CHAPTER 1

GENERAL INTRODUCTION
Walking, it seems so simple; most of us do it daily from early childhood on, apparently with little conscious thought and physical effort. However, for many individuals, for example those with an orthopedic or neurological impairment, walking is no longer automatic nor simple. For them, walking may have become a struggle, and pose a threat to one’s independence and quality of life. It is therefore not surprising that regaining or maintaining the ability to walk represents one of the primary rehabilitation goals for these patients\textsuperscript{5-6}. Despite tremendous efforts of both patients and caregivers to improve locomotor function, walking often remains a challenge for patients undergoing gait rehabilitation, and many will never achieve the level of independent community ambulation\textsuperscript{6-7}. An important aspect of impaired walking is that the associated energy demands are often elevated. The reasons for this increased energy demand are still poorly understood, but are generally sought in altered energy demands for weight bearing, propulsion and leg swing\textsuperscript{1,4}.

The focus of the present thesis is on the energy demand of another essential feature of walking, which might contribute to the increased energy cost of walking in patients: balance control. This feature will be examined in able-bodied individuals, as well as in people after lower limb amputation and people who have suffered a stroke.

In the first section of this General Introduction a short overview of the energy cost of walking in general, and the contribution of different subtasks of walking to this energy cost will be provided. The second section will focus on the energy cost for balance control itself, by identifying potential sources of the energy cost for balance control. This will be done through a review of pertinent literature in which the energy cost for balance control has been manipulated in a variety of ways, and by examining current knowledge regarding the energy cost for balance control in pathology. This will expose lacunae in the current knowledge, which will be addressed in the following chapters of this thesis, as will be stipulated in the final section.
THE ENERGY COST OF WALKING

Measuring the energy cost of walking

Physical activities such as walking require metabolic energy to replenish ATP stores in active muscles. This metabolic energy demand is reflected in the rate of oxygen consumption during submaximal steady state walking, which can be measured via indirect calorimetry. The oxygen consumption (\( \dot{V}O_2 \), in ml·min\(^{-1} \)) can be converted into caloric consumption, or energy expenditure (EE; in J·min\(^{-1} \)), using the following calorimetric equation:

\[
EE = (4.940 \cdot \text{RER} + 16.040) \cdot \dot{V}O_2,
\]

where RER is the respiratory exchange ratio, i.e. the ratio between oxygen consumption and carbon dioxide production. In studies on the energy cost of walking, energy expenditure is often expressed as net energy expenditure, with the resting metabolic rate subtracted from the gross energy expenditure. Moreover, since the energy expenditure of walking is known to vary with the size of the individual, it is customary to normalize the energy expenditure with respect to body mass. This allows comparison between individuals or within individuals over time. Furthermore, energy expenditure can be normalized to walking speed (expressed in m·min\(^{-1} \)), resulting in the energy cost of walking, defined as the energy expenditure to walk a given distance (in J·kg\(^{-1} \)·m\(^{-1} \)), which is a measure of gait economy.

The energy cost of walking in health and disability

In normal walking the energy demands are a function of walking speed. While the energy expenditure during walking (i.e. the energy consumption per unit of time) increases quadratically with walking speed, the relation between walking speed and energy cost (i.e. the energy consumption per unit distance) follows a U-shaped curve. Although quite some individual variation exists in the precise shape of this curve, it often has an optimum (i.e. minimum) around 1.3 m·s\(^{-1} \). This is close to the average preferred walking speed of healthy persons and the energy cost of able-bodied persons at this minimum is approximately 3.5 J·kg\(^{-1} \)·m\(^{-1} \) (gross energy cost). At speeds slower or faster than preferred the energy cost increases, although the
curve is rather flat between 1.1-1.4 m s$^{-1}$ (Figure 1)\textsuperscript{11,16}. Similar U-shaped curves have been found for energy cost in relation to other basic gait parameters such as stride frequency\textsuperscript{14}, step length\textsuperscript{17} and step width\textsuperscript{18}. These curves also have optima around the preferred value of the parameter in question, suggesting that healthy persons tend to walk in a manner that minimizes energy cost\textsuperscript{17}.

