

A biophysical muscle model to predict the metabolic energy cost of movement

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Summary

The metabolic energy cost of daily movements like walking remains poorly understood to date. Musculoskeletal simulations have the potential to elucidate causal relationships between musculoskeletal properties, movement patterns, and metabolic energy consumption, but current simulations vastly underestimate changes in metabolic cost across conditions. We hypothesize that errors in predicting the metabolic cost of movements are due to using Hill-type models and energetics models, which employ phenomenological relations derived from controlled experiments that do not capture muscle operating conditions during movements. We therefore developed a biophysical muscle model that incorporates the mechanisms underlying muscle mechanics and energetics. The biophysical model better captured the metabolic cost of single-joint experiments that mimic the conditions muscles experience during movements. Next, we will incorporate this biophysical model in whole-body simulations of walking.

Introduction

The metabolic energy cost of movement relates to movement conditions (e.g. speed) and to musculoskeletal properties (e.g. body mass), yet it remains unclear how energy consumption is partitioned spatially (i.e. between muscles) and temporally (e.g. between movement phases). Predictive simulations based on musculoskeletal models have the potential to elucidate causal relationships between properties of the musculoskeletal system, movement patterns, and energetics. However, while state-of-the-art predictive simulations can yield physiologically plausible movements (e.g. gait patterns), they vastly underestimate changes in the metabolic cost across a range of movement conditions (e.g. walking speed, external load, incline, and level of asymmetry [1]). This may be because existing simulations use phenomenological “Hill-type” and energetics models, derived from experimental conditions that do not generalize to movement conditions. In contrast, biophysical models of muscle dynamics and energetics have the potential to better generalize across conditions than phenomenological models, but their ability to predict energy consumption *in vivo* has not yet been tested.

Methods

We evaluated the ability of a biophysical muscle model to predict muscle energy consumption during single-joint experiments that mimic the conditions muscles experience during movements. To this end, we used a recently proposed biophysical muscle model [2] to predict muscle energy consumption from the modelled rates of crossbridge cycling and active calcium transport. Crossbridge dynamics were interfaced with elastic tendon and skeletal dynamics, as in [2]. Model estimates of muscle energy consumption were

compared to previous data from single-joint experiments at the knee [3] and ankle [4]. In these experiments, human participants were asked to produce specified joint torques while joint angle trajectories were imposed, either for various cyclic muscle contraction frequencies [3] or various joint angular velocities [4]. We performed inverse simulations of these experiments using a simple 2D model driven by a single agonist muscle. The biophysical muscle model was compared to two commonly-used phenomenological energetics models (i.e. ‘Bhargava’ [5] and ‘Umberger’ [6] models). Model accuracy was quantified as the root-mean-square deviation (RMSD) between simulated and empirical metabolic costs.

Results and Discussion

The biophysical muscle model better captured the energetics of cyclic single-joint muscle contractions, compared with two commonly-used phenomenological models (Fig. 1). The biophysical model had a smaller deviation between simulated and empirical metabolic cost than the phenomenological models, in both types of single-joint experiments (knee: RMSD = 2% vs. 61-94%, ankle: RMSD = 1% vs. 59-87%).

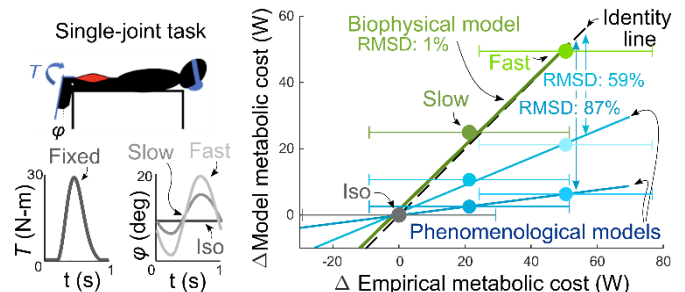


Figure 1: Biophysical model captures single-joint energetics better than commonly-used phenomenological energetics models [5,6].

Conclusions

A biophysical muscle model captured the metabolic cost of two single-joint experiments better than two commonly-used phenomenological models. Incorporating biophysical models in whole-body movement simulation may facilitate an improved understanding of the metabolic cost of movement.

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