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Is stability an unstable concept?

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Chapter 7: Epilogue

The objective of the work presented in this thesis was to evaluate and develop methods for the assessment of dynamic gait stability, and to employ these methods to examine the effects of walking speed and arm swing on gait stability. In doing so, the first experimental studies of this thesis focused on measures that may be derived from steady state (i.e. unperturbed) walking, while the last experimental study focused on measures derived from actual perturbations of the gait pattern. In this epilogue, first a brief summary of previous chapters will be given, after which the preliminary results of two recently performed studies will be presented. These results shed light on the question whether the gait stability measures derived from steady-state (i.e. unperturbed) walking do indeed correlate to real-life notions of stability. Finally, some directions for future research, as well as some possible clinical applications of the work presented in this thesis will be outlined.

Overview of chapters

In **chapter one** several measures were discussed that are currently used to assess dynamic gait stability. It appeared that each of these measures has its own advantages and disadvantages. More importantly, it was concluded that the relationship between these measures and real-life notions of stability is largely unknown. In **chapter two**, the statistical precision and sensitivity of two measures (maximum finite time Lyapunov exponents and Floquet multipliers) of dynamic gait stability were studied in the context of steady state walking. It was concluded that a considerable number of strides are required to obtain precise estimates for both measures, and more importantly, that a fixed number of strides across experimental conditions should be used in the analysis. In **chapter three** these methodological insights were exploited to study if slow walking is more stable than faster walking. In contrast to previous studies using the same measures [35, 50], it was found that this may not be the case. In all likelihood, the discrepancy with previous results was due to previous studies using an unequal number of strides in the analysis and/ or expressing maximum finite time Lyapunov exponents as rate of divergence/second rather than per cycle. In **chapter four**, it was concluded that the stability measures in question could also be calculated from data obtained with a simple wireless sensor, which implies that such sensors may be readily used in clinical applications.

Still, at the end of the first four chapters, concerns remained that these measures quantify a dynamical system's response to infinitesimally small perturbations, rather than more intuitive, real-life notions of gait stability (i.e. the probability that a certain person will fall). As it was concluded in the Introduction that real-life gait stability is probably correlated most to reactions to external perturbations, **chapters five and six** focused on a manipulation that could alter stability within a subject, and a method to quantify reactions after perturbations. In **chapter five** it was shown that arm swing plays a major role in counteracting leg angular momentum around the vertical, to keep the total body angular momentum low. This suggests that the arms may play an important role in maintaining stability during gait. In **chapter six** this idea was tested; a continuous version of the Gait Sensitivity Norm, alluded to in the Introduction, was developed and, using this method, it was shown that arm swing initially makes walking less stable, but allows for faster subsequent recovery. In studying this effect of arm swing on gait stability, **chapter six** was the first study of this thesis to employ a perturbation paradigm, allowing the first (indirect) comparison between maximum finite time Lyapunov exponents and selected measures (i.e. characteristics) of perturbation reactions. Interestingly, this comparison revealed that λ_s showed the same pattern as the initial response to a perturbation, suggesting that dynamic measures of steady state gait stability may indeed provide some information about initial reactions to external perturbations. However, the efficacy of later (i.e. non-initial) reactions was not reflected by maximum finite time Lyapunov exponents, suggesting that while λ_s is indicative of the stability of the unperturbed gait pattern, neither λ_s nor λ_L are indicative of recovery processes after a perturbation of the gait pattern.

The three approaches

In **chapter one**, we argued that studies seeking to establish the relationship between stability measures derived from steady state walking and real-life notions of stability, should follow a three-pronged approach: 1. determine how well a given measure works in a model with known stability properties, 2. correlate the measure with measures derived from external perturbations, and 3. test if the measure under investigation can distinguish subgroups with known stability problems from subgroups without such problems using comparative (cross-sectional) and/or prospective research designs. In this thesis, only the second approach was followed; still, no direct comparison (e.g. in terms of correlations between measures) was made. To further explore the relationship between the dynamic gait stability measures used in the present thesis and real-life notions of stability and, some recent modelling work, as well as a study in which stability was manipulated within subjects, will be presented here. It should be noted that the presented data are preliminary and therefore only suitable for presentation in this epilogue.

