# Step by step

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# SUMMARY

## Step by Step;

## Stepping strategies to prevent falling while walking

## 8.1 Introduction

The general aim of this thesis was to investigate which gait strategies can be used to decrease fall risk during walking and whether people with gait impairments are able to use these strategies. In the first chapters, experiments were presented with able-bodied subjects. The results of these experiments helped us to understand which gait strategies can be used, in the absence of any impairments, to withstand manipulations of gait stability (chapter 2) and gait adaptability (chapter 3), and how these adjustments influence the magnitude of the short-term Lyapunov exponent (λs) and the size of the margins of stability (MoS; chapter 4). In chapters 5 and 6, studies were presented in which the aim was to investigate whether people with a unilateral gait impairment, caused by a transtibial amputation (chapter 5) or a stroke (chapter 6), are able to use comparable strategies to withstand manipulations of gait stability and adaptability. Finally, in chapter 7, the possible role of step length asymmetry was examined in transtibial amputees in the regulation of backward (BW) MoS.

## 8.2 Gait adjustments used by able-bodied people to regulate gait stability and adaptability

In this paragraph an answer will be given on the first two research questions of this thesis:

1. Which gait strategies do able-bodied people use to cope with manipulations of gait stability and gait adaptability?
2. How do manipulations of stride frequency, stride length and walking speed affect the short-term Lyapunov exponent and the margins of stability in able-bodied people?

In chapters 2 and 3, balance perturbations and a gait adaptability task (GA-task) were used to assess how subjects adjusted their gait pattern, and whether gait stability changed, in response to these manipulations. In these chapters gait stability was quantified by λs (chapter 2) and the medio-lateral (ML) and BW MoS (chapters 2 and 3). In chapter 4, we manipulated stride frequency, stride length and walking speed, to investigate how these adjustments influenced both the λs and the MoS.

### *8.2.1 Responses to the manipulation of gait stability*

In chapter 2, a continuous medio-lateral translation of the walking surface following a pseudo-random pattern was used to perturb gait stability in able-bodied people (figure 2.1). In response to this perturbation, subjects decreased step length and increased step frequency and step width, while keeping walking speed constant. Besides, subjects became locally less stable, as indicated by the increase in λs, and subjects increased their ML and BW MoS in response to the perturbation. Following the theoretical models forming the basis for calculating the MoS, the increase in ML MoS can be explained as a consequence of the increases in step frequency and step width[58-59], and the increase of BW MoS as a result of the decrease in step length[38, 98]. Based on the results of this study it was not possible to conclude whether the increase in λs was solely an effect of the perturbation, or whether the gait adjustments partly counteracted this increase in λs.

### *8.2.2 Responses to the manipulation of gait adaptability*

In chapter 3, a GA-task was used to investigate which strategies able-bodied people used to maintain balance while at the same time fast and accurate adaptations in the movement pattern had to be made to hit virtual targets that appeared on the screen (figure 3.1). To investigate the potential conflict between the maintenance of balance and the facilitation of accurate adaptations, we offered the GA-task both in absence and presence of the balance perturbation described in chapter 2. While performing the GA-task, both with and without perturbation, subjects decreased their step length and walking speed, maintained step frequency and slightly increased step width. Again these adaptations in the gait pattern can be explained as a strategy to preserve or enhance the ML and BW MoS. When comparing the adaptations found in response to the GA-task (chapter 3) with the adaptations found in response to the balance perturbation (chapter 2), the most notable difference is the absence of an increase in step frequency, while performing the GA-task. A possible explanation for this difference might be that an increase in step frequency would reduce the available time to respond to the targets, which might have a detrimental effect on the accuracy of the adaptation[10, 20, 41].

### *8.2.3 Responses to the manipulation of the gait pattern*

To investigate whether the gait adjustments that were observed in response to manipulations of gait stability and adaptability could indeed account for the changes found in λs and the ML and BW MoS, in chapter 4, step frequency, step length and walking speed were manipulated systematically and independently. Local dynamic stability, expressed as the λs, did not change in response to the imposed differences in the gait pattern. ML MoS increased with an increase in step frequency, while BW MoS increased with an increase in walking speed and with a decrease in step length. These results were in line with the expectations based on the behavior of a simple inverted pendulum[59, 98]. Although the inverted pendulum model is a strong simplification of human walking, this model appeared to be applicable to understand and predict MoS during human walking.

