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

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Chapter 8

Summary, general discussion and future perspectives

Summary

Neurological disorders may impair various aspects of walking ability that are needed for safe and independent walking (cf. Balasubramanian et al. [1]), therefore requiring different rehabilitation strategies. A comprehensive assessment addressing the key components of walking ability may help to tailor management strategies to the individual needs of each patient. The Interactive Walkway (IWW) is a promising, unobtrusive and low-cost assessment tool of walking ability in daily practice. Nevertheless, it is unclear if 1) this approach can provide a valid assessment of walking ability and, if so, 2) if it has clinical potential in the assessment of walking ability and fall risk in patients with stroke and Parkinson's Disease (PD). The aim of this thesis was to gain insight into these two aspects.

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

The most commonly used outcome measure of walking ability is walking speed assessed over short distances, for example using the 10-meter walking test. Using the IWW, this 10-meter walking test can be expanded with quantitative gait assessments, performed in a quick, unobtrusive and patient-friendly manner. In doing so, standard clinical tests are complemented with additional information about gait and balance impairments derived from 3D kinematics during walking. The study described in **Chapter 2** aimed to validate the IWW for markerless quantitative gait assessments in terms of 3D full-body kinematics and associated spatiotemporal gait parameters against a gold-standard marker-based motion-registration system in a group of 21 healthy subjects. The 10-meter walking test was conducted at comfortable and maximum walking speed, while 3D full-body kinematics was concurrently recorded with the IWW and the Optotrak system (i.e., the gold standard). The results demonstrated that 3D kinematics agreed well between the motion-registration systems, particularly so for body points in motion. Moreover, spatiotemporal gait parameters also matched well between systems. The results of Chapter 2 thus indicated that quantitative gait assessments can reliably be performed with the IWW.

In addition to measuring steady-state walking, the IWW also allows for assessing walking adaptability by projecting interactive visual context onto the walkway in the form of, for example, stepping targets and obstacles. In **Chapter 3**, the between-systems agreement and sensitivity to task and subject variations for various walking-adaptability assessments on the IWW was addressed. Under varying task constraints, 21 healthy subjects performed obstacle-avoidance, sudden-stops-and-starts and goal-directed-stepping tasks. The results demonstrated that walking-adaptability outcome measures, such as obstacle-avoidance margins, generally agreed well between the IWW and Optotrak system. Second, walking-adaptability outcomes were sensitive to task and subject variations. With goal-directed stepping, task variations led to different step lengths, stepping accuracies and walking speeds while available response times and obstacle-avoidance margins varied with obstacle type. This testifies to the power of projected visual context to modify gait and to elicit (sudden) step adjustments, in line with previous studies exploring the same concept during treadmill walking [2-5]. Sensitivity to task and subject variations is important for walking-adaptability assessments in relatively high-functioning groups (such as community-dwelling older adults), where ceiling effects are a common concern [6]. The same holds for floor effects in relatively fragile patient groups. The IWW potentially allows for walking-adaptability assessments that are feasible for both high-functioning and fragile populations since task difficulty can be varied. In addition, IWW assessments are also relatively safe (e.g., visual instead of physical obstacles), unobtrusive (markerless data) and hence time-efficient and patient-friendly. The IWW walking-adaptability assessments were therefore deemed usable for obtaining an objective and more task-specific examination of one’s ability to walk, which warrants studies on its clinical potential as discussed in Chapters 5 to 7.

Based on the insights obtained in these two validation studies, another validation study of the Kinect v2 sensor of the IWW was performed. The study described in **Chapter 4** aimed to systematically evaluate the effects of distance to the sensor, body side (i.e., left or right) and step length on estimates of foot placement locations calculated using Kinect's ankle body points. Estimates of foot placement locations are required to quantify spatial gait parameters and outcome measures of walking adaptability. In total, 12 healthy subjects performed stepping trials with imposed foot placement locations at various distances from the Kinect sensor, for the left and right body side, and for multiple imposed step lengths, concurrently recorded with a Kinect v2 sensor and the Optotrak system. The results revealed a small but significant between-systems difference in foot placement locations and step lengths. These were likely caused by differences in body orientation relative to the Kinect sensor, whereby the ankle was estimated more posteriorly. This effect can be reduced by using smaller inter-sensor distances in the IWW set-up to estimate foot placement locations at greater distances from the sensor.

