An integrative approach to characterize the neuromechanical factors of muscle energy consumption

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Summary

The energetic cost of locomotion depends on the coordinated control of many muscles, and the energy required to contract each muscle will depend on a muscle's specific mechanical state, fiber-type physiology, and neural drive. Quantifying each of these neuromuscular properties is difficult during *in vivo* locomotion, particularly for dynamic tasks. However, using an integrative modelling and experimental approach, we characterize motor unit properties, including recruitment and fiber-type, and determine their role in muscle energy use.

Introduction

Quantifying energy consumption is critical for understanding movement strategies in health and disease. During non-steady and perturbed locomotor tasks, it is difficult to measure both individual muscle and whole-body energy consumption, which limits our understanding of the underlying biomechanics and energetics [1]. To enhance our knowledge of neuromechanical properties influencing muscle energy use, a combined modelling and experimental approach is required.

Methods

The integrative approach developed here utilizes a mathematical model informed and validated by *in vivo* experimental data on a subject-specific basis. The experimental data was obtained for isometric ankle dorsiflexion contractions. High density electromyography (OTB Quattrocento) was used to obtain motor unit properties within the tibialis anterior, while surface electromyography (Delsys Trigno) characterized co-contraction (*ie*: provided biofeedback to limit activation) in other lower limb muscles. Muscle fascicle dynamics were measured using B-mode ultrasound (Telemed ArtUs). Whole-body energetic cost was captured via indirect calorimetry (Vacumed Vistamx2). The experimental protocol consisted of ramping contractions at rates of 0.125, 0.25, 0.5, and 1 MVC s^{-1} for 5 minutes to measure energetic cost. A comprehensive mathematical model characterized muscle motor unit recruitment, excitation-activation dynamics, muscle mechanics, and energetics. We developed a predictive subject-specific motor unit model extended from [2] with data obtained from steady-state motor unit characteristics. A Hill-type model was used with parameters derived from dynamic ultrasound data during muscle contractions. Finally, the energetics were modelled at the motor unit level based on [3].

Results and Discussion

Model predictions demonstrated a strong relationship between neuromuscular properties and the energetic cost of muscle contraction. The model was able to reproduce experimental motor unit recruitment properties with changes in contraction rate (Figure 1A). Within the predictive framework, the dependence of the energetic rates on both fibre-type properties and recruitment highlighted their influence on energetic cost. Further, the model showed nonlinear increases in energetic rates from all motor units with increased contraction rate, which demonstrates the interplay between recruitment and energetic cost (Figure 1B). Predicted energetic rates were lower than experimentally measured (e_{rel}=2.52) but increased with contraction rate (77% from 0.125 to 1 MVC s^{-1}). These differences could be due to time-dependent ATP recovery processes and co-contraction not captured in the model.

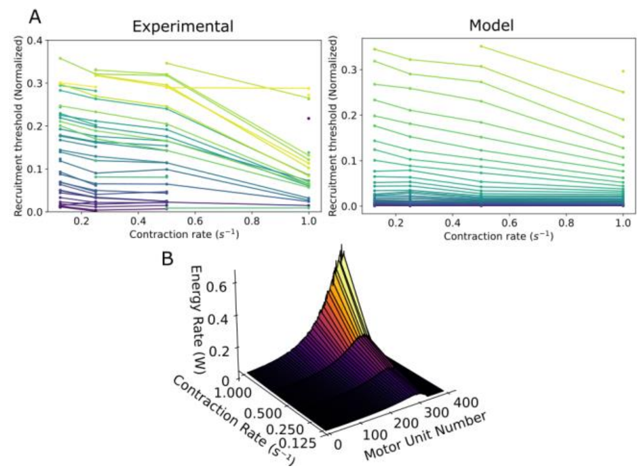

Figure 1: (A) Comparison of experimental and predicted motor unit recruitment thresholds. (B) Motor unit energetic cost predictions with varying contraction rates (0.125, 0.25, 0.5, 1 MVC s^{-1}). Energetic rates were averaged over a cycle.

Conclusions

We highlight fundamental relationships between muscle mechanical state, fibre-type physiology, neural control, and the energetic cost of muscle contraction. Further, this predictive modelling framework enables a better understanding of muscle energetics during dynamic tasks.

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