A comprehensive approach to assess walking ability and fall risk using the Interactive Walkway

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Chapter 1

General introduction

Gait and balance impairments in neurological disorders

Stroke and Parkinson's disease (PD) are two highly prevalent neurological disorders, with estimated prevalence rates in the Netherlands of 3,425 per 100,000 for stroke [1] and 1,350 per 100,000 for PD [2]. These neurological disorders can lead to a great variety of motor and non-motor symptoms [3-5]. Gait and balance impairments are among the most serious motor consequences of these disorders, because they negatively influence the ability to walk and loss of this ability has a significant impact on the quality of life of these patients [6-8]. In addition, fallers seem to experience greater impairments in walking ability compared to non-fallers [9-12]. A thorough insight into gait and balance impairments of patients is thus essential to provide the best treatment for regaining or maintaining their walking ability in order to reduce the risk of falling.

The archetypal gait impairment after stroke is hemiparetic gait, which is characterized by temporal and/or spatial asymmetry [13,14]. In addition, gait impairments in stroke patients often result in slower walking speeds, smaller step lengths, increased step times, reduced cadences and wider steps than healthy controls [15-17]. In PD patients, a different gait pattern is seen. Parkinsonian gait is characterized by a shuffling gait with a stooped posture and reduced arm swing [18]. Compared to healthy controls, slower walking speeds, smaller step lengths and increased cadences have been found [18]. Additionally, PD patients may also suffer from episodic gait impairments, such as freezing of gait (FOG) [6]. The gait impairments listed above can be evaluated objectively using 3D gait analyses. The results of these analyses provide a good understanding of the disease-specific gait impairments and severity of the motor symptoms.

In the clinic, extensive 3D gait analyses are often not performed, mainly due to the costs and time required to conduct the analysis. In contrast, subjectively-scored assessments examining disease-specific motor impairments are often administered. These include, for example, examinations of isolated limb movements with the Fugl-Meyer Assessment in stroke patients or the comprehensive Movement Disorder Society version of the Unified Parkinson's Disease Rating Scale in PD patients. Although these clinical tests provide useful information about the motor symptoms, they fail to reflect their influence on the walking ability of patients and are often time consuming. The most commonly used outcome measure of walking ability in the clinic is walking speed assessed over short distances, for example using the 10-meter walking test. It is a simple and cost effective outcome measure [19] and has been found to be associated with falls [20-25], hospitalization [23,24] and life expectancy [24,25] in older adults. Furthermore, generic gait and balance assessments examining functional mobility and balance outcomes, such as the Timed-Up-and-Go test and the Berg Balance Scale, are also frequently used clinical tests.

Although valuable, quantitative 3D gait analyses and clinical tests do not account for the full repertoire of walking skills needed for safe walking in order to prevent falls [26]. There is thus a need for a more comprehensive assessment of walking ability that incorporates factors directly associated with walking-related fall risk. A more task-specific assessment of walking ability could help identify people at risk of falling as well as help personalize treatments by targeting the identified risk factors.

The tripartite model of walking ability

Walking ability is defined as the ability to walk independently and safely from one place to the other [27]. In order to determine what should be in a comprehensive assessment of walking ability, we need to consider what walking ability entails. The tripartite model [26] is quite instrumental in that regard. This model comprises three overlapping components that are required for independent and safe walking (Figure 1.1). The person needs to be able to 1) generate effective stepping and 2) maintain balance while walking. These two components are often assessed with standard clinical tests, such as the 10-

meter walking test and the Berg Balance Scale. However, people should not only be able to walk safely in fairly simple and predictable environments, but should also be able to modify and adapt walking to both expected and unexpected changes in the environment in order to walk safely in everyday life [28], as reflected in the third component of the tripartite model: walking adaptability. The tripartite model was substantiated by the neural control frameworks put forward by Forssberg [29] and Grillner & Wallen [30], since differential neural control systems underlie walking adaptability and steady-state walking (for a review, see Balasubramanian et al. [26]). The three components of walking ability overlap (Figure 1.1) and the extent to which the various components are involved during walking depends upon the environmental and situational context, which is inherently variable and therefore imposes different demands on walking [27].

Walking adaptability is defined as the ability to modify walking to meet behavioral task goals and demands of the environment [26]. This component was previously described by Patla & Shumway-Cook [27], who proposed a theoretical framework where walking ability is not just the property of the individual to generate stepping and maintain balance, but reflects an interaction between the individual and the environment. Patla & Shumway-Cook [27] defined eight environmental domains that describe the complexity of the situation. Balasubramanian et al. [26], in turn, proposed nine domains, changing some domains of Patla & Shumway-Cook [27] and introducing domains as abilities of the individual to handle these situations. The domains consisted of obstacle negotiation (e.g., stepping over a doorstep), temporal constraints (e.g., walking faster to cross a street), cognitive dual-tasking (e.g., talking while walking), terrain demands (e.g., walking in a forest), ambient demands (e.g., walking in the dark), postural transitions (e.g., turning), motor dual-tasking (e.g., walking while holding a glass), physical load (e.g., walking with a heavy backpack) and maneuvering in traffic (e.g., walking around people in a busy shopping street). The demand on a particular domain and the number of domains involved may vary per environment, which clearly illustrates the challenge of assessing walking ability.

