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## Is stability an unstable concept?

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# **Is stability an unstable concept? Quantifying dynamic stability of human locomotion**

## **SUMMARY**

### **Objective and aims**

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.

### **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 Lyapunov exponents and Floquet multipliers) of dynamic gait stability were studied in the context of steady state walking. It was

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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, 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 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

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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 Lyapunov exponents and selected measures (i.e. characteristics) of perturbation reactions. Interestingly, this comparison revealed that  $\lambda_s$  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 Lyapunov exponents, suggesting that while  $\lambda_s$  is indicative of the stability of the unperturbed gait pattern, neither  $\lambda_s$  nor  $\lambda_L$  are indicative of recovery processes after a perturbation of the gait pattern.