![Figure 1: Relation between energy cost of walking and walking speed based on Ralston et al.\textsuperscript{11}](#)

Note that gross energy cost is depicted.

For lower limb amputees and stroke patients, the situation is somewhat different. Both patient populations exhibit substantial increases in energy cost at their preferred walking speed. This increased cost of walking in amputees and stroke patients can severely limit their ambulatory activity\textsuperscript{19}, often resulting in a vicious cycle of decreased physical activity and deconditioning. For lower limb amputees, increases in the cost of walking between 33-66\% have been observed, depending among others on the level and etiology of the amputation, with higher costs for those with a transfemoral amputation and an amputation due to vascular deficiency\textsuperscript{2,20}. Even higher increases have been reported for stroke survivors, with costs of walking up to twice as high as in healthy subjects of comparable age\textsuperscript{3,21-22}. While these increases in the cost of walking for stroke patients and people with a lower limb
amputation are partly attributable to a decreased walking speed\textsuperscript{2, 23}, the energy cost–speed curve also appears to be shifted upward (Figure 2)\textsuperscript{3, 21, 24}. As can be seen in the figure, patients seem to prefer to walk at a speed that is lower than their energetic optimum, and/or are often even unable to attain their energetically optimal speed\textsuperscript{23, 25}.

![Figure 2: Change in the energy cost–speed curve in people with a lower limb amputation due to trauma or vascular deficiency (from Wezenberg et al\textsuperscript{25}, reprinted with permission). Large squares indicate the average preferred walking speed of the group, while the inverted triangles indicate the energetically optimal speed based on the fitted curve. Note that the vascular amputees are unable to reach their energetically optimal speed.](image)

Sources of energy consumption during walking

To understand the energy cost of walking in able-bodied people, as well as the causes of the increased cost of walking in pathological gait, it is imperative to know the different sources of energy expenditure during walking. Seen from a biomechanical point of view, walking can be roughly subdivided into four basic tasks: a person must (1) support his or her body against gravity, (2) push off to redirect the body's center of mass from step to step in order to maintain forward motion, (3) swing the leg forward, and (4) maintain stability through balance control\textsuperscript{26–28}. Studies aimed at assessing the energy cost of walking in able-bodied persons have mainly focused on estimating the metabolic requirements for the first three tasks at the expense of the fourth.
The energy cost of body weight support has been estimated with reduced gravity simulations, and with weight added to the trunk. Large variations in the estimated contribution of body weight support to the total energy cost of walking have been found, with values ranging between 0-28%\(^\text{29-31}\). The cost of propulsion has been investigated by applying external aiding or impeding forces\(^\text{30}\)\(^\text{32}\), and by calculating the mechanical work associated with redirecting the center of mass\(^\text{33}\). This has led to estimations of the contribution of the cost of propulsion of approximately 33-53%.

The cost of swinging the leg has been estimated at 10%, by applying external aiding or impeding forces to the swing leg\(^\text{34}\). Simply adding up these individual components suggests that they can explain at most \(~90\%\) of the energy cost of walking. Although this value may represent an overestimation of the contribution of these three individual components due to possible cooperative actions between them, at least 10% of the energy cost of walking remains unaccounted for. Logical reasoning suggests that part of this cost may be due to a metabolic cost of the fourth subtask of walking: balance control.

To explain the increases in the cost of walking in people after lower limb amputation, and people who have suffered a stroke, researchers have also predominantly looked at biomechanical factors affecting the (external and internal) mechanical work performed for propulsion or leg swing. In people with a lower limb amputation, propulsion is impaired due to the lack of push-off power of the prosthetic limb\(^\text{35-36}\). Also, leg swing problems occur due to the diminished push off, a lack of dorsal flexion of the prosthetic ankle, and diminished knee flexion in the prosthetic leg\(^\text{35-37}\). Similar problems with push off and leg swing, although of an entirely different nature, often arise in stroke survivors.