Taken together, it can be concluded that the IWW can be used to validly assess both steady-state walking (Chapter 2) and walking adaptability (Chapter 3) in a group of healthy adults. In doing so, it yields a more comprehensive assessment, addressing important components of the tripartite model of walking ability (i.e., the ability to generate stepping, to maintain postural equilibrium and to adapt walking to environmental demands). The results of Chapters 2 to 4 also led us to improve the IWW set-up by reducing inter-sensor distances. Subsequently, we set out to evaluate the clinical potential of the IWW as a tool for assessing walking ability and fall risk in patient groups, as will be discussed next.

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

The aim of the study presented in **Chapter 5** was to evaluate the potential of the IWW as a new technology for assessing walking ability in stroke patients. Assessments of impairments in walking ability may aid in the development of individualized rehabilitation strategies. 30 stroke patients and 30 age- and sex-matched healthy controls performed clinical tests as well as quantitative 3D gait assessments and various walking-adaptability tasks using the IWW. The results of this study suggested good known-groups validity for IWW walking-adaptability tasks, similar to that of clinical tests and quantitative gait assessments. In addition, walking-adaptability tasks appeared to complement these assessments, as evidenced by the mainly low to moderate correlations between outcome measures of walking adaptability and those obtained from clinical tests and quantitative gait assessments. Our findings therefore suggested that using the IWW to evaluate steady-state walking and walking adaptability with obstacle avoidance and goal-directed stepping may provide a quick, unobtrusive and comprehensive quantitative assessment of walking ability with potential for monitoring recovery after stroke and informing rehabilitation strategies.

In **Chapter 6** steady-state walking (i.e., quantitative gait assessments), adaptive walking and dual-task walking were evaluated with the IWW in 14 PD patients with freezing of gait (FOG), 16 PD patients without FOG and 30 healthy controls. Similar to the results of the clinical tests, freezers scored worst, non-freezers scored in-between and controls scored best on most IWW tasks, suggesting good known-groups validity. PD patients especially experienced problems when having to deviate from their steady-state gait pattern, which requires dynamic balance control. Therefore, in order to obtain a more comprehensive characterization of a subject's walking ability, both steady-state and adaptive walking should be assessed, for example with obstacle avoidance and goal-directed stepping. It was demonstrated that these IWW tasks also provide additional information compared to clinical tests given the low to moderate correlations between these two types of assessment. Moreover, IWW outcome measures of adaptive walking slightly better discriminated freezers from non-freezers than clinical test scores. The IWW thus shows potential as a more comprehensive walking-ability assessment in PD, incorporating all its key aspects of which many may be linked to falls. The latter premise was explored in more detail in Chapter 7, as discussed next.

In **Chapter 7**, the potential merit of the IWW to identify prospective fallers and risk factors for future falls was evaluated in a composite cohort of stroke patients, PD patients and healthy controls. This study comprised an evaluation of subject characteristics, clinical gait and balance tests, and a quantitative gait assessment and walking-adaptability assessment on the IWW. Subjects' falls were registered with monthly falls calendars during a 6-month follow-up period to identify subjects as prospective fallers (i.e., experiencing at least one walking-related fall during the follow-up period) or non-fallers. Prospective fallers experienced more fear of falling and more fear-of-falling-related activity avoidance at baseline than non-fallers. In addition, prospective fallers walked slower and with smaller steps, and had a poorer performance on clinical gait and balance tests. As anticipated, prospective fallers also performed worse on various walking-adaptability tasks. In addition to fall history, obstacle-avoidance success rate and normalized walking speed during goal-directed stepping were identified as predictor variables for falls and these fall-risk factors improved the identification of fallers. It appears that subjects who performed worse on the obstacle-avoidance task without substantially lowering their walking speed during goal-directed stepping are most at risk of falling. Identification of these task-specific fall-risk factors may lead to more targeted, personalized and, possibly, more effective falls prevention programs. If validated in larger samples in future studies these measures hold promise as future entry tests for falls prevention programs.

Collectively, our findings show that the IWW contributes to the evaluation of walking ability in patients with stroke (Chapter 5) and PD (Chapter 6). Additionally, limitations in walking adaptability proved to be a risk factor for falls, which resulted in a better identification of prospective fallers (Chapter 7). The IWW thus seems to be a valuable option for a comprehensive assessment of walking ability and fall risk in stroke patients and PD patients.

