Inclusion of total angular momentum in performance criterion improves prediction of healthy gait

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1 Introduction

Multibody gait simulations are used to study the effect of orthopedic treatments on gait. Often an inverse analysis is performed based on measured 3D gait analysis data. However, inverse analyses do not allow us to identify cause-effect relationships between treatment and gait pattern. In contrast, forward simulations allow us to predict the effect of interventions on gait. However, predictive simulations are not yet widely available, since they are computationally expensive and there is large uncertainty on how to model control of healthy gait. Typically, a performance criterion is optimized but performance criteria used in inverse analyses do not always predict normal gait patterns. In this study, a multiple shooting framework is developed for predictive 3D gait simulations and minimizing total angular momentum as performance criterion is tested

2 Methods

A predictive simulation of a full cycle of normal human gait in 3D is performed using dynamic optimization [1]. The musculoskeletal multibody model consists of 19 DOFs and 54 Hill-type muscles [2] and is supplemented with a Hunt-Crossley contact model to simulate the foot-ground interaction. The optimization is defined as a multiple shooting problem, where the total integration interval is subdivided in four subintervals. For every subinterval a forward integration in time is performed, driven by the muscle excitation patterns and the initial states, which are the generalized coordinates, velocities, muscle fiber lengths and muscle activations. The muscle excitation patterns are parameterized using multimodal functions [3], with nine parameters per muscle for a full gait cycle. To further reduce the number of optimization variables, only half a gait cycle is simulated and right-left symmetry is assumed and imposed as a constraint. The optimization variables, consisting of the muscle excitation parameters and the initial states of each node, are found through minimizing a multi-objective performance criterion consisting of three terms:

$$\phi = w_1 * \phi_{musc} + w_2 * \phi_{pas} + w_3 * \phi_{Lx}$$

with ϕ_{musc} the muscular effort calculated as the sum of squared activations and ϕ_{pas} the sum of squared passive torques. The last term ϕ_{Lx} is total angular momentum in the frontal plane, calculated as in [4]. This performance criterion is tested for a model without and with arms. Additional constraints impose the consistency of the final and initial states of subsequent subintervals. Total pelvis anterior-posterior translation is constrained based on the desired walking speed. The optimization is performed in MATLAB using the interior-point algorithm (fmincon) and the forward integration is performed in OpenSim[5], which is called by MATLAB using a MEX-function. The gradient and the jacobian are calculated using finite differences. Due to the subdivision in multiple intervals, the jacobian is sparse and calculations are performed in parallel on 12 cores. Initial guess for the optimization is obtained from a static optimization solution of one trial of a subject. The predicted kinematics are compared with averaged measured kinematics from five healthy subjects, three trials each.

3 Results

The kinematics in the sagittal plane lies within two standard deviations of the measured data for all three simulations. The largest deviation between measured and simulated kinematics is found in the frontal plane. Figure 1 shows the kinematics of the hip adduction, pelvis list and lumbar bending for the three different simulations. Not including angular momentum minimization leads to an opposite motion for hip adduction, pelvis list as compared to the experimental kinematics. Minimizing angular momentum significantly improves the correspondence between simulated and experimental frontal plane kinematics. The inclusion of arms leads to a further improvement in hip adduction at pre-swing and pelvis list, such that the latter one fully lies within two standard deviations of the experimental kinematics.

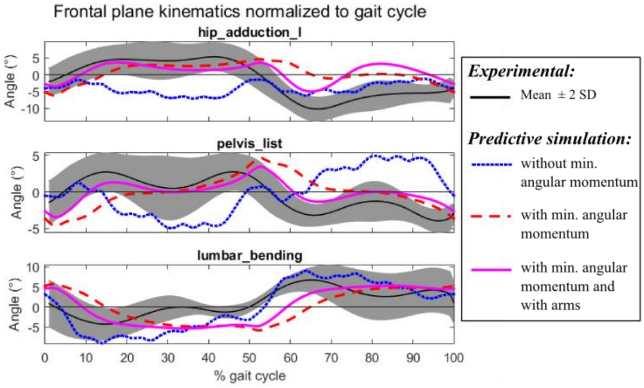

Figure 1: Frontal plane kinematics of hip adduction, pelvis list and lumbar bending, normalized to gait cycle.

4 Conclusions

A multiple shooting method for predictive forward simulations of walking was developed. It was shown that minimizing total angular momentum in the frontal plane is a valid assumption for prediction of healthy gait.

5 Acknowledgements

Funding for this study was provided by the Agency for Innovation by Science and Technology (IWT, no. 131040).

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