These problems, as well as associated compensatory actions (e.g., increased mechanical work performed by the intact or non-paretic leg, or compensatory movements of the hip and trunk), are thought to lead to increased external and internal mechanical work resulting in an increased metabolic cost\(^\text{2, 21-22, 38-39}\). However, they do not appear to fully account for the difference in energy cost between patients and able-bodied people\(^\text{38, 40-42}\). Perhaps factors not associated with forward propulsion and leg swing, such as balance control, also contribute to the increased cost of walking in these patient populations.
UNRAVELING THE METABOLIC COST FOR BALANCE CONTROL

In the remainder of this General Introduction the focus will be on the energy cost for the aforementioned fourth subtask of walking, balance control. In particular, three aspects will be covered: potential sources of a metabolic cost for balance control, methods and manipulations that can, and have been used to investigate this cost together with their limitations, and current knowledge about the effect of pathology on the energy cost for balance control.

Potential sources of a metabolic cost for balance control

Balance control may be effectuated through passive dynamics of the limbs, or through active neuromuscular control via the central nervous system. Modeling studies and empirical studies based on the dynamics of a simple inverted pendulum have shown that neuromuscular control is mostly needed to control balance in the sideward direction, while balance control in the direction of progression can largely be maintained passively. Using the inverted pendulum analogy of walking, several researchers have tried to find theoretical and empirical evidence for a metabolic cost for balance control.

The primary strategy for balance control of an inverted pendulum walker in the sideward direction is the foot placement strategy. With each step, the center of mass (CoM) ‘falls’ to the side. A sideward loss of balance is prevented by placing the foot lateral with respect to the center of mass in the subsequent step, at a position sufficient to prevent the CoM to cross this new base of support taking into account the center of mass velocity. This foot placement strategy is reflected in a nonzero step width and step width variability. Walking with nonzero step width carries a metabolic cost because at each step mechanical work has to be performed to redirect the center of mass velocity towards the contralateral side. The inverted pendulum model predicts that the mechanical work for these so called step-to-step transitions increases with the square of the step width. Due to this nonlinear dependency, a larger variability in step width will, for the same average step width, also increase the mechanical and the metabolic cost.
Empirical evidence for this interrelation between balance control, step width and the energy cost of walking comes from three studies in which subjects were stabilized laterally via stiff spring-like cords attached to the waist and pre-stretched in the lateral direction. These cords acted as stabilizers by opposing and reversing lateral motion of the pelvis, thereby removing or diminishing the need for balance control in the lateral direction. In healthy subjects this manipulation resulted in significant reductions in average step width (~50%) and step width variability (~40%), with a concomitant reduction in energy cost of ~3-6%^{47-49}.

Although useful, the inverted pendulum is a highly simplified model of human walking. In humans, balance control is not only achieved through foot placement. After foot placement has occurred, fine tuning takes place by producing an ankle eversion/inversion moment to alter the medio-lateral progression of the center of pressure under the foot, or by producing an abduction/adduction moment around the hip of the stance leg in order to alter the trajectory of the center of mass^{46, 50}. Also, muscle co-contraction can be used to stabilize individual joints. The metabolic cost involved in the muscle activity for these strategies is not taken into account when looking only at the mechanical and metabolic consequences of adopting a certain step width. Moreover, analyses of both external and internal work or joint work do not take into account isometric muscle contractions (producing force without performing work), or muscle co-activation that may be used for such strategies. Therefore, further analysis of the metabolic effects of balance control strategies may require the analysis of neuromuscular activation patterns. Previous research has indicated that in older adults, an increase in muscle activation could explain up to 70% of the differences in energy cost of walking between older and younger adults^{51}. Also, EMG activity of lower leg muscles correlates to energy expenditure during standing in destabilizing situations^{52}. While studies on the energy cost for balance control typically take into account spatiotemporal gait parameters, the relation between (altered) metabolic demands of balance control and muscle activation has received less attention. Therefore, in the studies described in Chapter 3 and 6 of this thesis the effect of altered balance control demands on the energy cost of walking will be studied by taking into account not only spatiotemporal parameters but also muscle (co-)activation and coordination.
Investigating the effort for balance control through experimental manipulation

There are many ways in which balance control demands can be manipulated during walking, but they can be roughly divided into manipulations that facilitate balance control and manipulations that challenge balance control. Both kinds of manipulation have been used to study the metabolic demands of balance control during walking. The challenge herein resides in altering the balance control demands of walking in isolation from the other three subtasks in order to disintegrate the metabolic cost for balance control from other metabolic costs of walking. The following paragraph will provide a short overview of the key literature on this topic.