General discussion

The overarching goal of this thesis was to examine if the IWW could provide a valid and comprehensive assessment of walking ability in various patient groups under the premise that this improves the identification of prospective fallers. The results showed that the IWW indeed allows for a valid and comprehensive assessment of walking ability, including the aspect of walking adaptability. Moreover, the IWW adds value to the evaluation of walking ability in stroke patients and PD patients, also uncovering limitations in walking adaptability that resulted in a better identification of prospective fallers. In the following sections, steps towards a more comprehensive fall-risk assessment are outlined by means of a roadmap (Figure 8.1). Furthermore, the broader implication of the insights obtained in this thesis are discussed for the IWW and beyond.

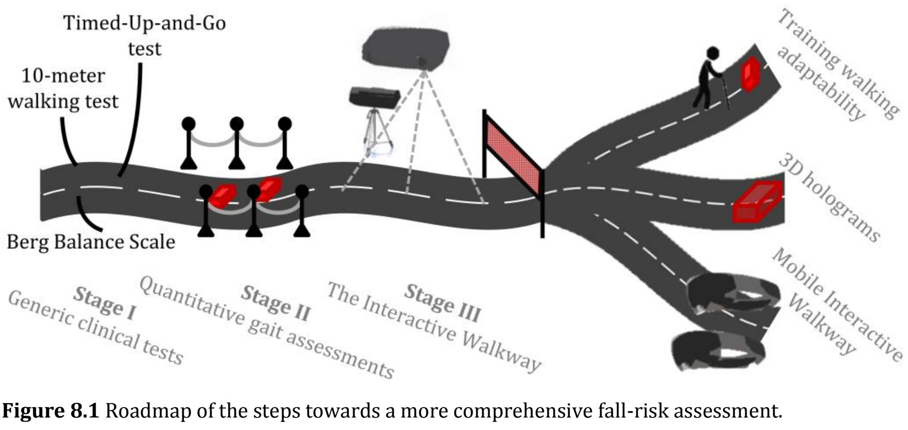

Figure 8.1 Roadmap of the steps towards a more comprehensive fall-risk assessment.

Towards a more comprehensive assessment of walking ability

Walking speed assessed over short distances, for example using the 10-meter walking test (stage I of the roadmap; Figure 8.1), is the most commonly used outcome measure of walking ability in the clinic. 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 (stage I of the roadmap; Figure 8.1). These clinical tests only give a single value as outcome of walking ability. More detailed insight into gait and balance impairments can be obtained using quantitative gait assessments (stage II of the roadmap; Figure 8.1). These clinical tests and assessments, however, do not account for the full repertoire of walking skills needed for safe walking. That is, they mainly address steady-state gait as seen on a 'red carpet' (stage II of the roadmap; Figure 8.1), which does not mimic the typically encountered real-life walking environments.

As mentioned in the General Introduction, walking ability is defined as the ability to walk independently and safely from one place (A) to the other (B) [7]. The environmental and situational context between A and B is inherently variable, placing different demands on walking [7]. With regard to the former, one can envision obstacles like doorsteps or other people. With regard to the latter, one may, for example, be distracted or in a hurry. The three components of the tripartite model of walking ability [1] comprehensively address such demands, comprising one's ability to 1) generate effective stepping, 2) maintain balance while walking and 3) adapt walking to environmental or situational context. Currently, the latter component of walking adaptability is typically not assessed in the clinic. One domain of walking adaptability, namely obstacle negotiation [1], has been examined using 3D kinematics when crossing real obstacles (stage II of the roadmap; Figure 8.1; [8-12]) and an impaired obstacle-avoidance performance was found in stroke patients and PD patients [8,11-15]. However, real obstacles are potential trip hazards and hence such assessments are relatively unsafe. Moreover, obstacle-avoidance tasks evaluate just a single domain of walking adaptability.

With the IWW, multiple domains of walking adaptability can be assessed (stage III in the roadmap; Figure 8.1). A projector is used to augment the walkway with (gait-dependent) visual context which allows for an assessment of various walking-adaptability domains (e.g., obstacle negotiation, postural transitions, maneuvering in traffic; [1]) in a safe manner. While quantitative gait assessments performed with the IWW predominantly address the stepping and balance components of the tripartite model, given the high correlations with clinical test scores in stroke patients (Chapter 5) and PD patients (Chapter 6), IWW tasks seemingly assess a complementary aspect of walking ability, namely the walking-adaptability aspect. Taken together, the IWW thus holds promise as a more comprehensive assessment of walking ability by addressing all key aspects of this motor function.

