A MUSCLE-ACTUATED SPRING MASS MODEL FOR THE PREDICTION OF ENERGY CONSUMPTION DURING RUNNING ACROSS DIFFERENT SPEEDS AND STRIDE RATE CONDITIONS

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Summary

We present an energetic model of running resembling a muscle-actuated spring mass system that enables estimation of energy consumption related to muscle states. The model was able to predict over 80% of the variance in absolute energy consumption rates across a range of individuals when running at different speeds and stride rates.

Introduction

The rate of energy consumption during activities like running has been well characterized, however variance with physical traits (e.g., mass distribution, leg length) biomechanical traits (e.g., ground contact time, leg stiffness) and physiological traits (e.g., anaerobic thresholds) makes it difficult to predict the energy rate for an individual under different conditions [1]. The aim of this study was to combine a model of the known spring-like mechanics of running with a conceptual model of energy consumption based on a compliant muscle-tendon unit (MTU) system and assess the ability of the model to predict metabolic energy rate (power) under differing velocity and stride rate conditions.

Methods

Participants and Protocol: Nine participants (8 male, 1 female) attended three separate sessions, running at combinations of three different speeds and five different stride rates (matched to metronome) for ~4-min periods, each condition repeated on separate visits whilst measuring breath-by-breath gas analysis and biomechanical measures. Data collection is ongoing. *Data Collection & Analysis:* Metabolic rate was calculated based on gas exchange during the final minute of each period. Ground reaction forces and kinematics were measured across a 10-s period at the start and end of the trial using a force-instrumented treadmill (AMTI Tandem) and markerless motion capture system (Vicon Nexus + Theia3D). Individual leg length was determined from the motion capture data. Ground reaction forces were divided into steps and averaged across the trial period for each condition. The average ground contact time and flight time were calculated. *Model:* A two-element spring mass model [2] based on the contact time, mass of the participant and leg length was applied to estimate the vertical and horizontal (fore-aft) ground reaction force and subsequent length changes of the leg-spring across each step. The length of the leg represented the length of an 'inverse' MTU, with an active 'contractile' element that generates a compressive force on the in-series spring with appropriate force-length-velocity properties. The required activation of the active element and estimated energy consumption were then calculated across the step based on the necessary forces and length of the MTU [3] with additional terms for spring energy loss, leg swing costs and basal energy rates. Muscle length and in-series spring stiffness were optimised to scale the energetic output appropriately. We used linear regression and linear mixed models with 'participant' as a random factor to predict the variance in metabolic cost explained with the model.

Results and Discussion

The model was able to predict over 80% of the variance (R^2 = 0.814) in absolute energy consumption across all trials (Fig 1A) with a similar mean metabolic rate across stride frequencies and velocities (Fig 1B). The slope of the relationship was less than one (0.594), suggesting that the model underpredicts energy rates as they increase.

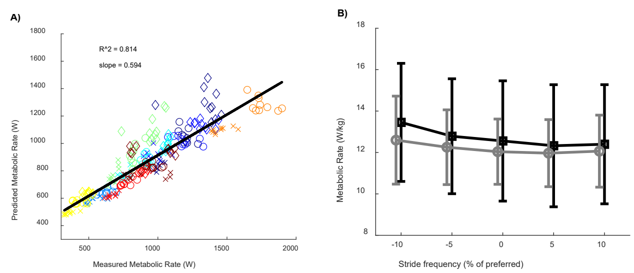

Figure 1: (A) Relationship between predicted metabolic rate (power) and the measured metabolic rate across all trials, with each participant in a different colour. (B) Mean measured metabolic rate across prescribed stride rates (black) compared to model prediction (grey)

When 'participants' were used as random factors in the analysis, the model was able to predict 94% of the variance, suggesting that further individual factors influence the metabolic rate. More work is required to understand the factors that drive individual differences in the slope of the relationships; e.g., why different individuals might have different series compliance (e.g., differences in muscle-tendon properties) and biomarkers that might allow us to predict individual variance from running biomechanics.

Conclusions

Whilst the model is conceptual in nature, it combines our general understanding of the spring-like mechanics of running with known muscle-tendon function and energetics to provide very reasonable energetic estimates related to general muscle function.

References

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