Facilitating balance control

Facilitation has been used in the previously mentioned studies using external lateral stabilization\textsuperscript{47-49}. These studies have provided an estimate of the energy cost for balance control during walking in a perturbation free environment, and have indicated that balance control in physically fit healthy subjects comes with a small but significant energy demand. While this set-up appears promising in investigating the energy cost for balance control, the stiffness of the stabilizing springs was arbitrarily chosen in these studies, and varied between 1200-1900 N·m\(^{-1}\). Since it is unclear whether the cords were stiff enough to provide optimal stabilization, resulting in a passively stable state, no definite conclusions regarding the magnitude of the effect of lateral stabilization on the energy cost of walking can be drawn. Chapter 2 of this thesis builds on this stabilization approach in healthy subjects and focuses on the effect of varying stiffness. In Chapter 4 this approach is used to study the energy cost for balance control in lower limb amputees.

Challenging balance control

On the other end of the spectrum of manipulations, challenges to balance control have also been used to gain insight into the metabolic effort for balance control. In contrast with the relative safety of the clinical lab environment, balance control during daily life walking is often challenged due to environmental factors (such as walking on a slippery floor) or the task itself (such as walking with a cup of coffee).
Such challenges may lead to substantially higher energy costs for balance control than estimated in stabilization studies. Several researchers have tried to investigate the effect of increased balance control demands on the energy cost of walking, using various manipulations. For instance, visual disturbances in the medial direction during walking to provoke a sense of imbalance, resulted in a significant 5.9% increase in cost with a concomitant increase in step width variability\textsuperscript{53}. In another study, participants were enforced to walk a copy of their own preferred gait pattern (in terms of step length, width and frequency)\textsuperscript{54}. This manipulation constrains the use of a foot placement strategy in case of gait disturbances and will lead to a more active ankle strategy. It resulted in a decreased gait economy of up to 13%. Lastly, in two studies participants were verbally instructed to adopt a more “relaxed/risky” or a more “conservative” gait pattern, or participants were threatened with perturbation, during downhill walking. The study showed that from a “relaxed” to a “conservative” gait strategy the energy cost of walking increased\textsuperscript{55, 56}. Moreover, even just the threat of perturbation increased the energy cost of walking downhill. These studies suggest that challenges to balance control, or even the perception or awareness of such a challenge, may, consciously or subconsciously, lead to the adoption of different control strategies resulting in an increased metabolic effort. In Chapter 3 this suggestion is investigated further.

\textit{Walking speed as a manipulation of balance control?}

As mentioned before, the increased energy cost in lower limb amputees and stroke survivors has been partly attributed to their slow(er) walking speed. This slow walking speed might not only influence the energy cost of walking, but also affect gait stability. The role of walking speed in maintaining stability is the source of a longstanding debate in the literature. Some authors have argued that slow walking is more stable\textsuperscript{57-58}, while other authors have demonstrated that this is not (necessarily) the case\textsuperscript{59-60}, or even that slow walking might be less stable than faster walking speeds\textsuperscript{61-62}. Either way, if a slow walking speed does have an influence on gait stability, walking speed itself may represent a manipulation of the balance control demands. None of the aforementioned studies on the energy cost for balance control have taken this potential effect of walking speed into account. While the effect of
walking speed on the energy cost for balance control may be difficult to examine in patient populations due to their limited ability to adjust walking speed, it can be readily assessed in a healthy population. Therefore, the experiments in able-bodied people described in Chapter 2 and 3 will involve multiple walking speeds, ranging from faster to slower than preferred, to evaluate the possible moderating effect of walking speed on the energy cost for balance control.