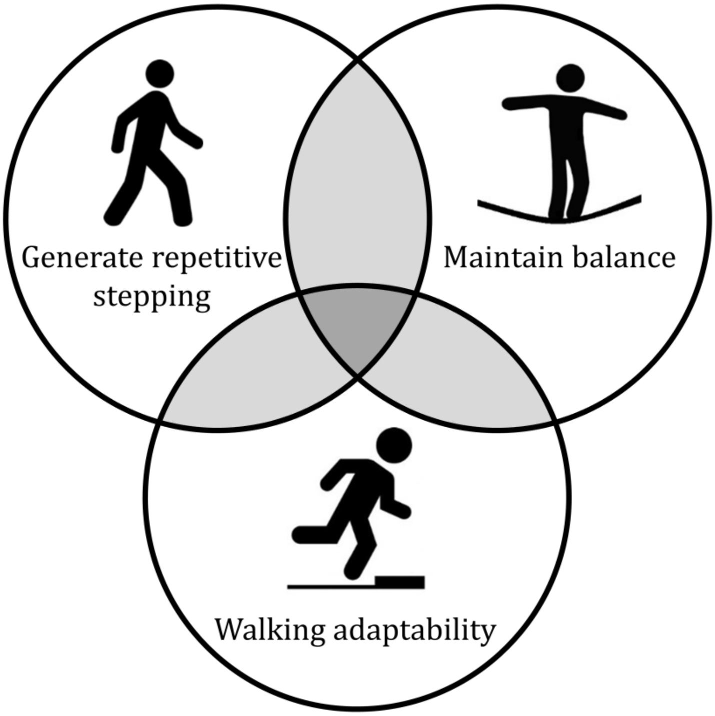

Figure 1.1 Tripartite model of walking ability.

Comprehensive assessment of walking ability

When measuring walking ability in the clinic, there are several points to consider. First, we would like to address all components of the tripartite model to provide a completer picture of a person's walking ability than currently obtained with standard clinical tests. Although good clinical tests assessing stepping and balance already exist, there is currently no good assessment of walking adaptability [26]. Walking-related falls often occur due to trips, slips or misplaced steps [31-35], suggesting that people have problems adapting walking. Walking adaptability therefore seems to be related to fall risk and appears to be an important component of safe walking. Second, for an assessment to be useful in the clinic, there are certain practical requirements that need to be taken into account. Assessments should not take up too much time and should be cheap, easy to use and patient-friendly. Furthermore, while some clinical tests use subjectively scored assessments, objective examinations of motor function are preferred. Nevertheless, the most important point is that a comprehensive assessment provides valid and meaningful information about someone's walking ability. Such an assessment may help physicians and physiotherapists to characterize a person's walking ability, to select the best treatment for a specific person, and to monitor changes in walking ability over time or in response to the selected treatment.

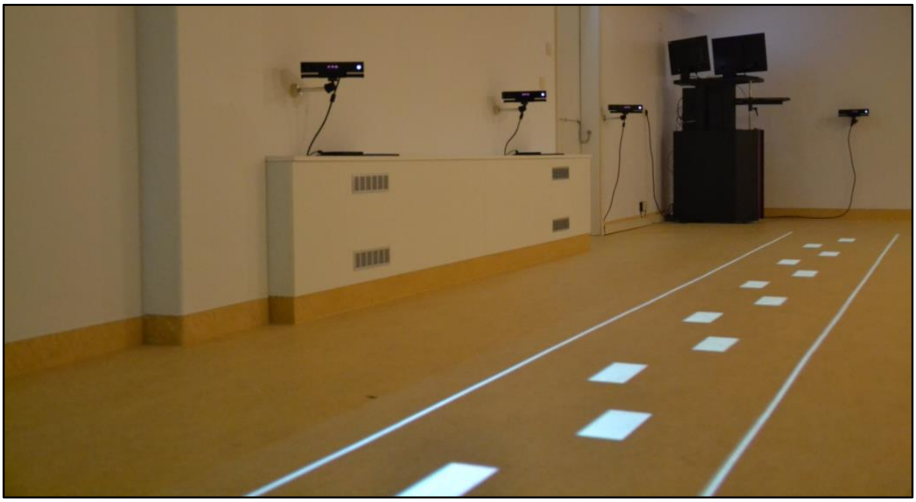

Figure 1.2 The Interactive Walkway with visual context projected onto the walkway.

