Benchmarking the predictive capability of human gait simulations

Maarten Afschrift[1], Dinant Kistemaker[1], Friedl De Groote[2]
[1] Department of Human Movement Sciences, Vrije Universiteit Amsterdam, Amsterdam, the Netherlands
[2] Department of Human Movement Sciences, KU Leuven, Belgium
Email: m.a.afschrift@vu.nl

Summary

Predictive gait simulation can predict the effect of various gait conditions (slope, added mass, speed, crouch) on stride frequency and joint kinematics with reasonable accuracy but underestimate metabolic power across gait conditions. The errors in the simulated metabolic power might be due to the high mechanical efficiency of the metabolic energy model and overestimation of positive muscle fiber work. This study highlights the need for more accurate models of muscle mechanics, energetics, and passive elastic structures.

Introduction

Physics-based simulations generate movement patterns based on a neuro-musculoskeletal model without relying on experimental movement data, offering a powerful approach to study how neuro-musculoskeletal properties shape locomotion. Yet, simulated gait patterns and metabolic powers do not always agree with experiments [1], pointing to modeling errors reflecting gaps in our understanding. Here, we systematically evaluated the predictive capability of simulations based on a 3D musculoskeletal model to predict gait mechanics, muscle activity and metabolic power across gait conditions. We specifically chose gait conditions that are simple to model, ensuring that prediction errors stem from shortcomings in the musculoskeletal and neural control models, rather than inadequate modeling of the intervention.

Methods

We used a published trajectory optimization workflow and 3D musculoskeletal model with 31 degrees of freedom driven by 92 Hill-type actuators [2]. Muscle excitations and corresponding gait patterns are calculated by minimizing a multi-objective cost function. The relation between muscle states and metabolic power was modeled as in [3].

In short, we ran simulations replicating a broad range of experimental studies on human locomotion that studied the effect of added mass, walking uphill or downhill, variations in imposed walking speed and crouched walking. These tasks introduce variations in average muscle activity, net mechanical muscle work, and in positive and negative mechanical muscle work, offering insight into potential modeling errors.

Results and Discussion

The simulations predicted stride frequency and joint kinematics with reasonable accuracy but underestimated changes in metabolic power with respect to level walking across gait conditions (figure 1). In particular, they underestimated metabolic power in tasks requiring substantial positive mechanical work, such as incline walking (27% underestimation). We identified two possible errors in simulated metabolic power. First, the muscle model and phenomenological metabolic power model produced high maximal mechanical efficiency (average 0.58) during concentric contractions, compared to the observed 0.2–0.3 in laboratory experiments. Second, multiplying mechanical work with more realistic estimates of mechanical efficiency (i.e. 0.25) overestimated the metabolic power by 84%. This suggests that positive muscle fiber work was overestimated, which may be caused by several assumptions and errors in the musculoskeletal model including its interacting with the environment and/or its many parameters.

Conclusions

This study highlights the need for more accurate models of muscle mechanics, energetics, and elastic structures to improve the realism of human gait simulations. Validating simulations across a broad range of conditions is important to pinpoint shortcomings in neuro-musculoskeletal modeling.

References

[1] Koelewijn et al. (2019). *PlOS ONE*, **18:** 14.
[2] Falisse et al. (2019). *J R Soc Interface*. **16**: 157.
[3] Bhargava et al. (2004). *J. Biomech.*, ***37:** 81*

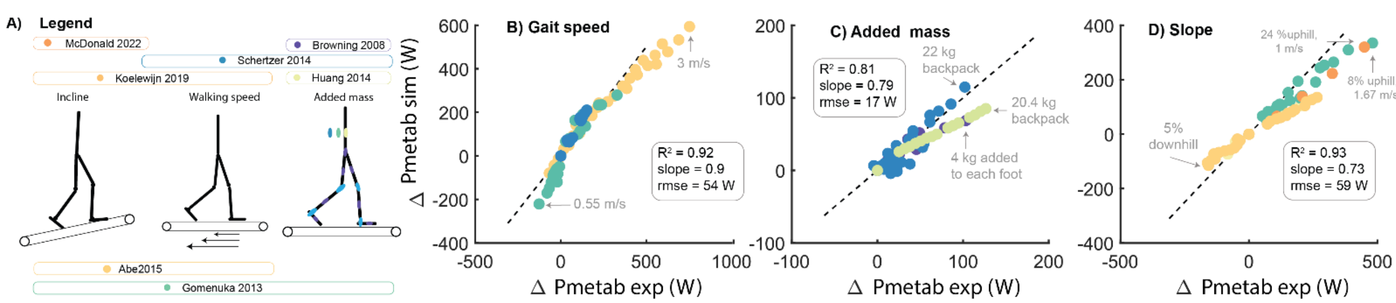

Figure 1: Predicted changes in average metabolic power (Pmetab) with respect to level walking at 1.1m/s with changes in gait speed (B), mass added to different body segments (C) and walking on a slope (D). The colors represent the subject-mean data reported in the different studies.