Safe walking requires the ability to make step adjustments in response to environmental demands, such as when walking over cluttered terrain or avoiding obstacles. This ability is often reduced in older adults and people who have sustained a stroke or lower-limb amputation, as reflected by the fact that falls frequently occur during walking, often in relation to environmental hazards. There thus seems to be a clear need for methods to assess and improve this important aspect of walking in fall-prone populations. The C-Mill is an instrumented treadmill developed specifically to elicit step adjustments relative to environmental context during walking. Environmental context, such as obstacles and targets, is projected on the belt’s surface to elicit step adjustments during walking, mimicking the task-specific step adjustments required for safe community ambulation in a cluttered environment.

Chapter 1 describes the rationale and objective of the research presented in this thesis, which was to examine the usability, validity and efficacy of the C-Mill for the assessment and training of walking adaptability in people with a lower-limb amputation, people who sustained a stroke and older adults with a recent fall-related hip fracture.

The study described in Chapter 2 aimed to investigate the face validity and construct validity of a protocol for objectively assessing walking adaptability using an instrumented treadmill with projected visual obstacles and stepping targets (i.e., the C-Mill). Twelve persons with a transtibial amputation, twelve with a transfemoral amputation and twelve able-bodied persons (control group) participated in this study. They walked at a self-selected speed on the C-Mill while visual obstacles and targets were presented on its belt. Walking adaptability was evaluated in terms of anticipatory and reactive obstacle avoidance performance (for obstacles presented 4 steps and 1 step ahead, respectively) and accuracy of stepping on regular and irregular patterns of stepping targets. In addition, several clinical tests were administered; including timed walking tests and reports of fall incidences and fear of falling. Inferior walking adaptability scores were found for the transfemoral group, intermediate scores for the transtibial group and superior scores for the control group, indicating adequate face validity of the walking adaptability assessment protocol. With regard to the construct validity, anticipatory obstacle avoidance performance was moderately correlated with timed walking test scores. Reactive obstacle avoidance performance and stepping accuracy performance were not related to timed walking tests, indicating that time-pressured walking adaptability scores quantified a unique, complementary construct of walking ability. Because walking adaptability was affected by walking speed, differences in
self-selected walking speed may have diminished differences in walking adaptability between groups. It was concluded that walking adaptability can be validly assessed by using an instrumented treadmill with a projected visual context. When walking speed is taken into account, this assessment provides unique, quantitative information about walking ability in people with a lower-limb amputation.

Chapter 3 describes a project that aimed to implement adaptability treadmill training using the C-Mill in clinical practice as a prerequisite for conducting training studies regarding its efficacy. Although the therapeutic possibilities of the C-Mill are legion, C-Mill adaptability treadmill training was until recently seldom used in rehabilitation practice. This had been mainly due to the lack of practical protocols for the use of C-Mill adaptability treadmill training in daily clinical practice for specific, well-defined target groups. The C-Mill implementation project (dubbed Cimple) was initiated with the aim to implement the C-Mill as part of daily treatment practice for people with acquired brain injury or lower-limb amputation in two Dutch rehabilitation centers (Reade and Heliomare). A multidisciplinary project team, consisting of scientists, engineers, software developers, patients and clinical professionals, specified relevant patient groups for C-Mill adaptability treadmill training, defined in- and exclusion criteria and developed training protocols with regard to pre-specified rehabilitation goals, which were implemented during a test phase involving 55 patients. Finally, a user manual was produced aimed at providing guidance for (future) C-Mill users with regard to its use and implementation as an integral part of clinical practice. As a result of Cimple, the C-Mill complies with the demands and wishes of both physical therapists and patients and has since found its way into daily rehabilitation practice in the Netherlands and abroad. Cimple also led to new research collaborations, resulting in the following studies on conceptual validity and efficacy of C-Mill adaptability treadmill training.

The concept of C-Mill adaptability treadmill training was evaluated in Chapter 4. Sixteen community-ambulating persons in the chronic stage of stroke (age: 54.8±10.8 years) received ten sessions of C-Mill adaptability treadmill training within 5-6 weeks. Before and after the intervention period, participants performed clinical assessments of balance and gait (10 meter walk test, timed Up-and-Go test, Berg Balance scale, obstacle sub-task of the Emory functional ambulation profile, and the Trunk Impairment scale) and their physical activity level was evaluated with a pedometer. In addition, step adjustments towards a displacing target were assessed with an instrumented Target-Stepping Task in the
laboratory, again pre and post intervention. Participant’s experience with the training was also evaluated. All clinical assessments improved significantly after training, except for the Trunk Impairment scale. Physical activity increased by 19.6% and improvements in Target-Stepping Task success rates depended on the specific testing condition. All participants appreciated the training. It was concluded that the concept of C-Mill adaptability treadmill training in the chronic phase of stroke is promising and warrants future research involving a randomized controlled trial.