### *8.2.4 Conclusions*

The adjustments in the gait pattern in response to the balance perturbation served the purpose to increase the ML and BW MoS, possibly to compensate for the decrease in local dynamic stability resulting from the perturbation. In response to the GA-task, both with and without perturbation, it appeared that able-bodied subjects were able to maintain their ML and BW MoS, while at the same time facilitating the required accuracy of the adaptation.
As already mentioned in paragraph 8.1, the results of the studies performed in able-bodied controls provided a reference with respect to the strategies that can be used to increase or at least maintain gait stability during challenging walking conditions. Subsequently, it is of interest to investigate whether people with gait impairments have the ability to use the same strategies in response to the manipulations of gait stability and adaptability and whether differences in the gait pattern during unperturbed walking between these groups can be attributed to the regulation of the MoS.

## 8.3 Gait stability and adaptability in people with gait impairments

Based on the results of the studies presented in chapters 5 and 6, we will answer the third research question:

3. Which strategies do transtibial amputees and post-stroke individuals use to withstand manipulations of gait stability and gait adaptability and do these strategies differ from the strategies used by able-bodied controls?

In these studies we first investigated whether there were overall differences in the gait pattern and gait stability between amputees and post-stroke individuals on the one hand and able-bodied controls on the other hand, during unperturbed walking. Subsequently, the response to the manipulations of gait stability and adaptability for the different patient groups were compared with able-bodied controls. By comparing the responses to the perturbation with the differences in unperturbed walking between patients and controls, it is possible to examine whether these differences in the unperturbed gait pattern can be interpreted as a strategy to enhance gait stability.

### *8.3.1 Differences in the unperturbed gait pattern*

Both transtibial amputees and post-stroke individuals walked overall slower compared to able-bodied controls. For transtibial amputees this was mostly due to a lower step frequency. As step length did not differ between the amputee group and the able-bodied group, the lower walking speed resulted in a lower BW MoS for transitibial amputees, in line with the relation between walking speed and the BW MoS observed in chapter 4. In contrast to the amputees, post-stroke individuals walked slower because of a reduced step length. Because of the positive effect of shorter steps on the size of the BW MoS, the lower walking speed only caused a tendency towards lower BW MoS for post-stroke individuals compared to able-bodied controls. Both transtibial amputees and post-stroke individuals walked with wider steps. For the transtibial amputees this resulted in a larger ML MoS, despite the lower step frequency. The larger ML MoS might compensate for the reduced local dynamic stability (i.e. higher values for $\lambda$s) found for the transtibial amputees.

For post-stroke individuals the ML MoS did not differ from able-bodied controls, although post-stroke individuals not only walked with a larger step width, but also with a relatively high step frequency. This limited ML MoS arose from a larger ML body sway in the post-stroke individuals, which resulted in a larger ML amplitude of the extrapolated centre of mass (XCoM).

### *8.3.2 Gait adjustments in response to the balance perturbation and the GA-task*

The adjustments in the gait pattern in response to the balance perturbation and the GA-task did not differ between amputees and able-bodied controls and were in line with the adaptations found in the studies described in chapter 2 and 3. For both these groups the adjustments in the gait pattern resulted in an increase in ML and BW MoS in response to the balance perturbations and maintenance of both MoS while performing the GA-task. Besides, the accuracy of knee-movements during the GA-task did not differ between both groups.

In contrast to the transtibial amputees, post-stroke individuals differed in their response to the manipulations compared to the able-bodied controls. In response to both manipulations post-stroke individuals decreased their already lower walking speed even further, which would reduce the BW MoS. However in response to the platform perturbation, they also showed a relatively large decrease in step length, which resulted in BW MoS of a comparable size for both groups during the perturbation trial. In response to the GA-task, the decrease in walking speed for the post-stroke individuals was not accompanied by this relatively large decrease in step length, which caused a smaller BW MoS in the post-stroke group compared to the able-bodied group. In addition, also the accuracy of knee movements while performing the GA-task was worse for the post-stroke individuals compared to the able-bodied controls.

