Dissecting the Metabolic Costs of Up- and Down-Hill Walking

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Summary

Cost models of locomotion have been used to link mechanical work to metabolic cost but do not capture the force and work demands of muscle driving energy use. Muscle energetics include "force-related costs" (heat due to activation and force maintenance) and "work-related costs" (heat and work due to active shortening/lengthening). A musculoskeletal modelling approach, involving a phenomenological energy cost model, was used to simulate muscle force- and work-related costs during sloped walking between ±15% grade. This approach was evaluated using experimental motion capture, force plate, electromyography, ultrasound, and indirect calorimetry data. Muscle force costs showed a U-shaped relationship with slope and moderate correlation with joint moments, while work costs increased linearly with slope and strongly correlated with net joint work. Our results highlight the state of the art of musculoskeletal modelling and the value of including a force-related cost term in cost models of locomotion.

Introduction

Work- and collision-based models of locomotion have been used to explain the relationship between mechanical work requirements and metabolic cost. These models do a solid job of relating mechanical work to metabolic cost at a system level but do not capture the underlying force and work demands of muscle that directly drive energy use. Energy is liberated as heat to activate muscle and maintain force production (termed "force-related costs") and as heat and work to shorten or lengthen active muscle (termed "work-related costs") [1]. Musculoskeletal modelling can be used to simulate muscle states, and these states can serve as inputs to a phenomenological energy cost model to derive total cost and partition force- and work-related costs [2]. We aimed to dissect how these individual costs contribute to total cost as humans walk on steeper uphill and downhill slopes.

Methods

Thirteen healthy subjects (5 F, 8 M) participated in this study. We collected motion capture, force plate, electromyography (lateral and medial gastrocnemius, soleus, tibialis anterior, vastus lateralis, rectus and biceps femoris, gluteus maximus), ultrasound (LG, SOL, VL), and indirect calorimetry data during sloped walking at grades of 0, ±5%, ±10%, and ±15%. A three-dimensional lower-limb musculoskeletal model [3] was driven by experimental data using OpenSim software [4], to compute muscle states that satisfy the required dynamics. Simulated muscle activations and fascicle dynamics were evaluated against measurements from the electromyography and ultrasound data. The simulated muscle states were then input into a phenomenological cost model [2] to compute total costs, which were evaluated against the indirect calorimetry data, and to partition costs into muscle force- and work-related components.

Results and Discussion

Simulated muscle activations and fascicle dynamics were qualitatively similar in shape, timing and magnitude to the experimental data. Simulated cost summed across the muscles whose states we evaluated showed a strong correlation with experimental cost (R^2 0.91) (Fig. 1A).

Muscle force costs exhibited a U-shaped relationship with slope (Fig. 1B) and were moderately correlated with mean joint moments (R^2 0.63), with unexplained variance attributed to changes in muscle operating lengths. In contrast, muscle work costs increased linearly with slope (Fig. 1C) and were strongly correlated with net joint work (R^2 0.97). Knee joint mechanics accounted for most of the variance in both costs.

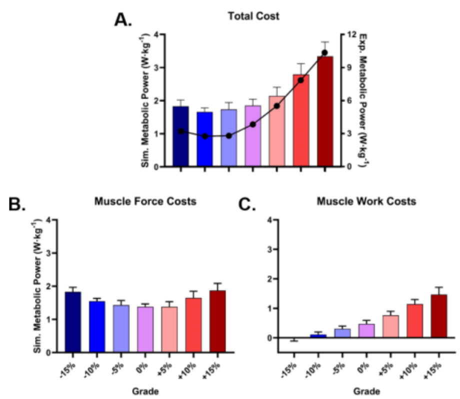

Figure 1: Simulated (bar) and experimental (line) total cost, and simulated muscle force costs and muscle work costs, across grade.

Conclusions

Compared to traditional work- and collision-based models, incorporating a force-related cost term offers a more direct and explanatory link to the mechanical demands of muscle.

Acknowledgments

Supported by FT190100129.

References

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