Walking ability and falls: moving to a task-specific assessment

Since most falls occur during walking [16-18], it seems useful to consider limitations in walking ability as potential risk factors for future falls. A comprehensive assessment of walking ability may therefore inform about factors that increase walking-related fall risk. Such assessments should be task-specific, meaning that they focus on functional tasks rather than impairments [19]. Examples of functional tasks are steady-state walking (stages I, II and III of the roadmap; Figure 8.1), specific movement tasks to test static and dynamic balance (i.e., Berg Balance Scale; stage I of the roadmap; Figure 8.1) and walking-adaptability tasks on the IWW (stage III of the roadmap; Figure 8.1). A task-specific assessment could help identify why people fall during walking and can help personalize treatments by targeting specific risk factors. Task-specific training, relearning a task by practicing that specific task, has been shown effective in gait rehabilitation [20,21]. In this thesis, important steps have been taken towards a task-specific assessment of fall risk. The IWW assessment presented in Chapters 5 to 7 included various walking-related tasks (i.e., steady-state walking and walking-adaptability tasks) to assess walking ability. As demonstrated in these chapters, some of these tasks usefully contribute to a comprehensive assessment of walking ability and fall risk, whereas others don't, which is helpful in shortening the assessment protocols (as described below).

The obstacle-avoidance and goal-directed stepping outcome measures were significantly different between stroke patients and controls (Chapter 5), between PD patients and controls (Chapter 6) and fallers and non-fallers (Chapter 7), in line with other studies [8,11-15,22,23]. In addition, goal-directed stepping differed between freezers and non-freezers, with better stepping accuracies for freezers. One earlier study [3], in which the C-Mill was used to assess walking adaptability in a group of amputees, showed the importance of obstacle-avoidance and goal-directed stepping tasks as informative tasks of walking ability. The C-Mill is a treadmill embedded with a force plate onto which gait-dependent visual context, such as obstacles and stepping targets, can be presented. The results demonstrated that obstacle avoidance and goal-directed stepping were unique, complementary aspects of walking ability given the low to moderate correlations with clinical tests. We confirmed and elaborated the findings of Houdijk et al. [3] to patients with stroke (Chapter 5) and PD (Chapter 6). Together, these results support the assumption that walking adaptability is not covered in clinical assessments of walking ability. Notably, obstacle-avoidance success rate and normalized walking speed during goal-directed stepping improved the identification of prospective fallers (Chapter 7). Poor obstacle avoidance or stepping performance has previously already been found to be associated with falls [22-25], emphasizing the merit of assessing walking adaptability for fall risk assessments.

Altogether, it is thus important to add task-specific factors associated with walking-related falls to an assessment of walking ability and fall risk, which can be done with the IWW. Since the obstacle-avoidance and goal-directed stepping tasks provide a valid assessment of walking adaptability and improve the identification of fallers, these tasks are advised to be included in a task-specific assessment of walking ability aimed at assessing fall risk.

Walking ability and falls: moving to a generic assessment

It is known that in most neurological disorders, fall incidence is higher than in the healthy population [26,27], which may be due to underlying gait and balance impairments. In fact, gait and balance disturbances significantly correlated with falls in patients with neurological disorders and were identified as risk factors for falls [26,27]. In addition, most fallers in this group of patients reported that they tripped over an obstacle [27], suggesting a reduced walking adaptability. A task-specific assessment of walking ability and fall risk focusses on limitations in walking of patients instead of on impairments associated with a particular disease or disorder itself. This task-specific approach therefore allows for a more generic fall-risk assessment, which could apply to various diseases and disorders. In this thesis, we have mainly focused on task-specific fall-risk factors (Chapter 7). Group (i.e., stroke, PD, control) was also included in the models of Chapter 7; as expected, group was not identified as a significant predictor variable for prospective falls. However, the sample size and the distribution of fallers and non-fallers across groups may have been too small to detect group differences. Nevertheless, in both groups, approximately half of the patients fell in the year prior to the assessment (Chapter 7). In addition, not all prospective fallers of the falls-naïve cohort in Chapter 7 belonged to the same group (i.e., three stroke patients, two PD patients and four healthy controls) and these fallers were classified by specific limitations in walking ability (i.e., suboptimal obstacle-avoidance success rates in combination with a maladaptive walking speed during precision stepping). As can be noticed, healthy controls without specific disorders also experienced falls. A decreased walking ability in older adults compared to younger adults has been demonstrated, both in steady-state walking and walking adaptability [28]. Age was also positively associated with the number of falls in patients with neurological disorders [26,27]. In Chapter 7, age did not differ significantly between prospective fallers and non-fallers, but was identified as a predictor variable for falls in the prediction models that did not include walking-adaptability outcome measures. Limitations in walking ability, regardless of their cause (e.g., neurological disorders, ageing), thus likely give a better indication of someone's fall risk, calling for a generic and task-specific fall-risk assessment.

