SUMMARY
Walking can be a challenging task for many individuals, for example those with an orthopedic or neurological impairment. An important aspect of impaired walking is that the associated energy demands are often elevated\textsuperscript{1-3}. The reasons for this increased energy demand are generally sought in altered energy demands for weight bearing, propulsion and leg swing\textsuperscript{1,4}. The focus of the present thesis has been on the energy demand of another essential feature of walking, which might contribute to the increased energy cost of walking in patients: *balance control*. The aim was to *assess* and *understand* the effort for balance control in terms of the metabolic cost of walking in able-bodied individuals, as well as in people after lower limb amputation and people who suffered a stroke. This summary will provide a short overview of the main findings of the studies presented in this thesis.
THE ENERGY COST FOR BALANCE CONTROL IN ABLE-BODIED INDIVIDUALS

The first two studies in this thesis addressed the energy cost for balance control in able-bodied people. In the study described in Chapter 2, we investigated the magnitude of the metabolic load for balance control by means of external lateral stabilization via spring-like cords attached to the waist. We examined the effects on metabolic load of different spring stiffnesses, and the effects of varying walking speed. External lateral stabilization led to an average decrease in the energy cost of walking of 6% as well as a decrease in step width (24%), step width variability (41%) and variability of medio-lateral trunk acceleration (12.5%). Increasing the stiffness of the stabilizing springs increased the effects on both energy cost and medio-lateral gait parameters up to a stiffness of 1260 N·m⁻¹. With this spring stiffness setting or higher stiffness the reduction in energy cost was 7.5%. Contrary to expectations, the effect of stabilization was independent of walking speed. These results indicated that medio-lateral balance control during walking in conditions without major challenges involves a significant energy cost, independent of walking speed.

In real life, balance control is often challenged by threatening situations, where consequences of a loss of balance may be severe, while regular balance control strategies can not always be employed. For instance, imagine walking on a narrow bridge over water, or a narrow sidewalk, where sidesteps are not an option and a loss of balance potentially has serious consequences. In the study in Chapter 3 we simulated such a situation of postural threat by means of applying mechanical perturbations (sideward pulls to the pelvis), while participants walked on paths of varying widths projected on a treadmill. Four postural threat conditions were created: no threat, low threat, medium threat and high threat. While the low threat condition did not result in significant changes in energy cost, the energy cost of walking increased by respectively 6.7% and 13% in the two conditions with the largest postural threat. In the highest threat condition, this increase in metabolic demand was accompanied by a minor decrease in stride time (2.2%) and length (2.6%), increases in both stride time and length variability (25% and 30% respectively), a decrease in step width and step width variability (13% and 15% respectively), and increases in muscle activation amplitudes of the main lower leg muscles, with increased co-activation. Perturbation responses showed that the rate of...
recovery in the high threat condition was lower, in spite of the gait adaptations which likely served to arm the participants against a loss of balance. Again, the observed changes occurred independent of changes in walking speed. This study showed that in conditions that are (perceived as) challenging to balance control, participants altered their balance control strategies as reflected in adaptations in step parameters and muscle coordination, leading to an increase in the energy cost of walking, independent of walking speed.

**THE ENERGY COST FOR BALANCE CONTROL LOWER LIMB AMPUTEES AND STROKE SURVIVORS**

In Chapters 4-6 the energy cost for balance control was examined in patients with musculoskeletal and neurological impairments with the aim to compare results to those found in able-bodied people. In Chapter 4, we used the external stabilization set-up of Chapter 2 in order to evaluate the energy cost for balance control in persons with a lower limb amputation. We expected larger decreases for the lower limb amputees than for the able-bodied controls. Unexpectedly, transtibial amputees showed a similar effect on energy cost due to stabilization (-5%) as able-bodied controls (-3%), and transfemoral amputees even exhibited an increase in energy cost (+6.5%). For transfemoral amputees, the step width and medio-lateral pelvic displacement remained higher during stabilized walking than for the able-bodied group during unstabilized walking, suggesting that the transfemoral amputees were resisting the springs. Based on these observations we speculated that the stabilizing springs constrained the use of functional compensatory gait strategies involving pelvic motion for the transfemoral, and perhaps to a lesser extent also for the transtibial amputees. Instead of being beneficial, the springs hindered them, negating the postulated beneficial effects of stabilization on the energy cost of walking.

To avoid similar effects of the stabilization set-up in stroke survivors, we decided to use a different kind of facilitation of balance control in this population, which also had more direct clinical relevance: facilitation by means of using a cane or handrail. A cane or a handrail can provide both a biomechanical and somatosensory advantage for balance control, and may as such facilitate balance control and reduce the concomitant energy cost. In Chapter 5 we investigated the effects of this kind of
facilitation of balance control in two groups of stroke survivors: a group depending on a walking aid in daily life (walking aid dependent ambulators) and a group of walking aid independent ambulators. On the treadmill, handrail support resulted in a significant decrease in energy cost of on average 19% for the dependent and 14% for the independent ambulators (difference between the groups n.s.). Interestingly, overground walking with support resulted in an 8.4% reduction in energy cost for walking aid dependent ambulators, but a 6.1% increase for walking aid independent ambulators. This study showed that balance support from a handrail or cane can result in a significant reduction in the energy cost of walking in stroke patients, but this effect depends on the mode of facilitation and the level of gait impairment.

In Chapter 6 the effect of handrail use was further evaluated. We investigated whether biomechanical support, augmented somatosensory information, or both, were responsible for the effect on the energy cost of walking, and determined which gait changes (spatiotemporal and neuromuscular) were associated with this effect. Participants performed three walking trials on a treadmill: No handrail contact, light touch contact with the handrail, which provided only augmented somatosensory information, and firm handrail hold. Handrail hold resulted in a significant reduction in energy cost of 11%, while light touch contact did not. Also, with handrail hold subjects took narrower steps (24.4%) and longer steps (16.3%) with improved step length symmetry (15.0%), together with an overall amplitude drop in muscle activation, an increased constancy of the muscle coordination pattern and decreased muscle co-activation. Light touch contact only resulted in a small, but significant, decrease in step width. The increase in stride time and length, the improved step length symmetry and the decreased muscle activation were most closely associated with the decreased energy cost during handrail hold. In sum, the use of a handrail for external force application facilitates balance control and allows the adoption a more economic step pattern requiring less muscular activation, without substantial changes in neuromuscular organization.

Finally, the Epilogue has revisited the results from the studies presented in this thesis in light of the overarching aim: to assess and understand the energy cost for balance control in human walking. The studies in this thesis have contributed to the limited body of knowledge about this subject. From the results it is evident that
balance control comes at a metabolic cost which varies with the level of challenge to balance control. In stroke survivors, the energy cost for balance control is comparable to that of able-bodied individuals in challenging situations. A substantial reduction in the energy cost of walking for these people can be achieved by providing balance support in the form of a cane or handrail. The changes in cost are accompanied by changes in step parameters and muscle activation that can be explained in light of balance control strategies. Future research could be directed towards a better quantification of the cost associated with different balance control strategies to better understand the energy cost of walking, as well as towards the effect of therapeutic strategies to improve balance control in order to decrease the energy cost for balance control in pathological gait.