Chapter 1

General introduction
Imagine a 75-year old woman who suffered a stroke nine months ago. She recovered well, but still has trouble when walking outside. Every time she goes outdoors with her husband to do groceries, she has to maneuver through a crowded shopping area, cross multiple busy streets and walk over uneven pavement. On her way back home, she carries the groceries while telling her husband what she will be cooking that night. Sometimes she is worried about tripping or falling while walking through this for her challenging environment; however, she is also fond of this walk and values the independence of doing her own groceries. Unfortunately, one day she tripped during her walk to the grocery store and was hospitalized for multiple weeks due to a hip fracture.

Walking adaptability

As illustrated by the made-up (but realistic) short story above, walking in everyday life is nothing like ‘walking on a red carpet’. Avoiding obstacles, securing safe foot placements in a cluttered environment and being able to maneuver through traffic is a prerequisite for safe community walking. In other words, walking ability is context-specific and involves the ability to adapt to environmental circumstances [1]. Besides the ability to generate stepping and maintain postural equilibrium, this so-called walking adaptability is one of the components of a tripartite model of gait control (stepping, equilibrium and adaptability) and is defined as the ability to adjust walking to environmental demands [1]. Walking adaptability is often reduced in people with gait and/or balance deficits (among whom people after stroke, people with a lower-limb amputation and fall-prone elderly). This may contribute to their high fall risk since most falls result from a trip, slip or misplaced step while walking [2-7]. Moreover, attentional demands of walking are often elevated in older people and people after stroke [8-12], especially when step adjustments are required and particularly so under high time-pressure demands [13,14]. This may cause additional problems when other tasks have to be combined with walking through a challenging environment, such as “carrying groceries while telling your husband what you will be cooking that night”. Therefore, issues of dual tasking should also be considered when looking into walking adaptability.

Despite the apparent relevance of walking adaptability, its assessment and training have received relatively little attention to date. There is thus a clear need to evaluate walking adaptability when assessing one’s ability to walk safely in daily life. Moreover, in the
case of poor walking adaptability there is a need to improve this aspect of walking in order to maintain or regain safe community ambulation and to lower the risks of falls.

**Walking-adaptability assessment and training**

Conventional forms of gait assessment and gait training have limited context specificity and typically do not address walking adaptability [1]. To assess or train walking adaptability, it is essential to enrich the assessment or training environment with context [6,7,16-22]. There are various environments in which assessment and training can take place (e.g., treadmill, overground, indoors, outdoors, et cetera), and those environments are or can be enriched in various ways, using for example, physical (i.e., real physical obstacles) or augmented and virtual (i.e., projector-generated visual images of obstacles) context that is continuously present (stationary context) or may appear suddenly in a gait-dependent manner (interactive context). Physical context can be used to recreate ADL tasks, which may enhance the ecological validity of gait assessment and training (mimicking walking in daily life). On the other hand, augmented or virtual reality may also be suitable for evaluation and training, as it is associated with a lower physical risk of falling than physical context and allows for tailoring the context to the specific needs, gait characteristics and abilities of an individual person. Context presented in a gait-dependent manner can be used to elicit step adjustments under time pressure, which is especially difficult for people with gait and/or balance deficits [13,14]. Moreover, these unexpected challenges should often be made during real life walking (e.g., sudden obstacle avoidance). These features may prove useful in the evaluation and training of walking adaptability.

**C-Mill and Interactive Walkway to assess and train walking adaptability**

The C-Mill ([23,24]; Motek, Amsterdam, The Netherlands) is an instrumented treadmill with interactive augmented context (Figure 1) that may be used to assess walking adaptability. The C-Mill can project visual context onto the walking surface in a gait-dependent manner due to online monitoring of the timing and location of foot placements and therefore-derived gait characteristics, following an analysis coined gaitography [25]. The C-Mill offers various individual-tailored walking-adaptability tasks (e.g., obstacle avoidance, goal-directed stepping, speed adaptation), which better mimic the task- and context-specific step adjustments required for safe community
ambulation in a cluttered environment than conventional treadmill walking without projector-generated context. Examples of projector-generated gait-dependent contexts are: 1) multiple obstacles that suddenly appear at the locations where one is about to place one’s feet such that step adjustments are required (Figure 1, top left), or 2) a pattern of projected stepping targets that corresponds to the patient’s own gait pattern in terms of step width, stride length and step-length asymmetry (Figure 1, top right). The C-Mill allows for an assessment of each step in an objective, safe and controlled manner without using markers.

Several studies have successfully used the C-Mill to assess walking adaptability, showing that walking adaptability is indeed reduced in healthy older people, people with reduced executive functions, people with lower-limb amputations and people after stroke [13,26-30]. However, a very common adaptation to a challenging walking environment is to adopt a slower walking speed [31]. Reducing walking speed on a fixed-speed treadmill is somewhat problematic, as one runs the risk of falling off the back of the treadmill. An overground walking-adaptability assessment tool, in contrast, does not constrain context-dependent speed adaptations. The Interactive Walkway (IWW [32-33]; Tec4Science, Vrije Universiteit Amsterdam, The Netherlands) offers such an overground
walking-adaptability assessment tool (Figure 2). This newly developed walkway is instrumented with multiple Microsoft Kinect sensors and a projector to present obstacles and targets in a gait-dependent manner. Both the C-Mill and the IWW seem promising tools for the assessment of walking adaptability.

Figure 2. The Interactive walkway, an instrumented walkway augmented with visual context.