Walking ability and falls: minimizing assessment time

As discussed in the previous two sections, it seems useful to assess fall risk in a task-specific and generic manner. From a more practical point of view, fall-risk assessments should also be concise. In an outpatient clinic a physician generally obtains a momentary impression of a patient's walking ability and fall risk. However, administering multiple clinical tests may imply redundancy, since several tests were highly interrelated, as demonstrated in Chapter 5, and thus only increase the burden for the patient. This is also the case when combining clinical tests with quantitative gait assessments. Given the high correlation between IWW quantitative gait assessments and clinical tests, a possibility could be to combine the IWW quantitative gait and walking-adaptability assessment to obtain the sought-after quick and comprehensive assessment of fall risk.

Previous studies have indicated that steady-state gait characteristics are associated with falls [27,29], while this is often not the case for clinical test scores due to potential ceiling effects [6]. This was however not confirmed by the results presented in Chapter 7. Nevertheless, significant differences were found between fallers and non-fallers for walking speed and step length, suggesting that a quantitative gait assessment might be informative in a fall risk assessment. Since gait parameters were highly correlated with conventional clinical test scores of gait and balance (Chapters 5 and 6), performing quantitative gait assessments with the IWW instead of clinical tests could therefore be a good option for a quick and comprehensive fall-risk assessment. A quantitative gait assessment with the IWW requires about the same time as the 10-meter walking test. The latter test only provides walking speed, while a quantitative gait assessment with the IWW provides more information, based on 3D kinematics of the whole body. A quantitative gait assessment and some complementary walking-adaptability tasks (i.e., obstacle-avoidance and goal-directed stepping as suggested above) on the IWW thus seems to be a good option for assessing walking ability in a quick (5-10 minutes) and comprehensive manner. However, removing clinical tests from the binary logistic regression models in Chapter 7 did not lead to the inclusion of spatiotemporal gait parameters as predictor variables and slightly worsened the classification of prospective fallers and non-fallers. Therefore, more research is needed to explore the feasibility of the IWW as a tool to quickly estimate fall risk.

The Interactive Walkway for a more comprehensive fall-risk assessment?

Though the task-specific and generic fall-risk assessment of the IWW seems promising, more research is needed to confirm its potential merit as a comprehensive fall-risk assessment. First of all, the fall prediction models presented in this thesis have to be cross-validated with an independent composite cohort of stroke patients, PD patients and healthy controls. Second, the responsiveness of IWW outcome measures to subtle changes over time has to be examined. In all studies of this thesis, assessments of walking ability were performed once. This will only provide the momentary status of a person. It is however important that IWW assessments can be used to validly monitor the effect of a disease or treatment on the walking ability and thus potentially also fall risk of a patient. Third, I have focused on assessing walking ability in two highly prevalent neurological disorders, namely stroke and PD. It is not yet known if the IWW can be used to asses walking ability validly in other patient populations. This is partly due to the fact that the Kinect v2 sensor best recognizes persons from a frontal view and occasionally fails to detect persons with an abnormal body posture. This could potentially be a problem in disorders like dystonia and cerebral palsy where body posture is severely affected. Future studies should therefore focus on a greater variety of patient groups to be able to determine for which disorders the IWW is best suited for fall-risk assessments.

	Positive	Negative
Internal	**Strengths** Markerless motion registration Assessment of sudden step adjustments Safe assessment of walking adaptability Overground assessment Individually tailored Comprehensive assessment	**Weaknesses** 2D projections Bound to a specific location Frontal view body recognition
External	**Opportunities** Entry point falls prevention program Personalized falls prevention programs	**Threats** Competition Discontinuation Kinect v2 sensor

Figure 8.2 Schematic of the SWOT analysis of the Interactive Walkway intended for use as a fall-risk assessment in the clinic.

SWOT analysis of the Interactive Walkway intended for use as a fall-risk assessment in the clinic

Currently, the IWW is still mostly a scientific tool and there are several steps to be made before it can be implemented into the clinic. A strengths, weaknesses, opportunities and threats (SWOT) analysis may help to determine where future research should focus on in order to implement the IWW as a fall-risk assessment tool in the clinic (Figure 8.2). The SWOT analysis has two main categories, namely internal and external factors. Internal factors are inherent to the product and dictate its strengths and weaknesses. External factors are the opportunities and threats presented by the environment external to the product. Below, these four SWOT categories are discussed for the IWW intended for use as a fall-risk assessment in the clinic.

