Do humans optimize trunk leaning to minimize energetic cost in distance running? – an integrative experimental and musculoskeletal simulation approach

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Summary

The study aimed to investigate whether trunk lean angle is optimized to minimize energetic cost in distance running using a metabolic analysis and 3D optimal control simulations. Metabolic analysis results indicate a U-shaped relationship between trunk lean angle and cost of transport (COT), suggesting that runners self-select their trunk lean angle to minimize COT. Musculoskeletal simulations provided insights into changes in COT at the level of individual muscle groups, indicating potential compensations for the altered kinematics and kinetics associated with anterior trunk leaning (ATL). However, simulated whole-body net COT estimates did not differ across different trunk lean angles to the same extent as in the experimental data.

Introduction

Due to the substantial mass and moment of inertia of the trunk segment [1], the angle of the trunk may play an important role in minimizing energy expenditure in human locomotion. However, the current literature has not explored whether ATL is optimized to minimize COT in distance running and whether ATL results in systematic changes in muscle-specific COT.

Methods

Musculoskeletal simulations of running at 2.5 m/s in 6 trunk lean conditions (self-selected, 28°, 20°, 12°, 4° forward lean, and -2° posterior lean) were generated based on group mean kinematic and ground reaction force (GRF) data from 28 recreational runners. A 3-D musculoskeletal model was modified from the Gait2392 model [2] and included 29 degrees of freedom, 92 muscles in the lower limbs and torso, and 8 idealized torques actuating the arms. Simulations that closely tracked the experimental data were generated using OpenSim Moco [3] with an objective function that included tracking and effort terms. The tracking term was the squared differences in kinematic and GRF data, and the effort term was squared muscle excitations. The metabolic cost of running in the simulations was estimated using a model of metabolic energy consumption [4].

During the experiments, metabolic gas exchange data were collected and averaged over the final minute of each 5-minute running trial for each ATL condition. Finally, the resting metabolic rate was subtracted to determine the net COT [5]. A one-way repeated-measures ANOVA ($\alpha = 0.05$) was used to identify the main effects of ATL on experimental COT.

Results and Discussion

The metabolic analysis results indicate that deviating from self-selected ATL increases COT (Figure 1A). Specifically, running with 28° ATL increases COT by 12.15% ($p_{bonf} < .001$) compared to self-selected ATL. At the level of individual muscle groups, systematically increasing ATL led to sharp increases in simulated COT for the hamstrings and uniarticular hip extensors, while simultaneously leading to a similarly strong decrease in COT for the plantar flexors (Figure 1B). Overall, several muscle groups exhibited offsetting changes in COT such that the simulated whole-body COT did not differ across trunk lean conditions to the same extent as in the experimental data.

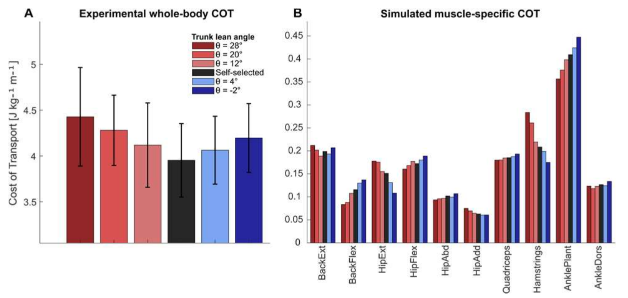

Figure 1: Experimental whole-body and simulated muscle-specific COT for all right-sided muscles for all trunk lean conditions.

It is important to note that our simulations did not take into account several aspects affecting COT in human locomotion. Besides errors introduced by modeling simplifications and assumptions, these could include, e.g., the increased energy expenditure of the neuromuscular system associated with performing an unfamiliar ATL angle and constant external feedback about trunk lean angle. These unaccounted-for differences may explain why the simulated whole-body COT did not match the U-shaped relationship of the experimental COT. Further research is needed to represent better the potential contributions of the neuromuscular system to simulated whole-body COT in musculoskeletal simulations.

Conclusions

Our metabolic analysis results suggest that ATL is optimized to minimize COT in distance running. Musculoskeletal simulations suggest that the experimental whole-body COT reflects systematic and offsetting changes in the metabolic demands of key muscle groups, specifically the hamstrings, uniarticular hip extensors, and plantar flexors.

References

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