Besides assessment, the C-Mill may be used for walking-adaptability training. C-Mill therapy is a promising example of walking-adaptability training in a safe and controlled environment with an emphasis on context- and task-specific training with gait-dependent patient-tailored feedback [34]. Moreover, one benefit of such an instrumented treadmill is the high amount of movement practice it offers for walking-adaptability training, that is, repetitive stepping in an ever-changing practice environment [34]. In a proof-of-concept study of C-Mill therapy in the chronic stage after stroke this form of training was well received and demonstrated training-related increments in walking speed and other gait-related clinical scores [35]. In addition, the ability to make step adjustments improved (i.e., higher obstacle-avoidance success rates) after C-Mill therapy. The improved obstacle-avoidance success rates were accompanied by lower attentional demands, suggesting that the step adjustments were made in a more automatized manner after a period of C-Mill therapy [14]. These studies were followed by several other studies that examined the effect of C-Mill therapy [36-39].
Fonteyn et al. (2014) provided preliminary evidence of a beneficial effect of walking-adaptability training on obstacle avoidance capacity and dynamic stability in patients with cerebellar degeneration [36], while Van Ooijen et al. (2014) found that adaptability treadmill training was well received and tolerated by older adults recovering from a fall-related hip fracture [37]. Adaptability treadmill training, conventional treadmill training and usual physical therapy resulted in similar improvements in walking ability, fear of falling and fall incidence in older adults rehabilitating from a fall-related hip fracture [38]. However, adaptability treadmill training and conventional treadmill training led to greater amounts of walking practice than usual physical therapy in older adults with fall-related hip fracture [37]. Hollands et al. (2015) showed that outpatient-based treadmill and overground walking-adaptability practice using visual cues were both feasible and may improve mobility and balance in people after stroke [39].

**Stepping beyond the state of the art**

Although several pertinent studies have been conducted, research on walking-adaptability assessment and training is still scarce. A first possible reason is that the validation of walking-adaptability assessment is hard. Walking adaptability is a rather unique aspect of walking ability and an external criterion to analyze its validity is not available. Hence, validation of any form of walking-adaptability assessment will have to be based on measures of content validity (e.g., face, item and sample validity) and construct validity. Secondly, although pertinent studies on walking-adaptability training have shown promising results, a follow-up and larger clinical trial aimed at examining the efficacy of walking-adaptability training still needs to be conducted. Thirdly, no objective guidelines are currently available with regard to the design of protocols for walking-adaptability training and how to adapt them to individual abilities and needs. These aspects are currently left to the therapist supervising the training, who has to be well versed in operating the various walking-adaptability tasks of the C-Mill and in adjusting them to the specific needs and abilities of the patient. This requirement may be a limiting factor for a large-scale introduction and evaluation of walking-adaptability training in clinical practice. Besides, operating such a system may draw the therapist's attention away from monitoring, instructing and assisting the patient. The C-Mill allows for instant data collection and thereby provides the possibility for adjusting the training on a session-to-session basis in an objective, standardized and largely automatized
manner. This warrants studies on the validity and efficacy of walking-adaptability assessments and training using gait-dependent augmented reality and the development of such an automatized paradigm in which assessments and training become literally intertwined.

**Aim and outline of this thesis**

The overarching aim of this thesis is to examine the reliability, validity, efficacy and feasibility of walking-adaptability assessment and training using gait-dependent augmented-reality tools like the C-Mill and the IWW as a preliminary step towards a large-scale implementation in clinical practice. Collectively, the studies in this thesis provide an encompassing evaluation with different patient groups, different training paradigms, different methods of assessment and evaluation at various time scales (from within-session to retention after rehabilitation). First, the repeatability and between-methods agreement of gaitography in persons with impaired gait will be examined. This is an important step towards the overarching aim because the so-obtained gait characteristics are not only useful to quantify gait, but also to determine features of gait-dependent contextual manipulations (i.e., obstacles presented at the location where one is about to place one’s foot without adjusting gait). To this end, **Chapter 2** describes the repeatability and between-methods agreement of temporal gait characteristics in a heterogeneous sample of persons with a lower-limb amputation. To underpin the relevance of walking-adaptability assessment and training, **Chapter 3** evaluates cognitive-motor interference and task prioritization in dual-task walking in people after stroke in a plain, uncluttered environment (10 Meter Walking Test [10MWT]) and in two more challenging environments enriched with either stationary physical context (the 10MWT with physical obstacles, stepping targets and a tandem walking path) or suddenly appearing projector-generated context (the IWW with suddenly appearing obstacle images). This chapter directly links to **Chapters 4** and **5**, which contrast training in enriched environments with either projector-generated context or physical context. To evaluate the efficacy of walking-adaptability training with gait-dependent augmented reality, **Chapter 4** reports the design of a randomized controlled trial comparing the efficacy of treadmill-based C-Mill therapy to the overground FALLS program (conventional therapy) in people after stroke. The results of this trial with respect to walking speed, walking adaptability and cognitive-motor interference are
described in **Chapter 5**. The next step preliminary to large-scale introduction and evaluation of walking-adaptability training with gait-dependent augmented reality in clinical practice requires bundling the knowledge into protocols and evidence-based guidelines. To address this, we developed an automatized, standardized and patient-tailored progressive C-Mill walking training protocol on the C-Mill, called ‘C-Gait’, which consists of an initial assessment and a decision-algorithm to automatically and progressively update training content and execution parameters based on participants’ performance and perceived challenge. In **Chapter 6**, this newly developed automatized and standardized patient-tailored progressive walking-adaptability training protocol, which intertwines assessment and training of walking adaptability, is evaluated. In **Chapter 7**, the research conducted in this thesis is summarized and discussed. The potential of walking-adaptability assessment and training in clinical practice is evaluated and directions for future research are discussed. Figure 3 presents a schematic outline of the core chapters of this thesis.

![Figure 3. Outline of this thesis.](image-url)
References


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