Strengths

The studies presented in this thesis have emphasized several benefits of the IWW that are relevant for its intended use as a fall-risk assessment in the clinic. First of all, 3D full-body kinematics is obtained without markers by using the Kinect v2 sensor. Normally, full-body kinematics can be obtained using expensive, high-end, marker-based motion-registration systems. The Kinect sensor is a cheap and easy-to-use alternative. Using the Kinect sensor for motion registration also significantly reduces preparation time, which is more convenient for the patient. In addition, the movements of the patients are not restricted by markers and are therefore expected to be more natural. Another advantage of the Kinect sensor is that the data are available immediately and can be processed online. This makes the system usable for movement-dependent event control [30]. Walking adaptability has so far mostly been assessed with fixed obstacles or targets in laboratory studies [8,11,12] or with specific clinical tests (e.g., Dynamic Gait Index; [31]). On the IWW, movements of the subject may trigger the presentation of the visual context, therefore requiring adjustments under controllable time pressure demands. The IWW can thus assess walking adaptability to both expected (e.g., slalom, goal-directed stepping) and unexpected (e.g., sudden obstacle avoidance, sudden stops-and-starts) challenges in the environment.

The additional benefit of using projections instead of real obstacles is that it makes the assessment of walking adaptability safer since patients cannot physically trip as could be the case when trying to avoid real obstacles. Furthermore, interacting directly with meaningful visual context in an overground walking environment may also be seen as a strength. An assessment with projected visual context has previously been performed on the C-Mill, demonstrating that this is an effective and safe way of assessing walking adaptability [32-35]. However, natural responses, such as slowing down in a complex environment, cannot be assessed on a fixed-speed treadmill. Furthermore, tasks such as stopping and turning cannot be performed. These tasks are all well possible with the IWW, since it entails an overground assessment. However, a potential problem might be task prioritization. In a study of Timmermans et al. [36], cognitive-motor interference and task prioritization was assessed for obstacle avoidance, contrasting avoidance of real physical obstacles and projected visual obstacles. Although the amount of cognitive-motor interference did not differ between tasks, task prioritization did. Motor performance was prioritized in an environment characterized by physical context as compared to an environment with projected context. In the study of Timmermans et al. [36] and in the studies presented in Chapters 5 to 7, subjects were instructed to perform both the dual task and the obstacle avoidance task as well as possible. Task prioritization could therefore explain the lack of a clear effect of the dual task on obstacle-avoidance performance in Chapters 6 and 7.

Another strength of the IWW is that tasks can be individually tailored, meaning that the difficulty of the walking-adaptability tasks can be adjusted to the ability of the individual (e.g., amount of variation, available response distance) making it suitable for both healthy controls and various patient groups. A final strength of the IWW for use as a fall-risk assessment is that it comprised both steady-state walking and walking adaptability, providing a comprehensive assessment of walking ability. This yields information complementary to standard clinical assessments (Chapters 5 to 7), mainly information about a patient's walking adaptability. Considering these strengths, is seems fair to conclude that the IWW seems promising for use as a fall-risk assessment.

Weaknesses

Despite the benefits of a fall-risk assessment with the IWW, there is still room for improvement. Currently, the IWW only uses 2D projections to evoke step responses. In real life, obstacles or other objects we need to interact with are not always flat. In many studies, foot clearance during obstacle crossing [8,11,12,37-39] was found to be an important factor for successful obstacle-avoidance behavior to avoid falls. Moreover, age-related changes in obstacle-crossing strategies were found to depend on the specific characteristics of the obstacle, such as obstacle height [40]. Simply adding real 3D obstacles to the IWW is possible but not preferable, considering that it increases the risk of falls during a fall-risk assessment and it then becomes impossible to assess sudden step adjustments. Using 3D holographic obstacles may be a solution to address this weakness (see also future perspectives) and could potentially also improve the ability of the IWW to elicit FOG in PD patients, which was not possible with 2D visual context as was found in Chapter 6. Nevertheless, the obstacle-avoidance task with 2D projections appeared effective, since obstacle-avoidance success rate did demonstrate differences between groups and improved the identification of prospective fallers (Chapters 5 to 7).