The study described in Chapter 5 aimed to evaluate the assumption of task-specific practice underlying adaptability treadmill training. The sixteen community-ambulating persons in the chronic stage of stroke who participated in the study reported in Chapter 4 also performed a laboratory based obstacle-avoidance task with and without a secondary attention-demanding auditory Stroop task. In this manner, their ability to make walking adjustments (i.e., obstacle-avoidance success rates) was evaluated before and after the ten adaptability treadmill training sessions, as well as the associated attentional demands of (adaptive) walking (i.e., Stroop success rates, stratified for pre-crossing, crossing, and post-crossing strides). Obstacle-avoidance success rates improved significantly after C-Mill adaptability treadmill training from 52.4±16.3% at pretest to 77.0±16.4% at posttest. This improvement was accompanied by significantly greater Stroop success rates during the obstacle-crossing stride only. In addition, the observed improvements in obstacle-avoidance success rates and Stroop success rates were strongly correlated. These results indicated that the ability to make walking adjustments and the associated attentional demands can be successfully targeted in persons with stroke using C-Mill adaptability treadmill training, suggesting that its underlying assumption of task-specific training is appropriate.

In Chapters 6, 7 and 8 a randomized controlled trial is presented, comparing the efficacy of C-Mill 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. In Chapter 6 the design of this randomized controlled trial is described. Briefly, older adults with a recent fall-related hip fracture were recruited from inpatient rehabilitation care and allocated to six weeks of C-Mill adaptability treadmill training, conventional treadmill training or usual physical therapy using block randomization. Study parameters related to walking ability were assessed as primary outcome before and after the intervention and at 4-week and 12-month follow-up. Secondary study parameters included measures related to fall incidence,
fear of falling and general health. In addition, the number of steps performed during training sessions was registered, and participants’ attitude towards the assigned intervention was evaluated.

In Chapter 7, the amount of walking practice during adaptability treadmill training, conventional treadmill training and usual physical therapy was assessed in 70 older adults with a recent fall-related hip fracture to evaluate the assumption of increased amounts of walking practice underlying (adaptability) treadmill training. In addition, participant’s attitude towards the three forms of training was evaluated, which is relevant given that a positive attitude towards training is a prerequisite for its efficacy. Participants’ attitude towards the assigned intervention was evaluated after the intervention period using a purpose-designed questionnaire on experienced usefulness, motivation, fun, challenge, enjoyment (rated from 1 [low] to 10 [high]) and perceived discomfort. The amount of walking practice during adaptability and conventional treadmill training was defined as the number of steps performed per training session, as registered by an instrumented treadmill. The number of performed steps per session of usual physical therapy was assessed manually by two observers in an additional representative comparison group of 16 older adults (85.1±6.3 years). All three training groups rated the received training favorably with median scores of 7.0 or higher for usefulness, motivation, fun, challenge and enjoyment, with no significant differences between groups. Participants in the adaptability treadmill (803.4 [426.1–1,174.5] steps) and conventional treadmill (847.8 [416.8–1,415.5] steps) groups performed significantly more steps per training session than the additional comparison group per session of usual physical therapy (368.0 [135.0–1,179.5] steps). All three types of training were thus well received by older adults with fall-related hip fracture. As assumed, adaptability and conventional treadmill training led to more walking practice per session than usual physical therapy, without a difference between both treadmill-based interventions.

In Chapter 8 the results of the randomized controlled trial are reported with respect to walking ability, fear of falling and fall incidence. Measures of general walking ability, general health and fear of falling improved significantly over time. Significant differences among the three intervention groups were only found for the Functional Ambulation Category and the dual-task effect on walking speed, which were in favor of conventional treadmill training and adaptability treadmill training, respectively. It was concluded that, overall, adaptability treadmill training, conventional treadmill training and usual physical therapy resulted in similar effects on walking ability, fear of falling and fall incidence in older adults rehabilitating from a fall-related hip fracture. However, additional post
hoc subgroup analyses, with stratification for pre-fracture tolerated walking distance and executive function, revealed several intervention effects in favor of adaptability and conventional treadmill training, which warrant further research to univocally identify the characteristics of individuals who will benefit most from adaptability and conventional treadmill training.

In Chapter 9, the main findings of the research presented in this thesis are summarized and discussed with regard to the continuum of translational research. Translation refers to the process of turning a basic science discovery into a practical application, and ultimately into an improvement of public health. The work presented showed that adaptability treadmill training successfully targeted task-specific walking adjustments with great amounts of movement practice, in line with its underlying assumptions. Adaptability treadmill training further appeared usable in terms of its safety and practicability. The C-Mill was thus demonstrated to provide a usable and valid therapeutic tool for training walking adaptability. Adaptability treadmill training was shown to be effective in improving walking-ability- and walking-adaptability-related outcome measures in persons in the chronic stage after stroke and in older adults with a recent fall-related hip fracture. However, the expected surplus value of adaptability treadmill training over other forms of therapy was not demonstrated, possibly because this new construct still lacks sensitive and comprehensive walking adaptability outcome measures. Walking ability and walking adaptability are complex, multifaceted constructs, difficult to assess in a comprehensive manner. The insights obtained in this thesis provide directions on the road forward to a proven clinical application of the C-Mill and underscore the importance of a complementary set of walking ability measures addressing the full repertoire of skills necessary to walk safely in everyday life. Two possible approaches regarding the future clinical application of the C-Mill are described in this chapter: within evidence-based protocols or as a therapeutic tool during single therapy sessions. Regardless of the approach taken, the clinical effectiveness (i.e., its effect in actual clinical practice) of the C-Mill needs to be examined to achieve an established standard of health care with public health impact in the future. This would ideally imply the deployment of the C-Mill to assess and train walking adaptability, leading to safer everyday walking, increased participation and less walking-related falls.