A muscle-driven simulation framework to investigate motor unit recruitment

Adrian KM Lai [1], Andrew A Biewener [2], James M Wakeling [1]

[1] Department of Biomedical Physiology and Kinesiology, Simon Fraser University, Burnaby, BC, Canada
[2] Concord Field Station, Harvard University, Bedford, MA, USA
Email: adrian_lai@sfu.ca

INTRODUCTION

Mammalian muscles are comprised of many motor units, which form the basic functional units that control human movement. Previous experimental and modelling studies investigating motor units have provided valuable insight into how a population of motor units is recruited, fire at variable rates and contribute to the overall force developed by the muscle during contractions (e.g. [1]). For example, Henneman et al. developed the size principle where during contraction, the smallest and slowest motor units are innervated first followed by subsequently larger and faster motor units [2]. Since then, many studies have expanded on this simple and efficient recruitment strategy. Yet most of these studies have been hindered by one critical drawback that limits their applicability to human movement; they are performed during isometric contractions. Muscles contract dynamically during movement and their force output is dependent not only on motor unit recruitment but also the length and velocity of the muscle fibres.

Muscle-driven simulation are capable of predicting the excitation of the motor units as well as muscle dynamics and therefore, may provide a potential avenue to examining motor unit recruitment during dynamic movement. In this study, we introduce a musculoskeletal simulation framework that is suitable for examining motor unit characteristics (e.g. recruitment threshold and firing rates) during different types of contractions and across muscles with different properties.

METHODS

A musculoskeletal model was adapted to illustrate the feasibility of using muscle-driven simulations to predict motor unit recruitment. The model consisted of one degree of freedom that represented the knee joint and was actuated by a muscle-tendon unit (MTU) Hill-type actuator that was given properties taken from the vastus lateralis. To represent a motor unit population within a muscle, we modelled the MTU with multiple contractile elements connected to a series elastic element. For this study, we assumed that ten motor unit pools were sufficient to represent the broad continuum of motorneurons innervating the muscle. Fibre type properties and maximum firing rates were assigned linearly from the slowest to the fastest motor unit. The maximal force of each motor unit was varied according to two configurations: (1) distributed relative to twitch characteristics [3], and (2) distributed uniformly.

A ramped isometric contraction was simulated over 30 secs at a rate of 10% of maximal voluntary contraction (MVC) per second. We simulated two contraction levels: 50% and 100% MVC. OpenSim was used to obtain muscle-tendon properties, MTU dynamics, moment arms and net joint torques as inputs to the simulation. Direct collocation methods were used to solve the muscle redundancy problem by formulating the optimal control problem as a non-linear programming problem and solving for muscle excitations and tendon forces [4]. Implicit formulations of the muscle-tendon dynamics and the equations of motion and explicit formulations of the activation dynamics were set as constraint equations. Each simulation was discretized into 100 mesh intervals per sec and a random initial guess was used to start the simulation. All simulations were run in MATLAB and CasADi was used to perform the non-linear optimisation and algorithmic differentiation.

A mixed, weighted cost function was minimised that consisted primarily of two components: minimising metabolic cost [5] and minimising the sum of muscle activations squared. Two weightings were simulated: (1) 90% weighting to metabolic cost (J_{mixed}), and (2) 100% weighting to muscle activations (J_{act}). To illustrate the potential use of the framework for dynamic movement, we used predicted time-varying motor unit recruitment during cycling at 80 RPM.

RESULTS AND DISCUSSION

On average, the simulations took ~4 mins to converge to an optimal solution (constraint tolerance = 1e-7).

During isometric contractions at both 50% and 100% MVC, the weightings for the mixed cost function and the force distribution configuration influenced the recruitment and firing rate patterns of the motor units. For example, when the cost function weighted metabolic cost over muscle activation, the recruitment and firing rate patterns were consistent with size principle and the onion-skin control scheme (Fig. 1(top)). In contrast, when muscle activation was weighted, all motor units were recruited and decruited simultaneously. In addition, when the force was distributed based on physiological twitch characteristics compared with a uniform distribution (Fig. 1(bottom)), the recruitment of more motor units was favoured over increasing firing rates. These differences in motor unit patterns are similar to the observed differences in motor unit patterns between muscles of different physiological properties.

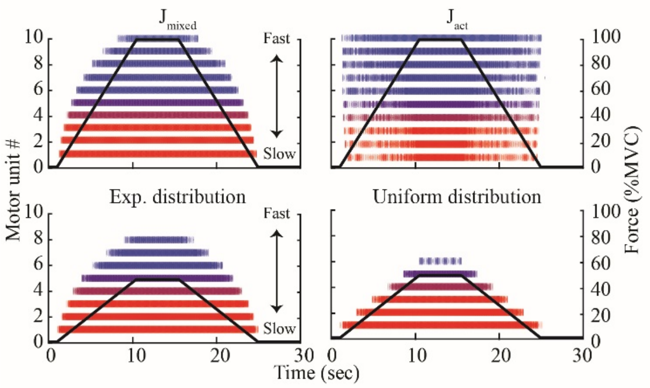

Figure 1: Recruitment and firing rate of motor unit pools and the total force generated during a ramped isometric contraction at 100% MVC varying cost function (top), and 50% MVC varying max force distribution (bottom).

We used J_{mixed} cost function and twitch characteristic force distribution to simulate motor unit recruitment patterns across 5 cycles of cycling at 80 RPM (Fig. 2). The predicted patterns were consistent with the orderly recruitment of motor units at slow contraction speeds.

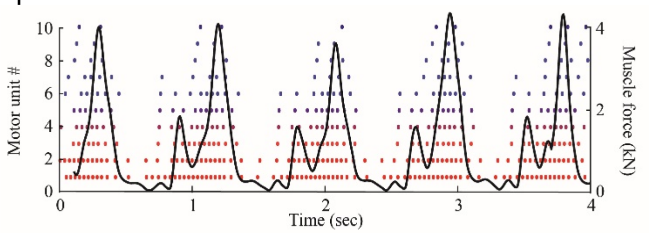

Figure 2: Motor unit patterns and total force generated across 5 cycles of cycling at 80 RPM.

CONCLUSIONS

Current studies investigating motor unit recruitment have been largely restricted to isometric contractions. The use of muscle-driven simulations to reverse engineer the recruitment and firing rate patterns with varying muscle properties and contraction types illustrate the potential to extending research beyond static contractions and predict motor unit recruitment that is directly applicable to how muscles coordinate human movement.

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