Another weakness of the IWW for use as a fall risk assessment is that it is bound to a specific assessment space, comparable to other motion registration systems. This does however not need to be a big space, because the IWW has been optimized for use in a corridor. An additional instrumental weakness of the IWW set-up used in this thesis is that it is bound to measuring walking in one direction. The Kinect v2 sensor is trained to recognize persons from a frontal view. This means that the patient has to walk twice the distance, making the assessment twice as long. This can however be solved by using Kinect sensors on both sides. Another weakness of the IWW for use as a fall-risk assessment is that the Kinect sensor sometimes has difficulty recognizing patients (i.e., considering the 3.4% of removed trials in Chapter 7). It seems that this was caused by certain body postures, such as a body posture turned away from the sensor (e.g., as a result of a hemiplegic gait in stroke on the side opposite to the sensor placement) or a very stooped posture (e.g., in severely affected PD patients). This may reduce the quality of the 3D full-body kinematic data.

Opportunities

Instead of only being used to screen who is at risk of falling, IWW assessments of walking ability may provide specific entry points for fall prevention programs to target task-specific risk factors for reducing fall risk and improving walking ability. In Weerdesteyn et al. [25], a decrease in fall risk was associated with an improved obstacle-avoidance performance. Poor obstacle-avoidance success rate was also a risk factor for falls in Chapter 7. It thus seems imperative to train obstacle-avoidance in generic falls prevention programs. Furthermore, assessments of walking ability may be used to provide a more personalized falls prevention program. A personalized approach might increase adherence to the falls prevention program (i.e., by being challenging, but feasible for the patient) and foster lasting change (i.e., by targeting the right limitations in walking ability; [41,42]). The potential of the IWW to guide personalized therapy still needs to be examined, since the outcomes of the studies in Chapters 5 to 7 have only focused on comparing groups (i.e., patients vs. controls and prospective fallers vs. non-fallers) instead of looking into individual traits that increase fall risk. High-end machine learning techniques permit the individualization of fall-risk assessments [43]. These techniques require a large dataset that can be collected relatively easily with the IWW. In order to provide personalized therapy to patients, future studies should thus focus on IWW fall-risk assessments in a large group of patients with various disorders.

Threats

Finally, there are some threats that may jeopardize the use of the IWW for use as a fall-risk assessment. The biggest threat is the competitive field in which several fall-risk assessments are available. Further, many of these assessments have already been cross-validated in much larger patient groups [44,45]. Although our studies suggest that walking adaptability has additive value in a fall-risk assessment, more evidence is needed before the IWW assessment will be adopted in the clinic.

It is relevant to note that Microsoft has decided to discontinue the production of the Kinect v2 sensor. Although this is an unfortunate event, the principle of the IWW (i.e., using real-time processed markerless 3D data to interactively present visual context to evoke step responses and assess walking adaptability) remains. Other sensors may serve as input for the IWW (e.g., Orbec, SIMI), and Microsoft will soon release the Kinect v4 sensor, which can be regarded as an upgrade of the Kinect v2 sensor given the better specifications (e.g., increased depth resolution). These sensors may be examined for their potential to replace the Kinect v2 sensor, which would require new validation studies comparable to those presented in Chapters 2 to 4.

Future perspectives

In the SWOT analysis of the IWW as a fall-risk assessment tool for use in the clinic, some directions for future research were already mentioned. We have now reached the finish of the roadmap, as presented in Figure 8.1. This does not mean however that the development of the IWW ends here. I propose three future paths for the IWW: 1) moving from assessment to training, 2) moving from 2D to 3D context, and 3) moving from a location-bound to a mobile set-up (see crossroads in Figure 8.1), as will be discussed next.

The Interactive Walkway for training walking adaptability

The IWW can also potentially be used to train walking adaptability in a falls prevention program. Walking adaptability has already been trained on a treadmill using projected visual context (i.e., the C-Mill; [32-35]). Results of these studies demonstrated that walking ability improved after task-specific training with visual context [32-35]. In contrast to the C-Mill, the IWW allows for training of walking adaptability in an overground setting. This leaves room for natural responses to environmental context, such as slowing down or even stopping before crossing an obstacle, which is not possible on a fixed-speed treadmill. This makes training of walking adaptability with the IWW especially useful in fragile populations, who often slow down in complex environments [36]. In Chapter 5, it was shown that stroke patients lowered their walking speed relatively more in complex situations compared to healthy controls. In addition, overestimation of someone's walking ability (i.e., not substantially lowering walking speed when walking adaptability is limited) increases the risk of falling as demonstrated in Chapter 7. Training people to adopt a safer strategy when walking in a complex environment might therefore be useful. This is all well possible with the IWW, confirming its potential as a training tool in addition to an assessment tool of walking ability and fall risk.

