The Effect of Energetic Efficiency Prioritization on Experimental Tracking Simulations

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Summary

Musculoskeletal simulations were used to investigate the impact of varying energetic efficiency weightings, or effort, in tracking simulations of human gait**.** As expected, tracking errors increased with higher priority on minimizing effort. However, the point at which tracking accuracy was no longer considered accurate varied between subjects. These results suggest that individuals may not be prioritizing energetic efficiency equally and highlight the importance of individualized cost function weighting strategies.

Introduction

Musculoskeletal simulations often incorporate energetic efficiency as an objective, reflecting its importance in walking. Despite the likelihood that individuals prioritize energetic efficiency differently, simulations often apply uniform weight across individuals. To explore the consequence of assuming equal weight on minimizing effort across participants, we performed as series of tracking simulations of gait in OpenSim Moco [1]. Based on our hypothesis that individuals prioritize energetic efficiency differently, we predicted that the threshold at which increasing the priority to minimize energetic efficiency would no longer produce observed motion would vary across participants.

Methods

Electromyography (EMG), kinetic, and kinematic data were collected from seven older adults walking at self-selected speed (5F, 62.7±6.3yrs). Simulations used a 3D musculoskeletal model with 21 degrees of freedom and 80 lower-limb muscle-tendon units (modified RajagopalLaiUhlrich2023), scaled to each participant using AddBiomechanics [2]. Tracking simulations of a single gait cycle per participant were performed using a cost function that tracked joint coordinates and ground reaction forces (GRF) while minimizing energetic efficiency, or "effort," modeled as the sum of squared muscle activations [3]. Simulations were first performed with a torque driven model, where the tracking weights were set to the minimum required to ensure model convergence and kept consistent across participants. This solution served as the initial guess for the muscle-driven problem. "Effort" was weighted using a grid search with 11 values, from 0.00001 for Grid 1 to 1.0 for Grid 11, with higher weights corresponding to increased priority to minimize effort. Simulation accuracy was evaluated by using root mean square error (RMSE) between experimental and simulated data. Simulated muscle activations, kinematics, and kinetics were compared across grids to assess participant-specific impact of altering effort weighting in the cost function.

Results and Discussion

As expected, prioritizing efficient muscle recruitment impacted tracking across all participants. RMSE generally increased as effort was prioritized, though joint-specific accuracy varied (Fig. 1). For most participants, RMSE for the pelvis, hip, knee, and ankle remained below 5°. However, two participants consistently exhibited higher RMSE across all grids, with one reaching 6.7° at the ankle and another 6.6° in hip flexion. These deviations were due to inherent tracking limitations rather than the weighting strategy.

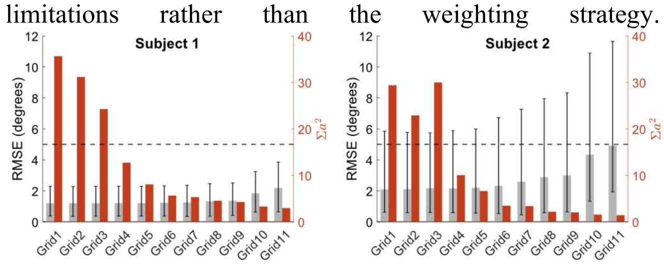

Figure 1: RMSE averaged across pelvis, hip, knee, and ankle (grey) and sum of squared muscle activations (red). Error bars indicate RMSE range. Dotted lines indicate 5° tracking accuracy.

The point at which RMSE began to rise, or where tracking accuracy was no longer acceptable, varied between participants (Fig. 1). Some showed minimal changes until Grid 10, while others experienced increases as early as Grid 7. The effort weight in Grid 10 was 55 times higher than in Grid 7, highlighting the large difference in weighting magnitude. These findings highlight that individuals prioritize efficiency differently, suggesting that a uniform weighting strategy may not be ideal. Instead, subject-specific adjustments may be necessary to optimize simulation accuracy and maintain reliable motion tracking.

Conclusions

This study shows that individuals prioritize energetic efficiency differently, as seen in the varying impact of effort weight on tracking accuracy. In predictive simulations, where kinematics are prioritized through additional cost function terms (e.g., speed and balance) [4], participant-specific weightings may be even more crucial. Future work should explore additional energetic cost models and validate these findings against experimental muscle activity.

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