.e., more task-specific practice, greater amount of movement practice) was evaluated and its usability was assessed in terms of safety and practicability. With regard to the assessment of walking adaptability using the C-Mill, the face validity and construct validity of a
protocol consisting of obstacle avoidance with and without time pressure and visually guided stepping to a sequence of regularly and irregularly spaced stepping targets was assessed in people with a transfemoral or transtibial amputation and their performance compared to that of healthy controls (Chapter 2). Before assessing adaptability treadmill training in terms of its efficacy and its assumed underlying rehabilitation principles, Chapter 3 first describes a project that aimed to implement adaptability treadmill training with the C-Mill in clinical practice as a prerequisite for conducting training studies regarding its efficacy. In Chapters 4 and 5, 16 participants in the chronic stage after stroke received ten sessions of adaptability treadmill training. Chapter 4 reports on the feasibility and clinical potential of the adaptability treadmill training using standard clinical balance and gait tests and a laboratory target-stepping task during standing. In Chapter 5, task-specific improvements in walking adaptability and the associated attentional demands were evaluated to test the assumption of task-specific training underlying adaptability treadmill training. For this purpose, participants performed a laboratory obstacle-avoidance task with and without performing a secondary attention-demanding task before and after adaptability treadmill training. Chapters 6, 7 and 8 focus on a randomized controlled trial comparing the efficacy of adaptability treadmill training, conventional treadmill training and usual physical therapy for improving walking ability and reducing fall incidence and fear of falling in older adults with a recent fall-related hip fracture. The design of this randomized controlled trial is described in Chapter 6. In Chapter 7, the amount of walking practice was examined in order to evaluate the assumption of increased amounts of walking practice underlying (adaptability) treadmill training. In addition, the attitude of older adults with recent fall-related hip fracture towards the three forms of training was evaluated, which is relevant given that a positive attitude towards training is a prerequisite for its efficacy [80, 81]. Chapter 8 reports the results of the randomized controlled trial with respect to walking ability, fear of falling and fall incidence. In Chapter 9, the research conducted in this thesis is summarized and discussed. The potential of the C-Mill for assessing and training walking adaptability is evaluated, its assumed underlying mechanisms are discussed and directions for future research are described.
References

General introduction


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