The Interactive Walkway

The Interactive Walkway (IWW; Figure 1.2; [36]) is a system that may be used to address all components of walking ability and meets all practical requirements mentioned above. With the IWW, a quantitative gait assessment may be performed to gain more insight into gait impairments, which may provide information about the stepping and balance components of walking ability. The IWW is an 8- or 10-meter walkway instrumented with an integrated multi-Kinect v2 set-up for markerless registration of 3D full-body kinematics during walking. This multi-Kinect v2 set-up may be a good alternative for other 3D motion registration systems, since it is patient-friendly, cost-efficient and easy to use. Besides performing quantitative gait assessments, the IWW may also be used to assess walking adaptability. The IWW is equipped with a projector to augment the entire walkway with (gait-dependent) visual context, such as obstacles, sudden-stop-and-start cues and stepping targets. Using the real-time processed integrated Kinect data, obstacles can suddenly appear at the position one would step next, demanding a step adjustment under time pressure demands. The so-elicited gait-environment interactions potentially allow for assessing various walking-adaptability aspects and domains (e.g., the ability to avoid obstacles, suddenly stop or start, perform accurate goal-directed steps) in a safe manner. Taken together, the IWW has great potential to provide a comprehensive assessment of walking ability while fulfilling the practical assessment requirements of being efficient, unobtrusive, patient-friendly, low-cost and objective.

Aims and outline of this thesis

Although the IWW seems promising, it remains still unknown if 1) it can provide a valid assessment of walking ability and, if so, 2) what its clinical potential is for assessing walking ability and fall risk in stroke patients and PD patients. The aim of my thesis is to gain insight into these two aspects.

Part 1: Can the IWW be used for a valid comprehensive assessment of walking ability?

In the next three chapters, studies to validate the IWW are described. In **Chapter 2**, the validity of the IWW for quantitative gait assessments is evaluated in a group of 21 healthy subjects. The 10-meter walking test is conducted at comfortable and maximum walking speed, while 3D full-body kinematics is concurrently recorded with the multi-Kinect v2 set-up of the IWW and a gold-standard motion-registration system. In **Chapter 3** the between-systems agreement and sensitivity to task and subject variations for various walking-adaptability assessments on the IWW is addressed. Under varying task constraints, 21 healthy subjects perform obstacle-avoidance, sudden-stops-and-starts and goal-directed-stepping tasks. Outcome measures are concurrently determined with the IWW and a gold-standard motion-registration system. Based on the insights obtained in these two studies, we performed another validation study, described in **Chapter 4**, with the aim to systematically evaluate the effects of distance to the sensor, body side and step length on estimates of foot placement locations calculated with Kinect's ankle body points in a group of 12 healthy subjects. Estimates of foot placement locations are required to quantify spatial gait parameters and outcome measures of walking adaptability. The results of **Chapters 2 to 4** were used to improve the IWW set-up before it was used to examine the clinical potential of the IWW for assessing walking ability and fall risk in stroke patients and PD patients (**Chapters 5 to 7**).

Part 2: What is the clinical potential of the IWW for assessing walking ability and fall risk?

Stroke and PD are two neurological disorders that are highly prevalent and that have a severe impact on the walking ability of patients. In **Chapter 5**, the potential of the IWW as a new technology for assessing walking ability in stroke patients is evaluated. In total, 30 stroke patients and 30 age- and sex-matched healthy controls perform clinical tests as well as quantitative 3D gait assessments and various walking-adaptability tasks using the IWW. The known-groups validity of the assessments is examined as well as the added value of assessing walking adaptability over standard clinical tests. A similar study evaluating the expected added value of IWW assessments in 30 PD patients is described in **Chapter 6**. Again, the known-groups validity of all assessments is examined. Furthermore, the IWW outcome measures are related to commonly used clinical test scores to indicate their added value. Finally, the added value of IWW outcome measures over clinical tests scores for discriminating PD patients with and without FOG is examined.

The final objective of this thesis is to gain insight into the potential merit of the IWW for assessing fall risk in these patient groups. As indicated above, walking adaptability seems to be an important risk factor for falls, so including it in an assessment would potentially allow for a better identification of (future) fallers. The aim of **Chapter 7** is to evaluate the potential merit of the IWW to identify fallers and risk factors for future falls in a cohort with 30 stroke patient, 30 PD patients and 30 healthy controls. This study comprises subject characteristics, clinical gait and balance tests, a quantitative gait assessment and a walking-adaptability assessment. The results will provide insight into the (relative) importance of stepping, balance and walking adaptability for independent and safe walking. In **Chapter 8** a summary of the main conclusions, a general discussion of the results and suggestions for future research are outlined to further develop the IWW as a comprehensive assessment of walking ability to assess fall risk.

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