The energy cost for balance control in people with gait impairments

The aforementioned studies already indicate that balance control incurs a small but significant metabolic cost in able-bodied people, and that increasing the balance control demands also increases the energy cost of walking. In people with gait impairments due to, for example a lower limb amputation or stroke, ‘unperturbed’ walking might pose a significant threat to balance control, resulting in a markedly increased energy cost. Only a single study specifically investigated the energy cost for balance control in a stroke population, albeit in the context of standing rather than walking52. It revealed that stroke patients have a substantially higher energy expenditure during upright standing than able-bodied subjects and that the energy expenditure increased twice as much during more challenging upright standing conditions (such as standing with eyes closed or on foam) for stroke patients compared to healthy subjects52. This study provides a first indication that the energy cost for balance control is elevated in the stroke population. To our knowledge, similar information regarding people with a lower limb amputation is lacking. Chapters 4-6 of this thesis elaborate on this theme, by investigating whether and how impaired balance control can contribute to the increased cost of walking in lower limb amputees and people who have suffered a stroke.

AIMS AND OUTLINE OF THE THESIS

Gaining insight into the relationship between gait economy and balance control is important from both a fundamental and a clinical perspective. From a fundamental point of view, there is an evident need to better understand the energetic demands of walking. In addition, studying the effort for balance control from an energetic point of
view may enhance our understanding of the processes underlying balance control. From a clinical point of view, it can help to understand the energy cost of pathological locomotion and thereby improve therapeutic strategies aimed at restoring gait economy. Therefore, the general aim of this thesis is to assess and understand the effort for balance control in terms of the metabolic energy cost of walking in both healthy people and patient populations.

As has already been alluded to in the previous paragraphs, various outcome measures (spatiotemporal and muscle activation parameters), interventions (facilitating and challenging balance control) and populations (able-bodied people vs. people with a lower limb amputation and stroke survivors) will be studied to attain this aim in the experiments incorporated in this thesis. Different combinations of these (dependent and independent) factors culminate into the different chapters in this thesis which are schematically represented in Figure 3. The first two studies reported in the thesis focus on the energy cost for balance control in an able-bodied population. Three questions will be addressed in these studies: 1) How do manipulations of the balance control demands during walking affect the metabolic energy cost of walking in healthy subjects? 2) What is the effect of walking speed on the effort for balance control? And, 3) Which changes in the gait pattern and muscle coordination are responsible for the effects of the manipulations on energy cost? In Chapter 2 balance control is facilitated by means of medio-lateral stabilization with spring like cords, in a similar manner as in the previously described stabilization experiments. In addition to addressing the aforementioned questions, it is also investigated which stiffness of the stabilizer cords is necessary to stabilize human walking. In contrast to the stabilization of Chapter 2, Chapter 3 uses increasing levels of postural threat during level walking to investigate the changes in energy cost and the gait pattern and muscle activation in a situation which challenges balance control. These two studies build on the limited body of knowledge on the energy cost for balance control in healthy people, and as such serve as a reference for the studies in the second part of this thesis.

The second part of this thesis focuses on the energy cost for balance control in people with a lower limb amputation and stroke survivors. In Chapter 4 the
stabilization set-up used in Chapter 2, is used in people with a lower limb amputation. It is investigated whether the increased cost of walking in this population can be attributed to an increased cost for medio-lateral balance control. In Chapter 5 and 6 people who suffered a stroke are studied. In these studies a clinically more realistic method to decrease balance control demands is used: facilitation of balance control via a handrail or cane. Chapter 5 describes the effect of this manipulation on energy cost, while Chapter 6 describes in more detail how the support provided by a handrail can affect the energy cost of walking. The effects of the potential mechanical support and the additional sensory information that is obtained through the handheld support are disentangled. In addition, the adaptations in gait parameters and muscle coordination that might underlie the change in metabolic cost are investigated.

Finally, Chapter 7 summarizes and discusses the results of the aforementioned studies to present a general conclusion and recommendations for future research and clinical practice.

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**Figure 3:** Schematic overview of the thesis outline