As mentioned in **chapter one**, Su and Dingwell [55] already used the simplest walking model to study the relationship between measures of dynamic gait stability and the actual probability of falling. They found that λ_s correlated with the probability of falling, while λ_L and MaxFm did not. From this, they concluded that while λ_s reflects the probability of falling of the model, λ_L and MaxFm reflect the inherent stability of the model. In their study however, the probability of falling was only modified by varying the bumpiness of the slope the model walked on. Thus, the inherent stability of the model was not altered. By using an extended version of the simplest walking model, with arced feet, inherent stability of the model can in principle be altered by changing the radius of the feet [24]. In a recent modelling study, we performed simulations of such a model walking over a bumpy slope with different foot radii, keeping step length equal by changing the slope. For each simulation, λ_S, λ_L, and MaxFm were calculated. Moreover, for each foot radius, the gold standard of stability was calculated as the Gait Sensitivity Norm, which had previously been shown to reflect actual probability of falling in these models [24]. Results of these simulations are shown in Figure 7-1.

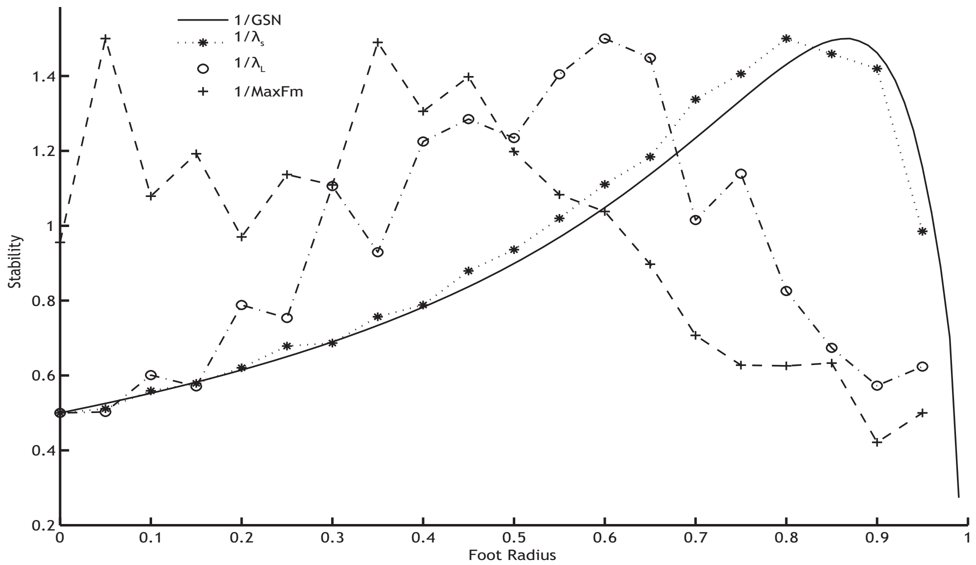

Figure 7-1: *Simulation results. For each foot radius the model was run 10 times with a trial duration of 100 strides: results shown here represent the means of those ten trials. To facilitate the comparison with the results of Hobbelen and Wisse [24], we plotted 1/stability measure for all stability measures, and to allow comparison between variables all variables were normalized. Increasing foot radius while keeping the same step length increases the stability of the model, as indicated by higher values of 1/GSN. Only 1/*λ_S *shows the same pattern as the Gait Sensitivity Norm, which we took as gold standard.*

As can be appreciated from this figure, even when changing the intrinsic stability of the model by changing the feet radius, only λ_S showed the same pattern as the Gait Sensitivity Norm. Thus, from these results, it is questionable whether λ_L and MaxFm relate to fall risk at all.

To further investigate the relationship between the measures used in this thesis and real-life notions of stability in humans, we also studied the effect of imposed instability on these measures. In this particular study, subjects were asked to walk on a treadmill at three speeds, both in a normal condition and in a condition in which stability was experimentally reduced. This experimental reduction of stability was applied by using randomly varying Galvanic Vestibular Stimulation [203], which ensured that subjects could no longer rely on vestibular information to maintain stability. Results (see Figure 7-2) showed that, as in the modelling work, only λ_S showed a significant reduction in stability, while MaxFm and λ_L showed no effects, or effects opposite to those expected from impaired stability.