### *8.3.3 Conclusions*

We concluded that, just as the able-bodied subjects, the transtibial amputees who participated in our study were able to select a strategy resulting in an increase in ML and BW MoS when stability is perturbed, and a maintenance in MoS in situations that require fast and accurate adaptations of the gait pattern while retaining balance. Because transtibial amputees were, among others, able to increase the BW MoS in response to the balance perturbation, the overall lower BW MoS, during perturbed and unperturbed walking, seems not a result of a lack of balance control in this direction. Probably it should be considered as a side effect of other constraints of walking with a prosthesis, like a reduced walking speed to compensate for the higher energetic demands of walking with a prosthesis[64, 125], although this strategy is at the cost of the size of the BW MoS.

In contrast to the amputees, post-stroke individuals had difficulties with the regulation of the BW MoS, especially during the GA-task. These results could imply that post-stroke individuals lack the ability to adjust their gait pattern in such a way that MoS are preserved. Besides, the accuracy of the knee movements, necessary to hit the targets during the GA-task, was worse for the post-stroke group. This suggests that they are at an increased risk of falling, when obstacles have to be avoided during life walking, because of a higher probability of an obstacle hit, but also of a higher chance on a backward loss of balance. This is in line with previous experimental findings[108]. Possibly, training post-stroke individuals to use adjustments of step frequency and step length, while keeping walking speed constant, might help them to better control the BW MoS. Such a training might therefore help to create a gait pattern that is more robust against perturbations that have may cause a backward fall or slip, when walking in a challenging environment. This aspect will be discussed further in paragraph 8.6.

## 8.4 The role of step length asymmetry in the regulation of the backward margins of stability in transtibial amputees

In the preceding paragraphs, we focused on the role of average adjustments in step parameters over both legs. However, one of the characteristics of people with an unilateral gait impairment is an asymmetry between legs during walking. For example, the step of the unaffected leg, in which the healthy leg is the leading leg, is generally found to be shorter compared to the step with the affected leg[2, 4, 19, 67, 73, 84, 117]. Gait asymmetry is often seen, as a detrimental effect of a disorder, but a shorter unaffected step might be beneficial in the regulation of the BW MoS. Based on the results presented in chapter 7, we will answer the fourth research question:

4. How does step length asymmetry in amputees contribute to the regulation of the backwards margins of stability?

From this observational study, it appeared that a shorter non-prosthetic step (the step in which the healthy leg is leading), and more specifically a shorter non-prosthetic foot forward placement (distance between leading foot and centre of mass at initial contact), resulted in a larger BW MoS at initial contact compared to the prosthetic step. This large BW MoS at initial contact of the non-prosthetic step, appeared to be a compensation for a limited increase in velocity of the centre of mass during the transition from non-prosthetic to the prosthetic step. Consequently, at the end of this transition phase, the BW MoS was sufficient to prevent a backward loss of balance. Although, it is difficult to conclude whether the regulation of the BW MoS is the primary reason for the asymmetry in step length, this observation at least illustrates that an asymmetry is not necessarily a detrimental effect of the impairment, but could be beneficial in the regulation of gait stability. Therefore, pursuing a symmetric gait pattern during rehabilitation may not be indicated.

## 8.5 General conclusions

The research presented in this thesis contributes to a better understanding of how adjustments of the gait pattern can contribute to maintain or even increase gait stability, when facing balance manipulations, or being required to make fast and accurate adaptations of the gait pattern. It was demonstrated that some of the differences in the gait pattern between people with gait impairments and able-bodied people, like for example the larger step width in both amputees and post-stroke individuals, or the asymmetry in step length for amputees, might represent a functional adaptation in view of the regulation of the size of the margins of stability, while other gait changes, such as the reduced walking speed in amputees and post-stroke individuals appear less functional.

Especially post-stroke individuals appeared to have difficulties to select a strategy that enhances or preserves backward margins of stability, in challenging walking conditions. Future research should reveal which impairments or other constraints (for example minimizing energy cost) cause this suboptimal gait pattern in terms of the MoS. Secondly, it would be of interest to investigate whether specific training on the adjustments of step frequency and step length, helps these people to enhance margins of stability in response to balance perturbations and to conditions requiring gait adaptability and subsequently whether such a training does reduce fall incidence in daily life.