The Interactive Walkway with 3D holograms

As already mentioned, the IWW uses 2D projections for an assessment of walking adaptability, which could be considered a weakness of the system although promising results of such an assessment have been obtained in this thesis and beyond (e.g., C-Mill studies; [32-35]). However, there are new techniques available that can be used to present 3D holographic context for an assessment or training of walking adaptability. The HoloLens (Figure 8.3) is a mixed-reality headset which uses multiple Kinect v3 sensors to scan the environment in order to present holograms at a fixed position in the real world. This could potentially be used in combination with the IWW in order to give an extra dimension to the presented visual context. In the study of Binaee & Diaz [46], illusionary 3D augmented reality obstacles produced realistic obstacle-avoidance behavior in terms of foot placement and foot clearance. In an unpublished pilot study conducted at the Department of Human Movement Sciences of the Vrije Universiteit Amsterdam using the HoloLens for 3D obstacle avoidance, it was demonstrated that scaling the obstacle height indeed also leads to scaling of the foot clearance of the leading limb during obstacle crossing. The holographic context presented with the HoloLens thus seems suitable for evoking step adjustments in 3D. Nevertheless, although people seem to step over the obstacle quite well with their leading limb, this is not always the case for their trailing limb (Figure 8.3). The limited field of view is often reported by participants as a drawback of the current version of the HoloLens. Hence, the presented obstacle is not entirely visible when a person steps over it, unless the person looks directly down. The field of view is supposed to increase with the newer version of the HoloLens, which could potentially improve the ecological validity of 3D holographic obstacle avoidance. Besides, it needs to be determined whether certain additions, such as providing (direct) feedback on performance, can improve the obstacle-avoidance performance and as such the potential of the HoloLens for use in fall-risk assessments and for training walking adaptability in falls prevention programs.

The mobile Interactive Walkway

Technology is always moving and develops fast. Within the time period of my PhD project, the Kinect sensor progressed from the v1 sensor with relatively poor depth resolution to the v2 sensor as used in this thesis to a mobile v3 sensor embedded in the HoloLens and soon a v4 sensor will be launched with even better technical specifications and extra options. The development of these new techniques (i.e., Kinect sensor, HoloLens) yields new possibilities for the assessment of walking ability and fall risk and for training of walking adaptability.

The IWW was developed and tested within the 'Technology in Motion' project (tim.lumc.nl). In this NWO-funded project, new emerging low-cost techniques, such as the Kinect v2 sensor, were used to quantify motor disorders in an unobtrusive and patient-friendly manner. The multi-Kinect based IWW fitted well within the aims of this project, as does the HoloLens. The HoloLens has the potential to be used as an extension of the IWW to move from 2D to 3D context as described above, but might potentially also be used as a stand-alone system to assess and train walking adaptability. The HoloLens is able to scan the environment in order to present holograms at a fixed position. In addition, this information can be used by the HoloLens to determine where someone is in that environment in order to present holograms in a movement-dependent manner. This would allow for a safe assessment of walking adaptability with 3D holograms, without being bound to a specific location as is the case for the IWW. Furthermore, head position data can be measured to calculate spatiotemporal gait parameters. Preliminary data demonstrated good agreement between the IWW and HoloLens for step length (absolute between-systems difference ≤ 0.87 cm), walking speed (absolute between-systems difference ≤ 1.72 cm/s) and cadence (absolute between-systems difference ≤ 2.02 steps/min). However, walking-adaptability outcome measures, such as obstacle-avoidance margins, require more detailed kinematics stemming from an external motion-registration system (such as a location bound IWW). Nevertheless, with the arrival of the Kinect v4 sensor for the HoloLens, it might be used as the desired motion registration system when worn by the assessor(s) looking at the patient. This could yield a more flexible way of performing quantitative gait assessments and walking-adaptability assessments in the clinic, without being bound to a particular location. Linking the HoloLenses of the patient and the assessor(s) further enables that they both can see the holograms. The envisioned mobile IWW, based on coupled HoloLenses, thus seems promising for assessment and training of walking ability and fall risk and is definitely a path worth exploring.

Figure 8.3 The HoloLens (A) and obstacle avoidance over a holographic obstacle presented with the HoloLens with the leading (B) and trailing (C) limb.

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