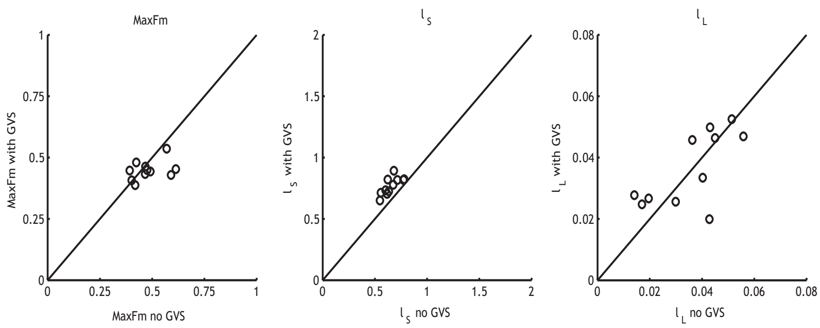

Figure 7-2: *The effects of Galvanic Vestibular Stimulation (GVS) on measures of dynamic gait stability. Data shown are for normal walking and walking with GVS at preferred walking speed. Each dot represents a subject. Since walking with GVS is less stable, data points are expected to be positioned above the identity line. As can be appreciated, only λ_S showed a consistent effect of GVS.*

All in all, the above results suggest that only λ_S relates to real-life notions of stability. As suggested earlier, however, this still remains to be confirmed in prospective studies. More importantly, these results also suggest that past work on gait stability may have reported changes in measures that do not reflect real-life notions of stability [51, 61]. This may explain why some of these studies have found rather counter-intuitive results [114]. Of course, it may well be that while λ_L and MaxFm do not reflect stability, they do capture other important aspects of movement control during walking. For now however, it seems safe to say that whatever those measures reflect, it is not stability in the sense of the probability of falling.

Future work

The work presented in this thesis suggests that the short-term maximum finite time Lyapunov exponent (λ_S) may be a valuable measure to assess dynamic gait stability. Not only does it relate to real-life notions of stability in both models and human walking, it was also shown to be sensitive to various changes in walking behaviour, such as alterations in speed (**chapter three**), walking while performing a dual task (**chapter two**), walking without arm swing (**chapter six**), and walking with distorted vestibular information (**chapter seven**). Moreover, data may be captured in any reference frame, and there is no need for position data, which allows for using small and cheap inertial sensors (**chapter four**). Still, a relatively large amount of gait data is needed to obtain precise estimates of λ_S. However, it was already suggested that precision may also be increased by using multiple episodes [43, 113], which may be more practical in a clinical setting. As of yet however, there is no data on how much precision increases when using multiple episodes per subject, and this also remains to be assessed in future studies.

The fact that λ_S is affected by walking speed [35, 46, 50] may be regarded as a problem when studying differences between populations. Here, on the question may arise what exactly it is one would like to know. If the aim of the study is to assess whether a certain patient group is more prone to falling in daily life, measuring at preferred walking speed preferable. If, on the other hand, the goal of the study is to assess factors associated with a particular disease or handicap that may influence gait stability, it would be preferable to test all groups at a specified (equal) walking speed, such that walking speed does not confound the results.

In agreement with the line of reasoning presented in this thesis, it seems that a logical next step would be to start using λ_S in prospective and/ or comparative research to see how well it can be used to predict falls in elderly and or patients groups.

Moreover, since it seems that λ_S does indeed provide a direct quantitative measure of dynamic gait stability, it may allow for more precise studies on the factors underlying gait stability. Hausdorff [67] already suggested that these factors may be very diverse in nature, ranging from psychosocial to cardiovascular factors, and there is a large and rapidly growing body of research trying to pinpoint determinants of gait stability. Still, most of these studies relate the potentially determining variables to prospectively or retrospectively determined falls within a person, which may be a somewhat crude and imprecise measure. By including λ_S in such studies, greater precision may be achieved, and factors responsible for gait instability may be assessed in a more reliable manner.

Finally, given the relative ease with which estimates of gait stability can be obtained when using λ_S (a walking track or treadmill and a single inertial sensor are in principle sufficient), there is a host of possible clinical applications. Such applications may for instance include diagnostics, identification of fall prone subjects, and evaluation of treatment programs.

Acknowledgements

The modelling study presented in this epilogue was performed in collaboration with Daan Bregman. Kim van Schooten en Lizeth Sloot collected and processed the data of the GVS study, which would have been impossible without the GVS apparatus supplied by Herman Kingma.

Hoofdstuk 8: Samenvatting

Vallen, en de medische kosten alsook de nadelige sociale effecten die ermee gepaard gaan zijn een groeiend probleem in onze vergrijzende samenleving. Het is bekend dat een groot gedeelte van deze vallen gebeurd tijdens lopen. Om beter in staat te zijn vallen te voorkomen, is het nodig de mensen die onstabiel lopen, en dus een grote valkans hebben, op tijd te identificeren.

Alhoewel stabiliteit goed gedefinieerd is in bijvoorbeeld de mechanica, is er geen consensus over hoe stabiliteit van menselijk lopen gemeten zou moeten worden. Op dit moment zijn er diverse maten te vinden in de literatuur, die allemaal claimen stabiliteit te meten. In **hoofdstuk één** werd een overzicht gegeven van de verschillende maten die momenteel gebruikt worden om stabiliteit van lopen vast te stellen. Het bleek dat elk van deze maten zijn eigen voor en nadelen kent, en dat de relatie tussen deze maten en de kans op vallen nog grotendeels onbekend is.

In **hoofdstuk twee** werden de statistische precisie en sensitiviteit van twee maten (maximum Lyapunov exponents and Floquet multipliers) van dynamische loopstabiliteit bestudeerd. Deze maten hebben als voordeel dat ze berekend kunnen worden op basis van onverstoord lopen, en dus mogelijk goed toepasbaar zijn in klinische situaties. De conclusie van dit hoofdstuk luidde dat er een aanzienlijke hoeveelheid data (~150 schredes) gemeten dient te worden om precieze schatters voor beide maten te verkrijgen. Belangrijker nog was de bevinding dat het erg belangrijk is om altijd een zelfde hoeveelheid data (aantal schredes) te analyseren voor verschillende condities.

In **hoofdstuk drie** werd dit laatste inzicht vervolgens gebruikt om de relatie tussen loopsnelheid en stabiliteit opnieuw te bestuderen. Anders dan in eerder gepubliceerde studies, werd gevonden dat sneller lopen waarschijnlijk stabieler is. Naar alle waarschijnlijkheid komt deze discrepantie voort uit het feit dat eerder gepubliceerde studies een vaste tijd analyseerden per snelheid (en dus op hoge snelheden meer schredes), terwijl in deze studie een vast aantal schredes geanalyseerd werd.

In **hoofdstuk vier** werd verder gekeken naar de haalbaarheid van het klinisch toepassen van deze maten, en bleek dat de stabiliteitsmaten die verkregen kunnen worden van onverstoord lopen ook gemeten kunnen worden met een ander soort, lichtgewicht en draadloos sensor. Deze bevinding maakt dat het gebruik van deze maten weer een stap dichter bij de kliniek komt te staan.

Toch bleef er aan het einde van de eerste vier hoofdstukken de vraag in hoeverre de maten die gemeten kunnen worden van onverstoord lopen ook echt een goed beeld geven van iemands stabiliteit, zoals die een rol gaat spelen wanneer echte verstoringen van het lopen optreden. Daarom waren **hoofdstukken vijf en zes** gericht op een manipulatie die stabiliteit zou doen afnemen, en op een methode om stabiliteit te kwantificeren aan de hand van reacties op verstoringen van het looppatroon.

In **hoofdstuk vijf** werd aangetoond dat armzwaai tijdens lopen een belangrijke rol spelt in het beperken van het angulair momentum om de verticale as dat door de beenzwaai ontstaat. Deze bevinding suggereert dat armzwaai een belangrijke rol zou kunnen spelen in de stabiliteit van lopen. Dit idee werd getest in **hoofdstuk zes**. Met behulp van verstoringen van het looppatroon en een nieuw ontwikkelde maat, werd aangetoond dat lopen met normale armzwaai initieel minder stabiel is, maar wel meer adequate herstelreacties toelaat.

Naast de verstoringsmaten werden in deze studie ook maximum finite time Lyapunov exponents, die berekend worden van onverstoord lopen, gebruikt om stabiliteit vast te stellen. Dus, de data van deze studie maakte het mogelijk een eerste (indirecte) vergelijking te maken tussen maximum finite time Lyapunov exponents, en maten verkregen van echt verstoord lopen. Hieruit bleek dat de short term maximum finite time Lyapunov exponent de zelfde effecten van het ontbreken van armzwaai aantoonde als de mechanische parameters die de initiële reactie op de verstoring kwantificeren, maar niet als de maten die de herstelreacties na de verstoring kwantificeren. Dit suggereert dat de short term maximum finite time Lyapunov exponent inderdaad informatie bevat over de stabiliteit van het looppatroon, maar niet over de adequaatheid van reacties die nodig zijn als het lopen een maal uit dit patroon gebracht is.

In de epiloog (**hoofdstuk 7**) werden al deze bevindingen naast elkaar gelegd, en werd geconcludeerd dat alhoewel er bewijs lijkt te zijn dat maximum finite time Lyapunov exponent inderdaad iets zeggen over stabiliteit, daar meer onderzoek naar nodig is. De eerste twee van zulke onderzoeken zijn al gedaan, maar de resultaten zijn nog niet gepubliceerd, maar worden in dit hoofdstuk gepresenteerd. In de eerste studie is een simulatiemodel van menselijk lopen gebruikt om te kijken hoe goed maten die van onverstoord lopen gemeten kunnen worden correleren met de actuele kans op vallen in het model. Het bleek dat alleen de short term maximum finite time Lyapunov exponent correleerde met de actuele kans op vallen van het model.

In het tweede onderzoek werden mensen instabiel gemaakt door middel van galvanische vestibulaire stimulatie, dat het evenwichtsorgaan in de war brengt. In overeenstemming met de eerdere simulatiestudie werd er gevonden dat de instabiliteit die zo geinduceerd werd goed gedetecteerd kon worden met de short term maximum finite time Lyapunov exponent, maar niet met de de long term maximum finite time Lyapunov exponent of maximum Floquet multipliers.

Deze bevindingen suggereren dat de short term maximum finite time Lyapunov exponent een goede maat kan zijn om te gebruiken in toekomstig onderzoek naar valrisicos in verschillende populaties

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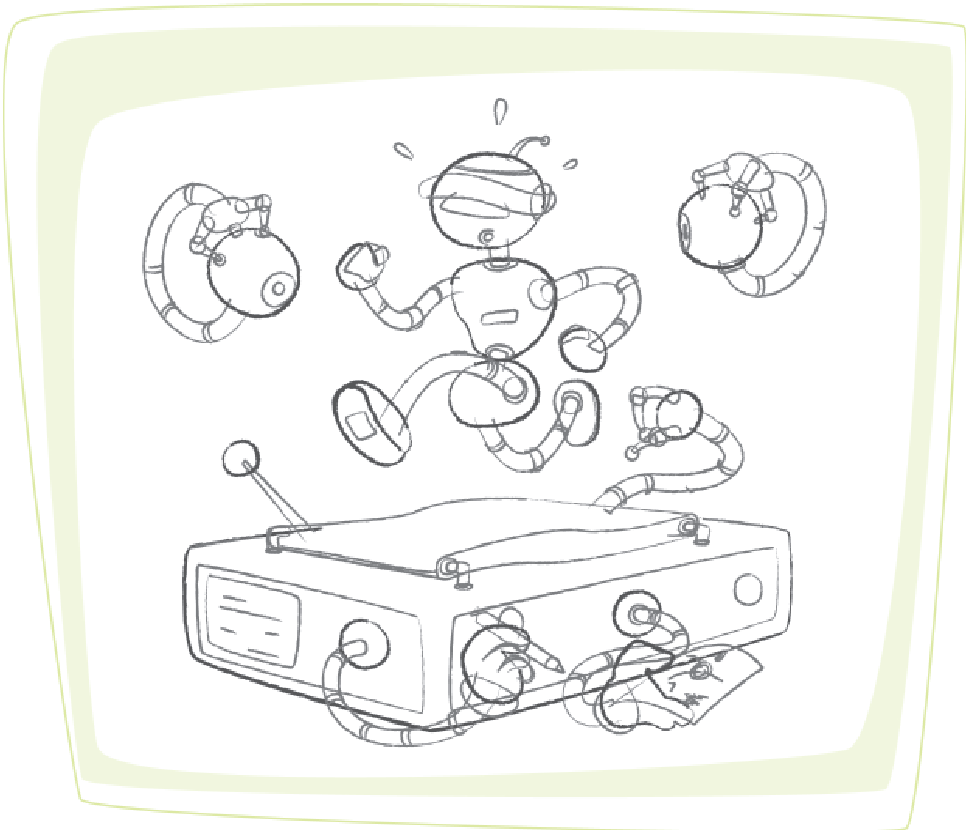

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