POWER AUGMENTATION IN A COMPLIANT MUSCLE-TENDON SYSTEM

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INTRODUCTION

In a compliant muscle-tendon (MT), peak power output can exceed that of the muscle alone during contractions against inertial loads. In the early stages of the contraction, the series tendon is stretched, storing energy; in the later stages, this stored strain energy is released and aids in the acceleration of the mass. This stretch and recoil of the tendon essentially decouples in time the production of the mechanical work by the muscle and the delivery of this work to the load [**1**]. A theoretical study exploring this phenomenon estimated that maximum achievable power amplification should approach twice that of peak isotonic power [**2**]. However, few *in vitro* studies have been undertaken to examine real-world muscle-tendon performance during contraction against an inertial load. The goal of this study was to determine the maximal possible power amplification for muscle-tendon operating against varying inertial loads. We hypothesized that peak power output during contractions against an inertial load would exceed peak isotonic power of muscle alone, and that magnitude of power amplification would be load dependent.

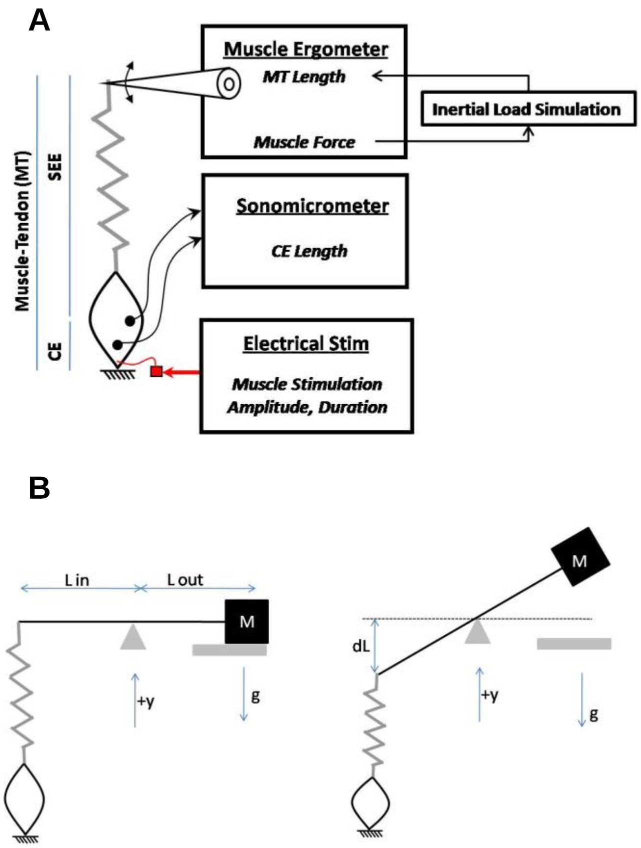

Figure 1. A diagram of the experimental setup (A) and the inertial-mass simulation used to control the ergometer position during contraction (B). MT force was sampled in real-time from the muscle ergometer and fed into the inertial load simulation, where the change of position (dL) was calculated using equations of motion. Position of the muscle ergometer was then controlled based on dL. Lin/Lout =1 and $g = 9.8$ m/s^2.

METHODS

We tested four bullfrog plantaris muscle-tendons *in vitro*. We attached a nerve-cuff to the sciatic nerve and stimulated the muscle using a 4V 100 ms pulse train (.2 ms pulses, 100 pps). For each preparation, we used a muscle ergometer to simulate an inertial load lever system (**Figure 1**). Ergometer length was controlled using a feedback system involving real-time force samples (1000 Hz) from the muscle ergometer. These force values were used in conjunction with the equations of motion of the simulated mechanical system to calculate change in lever position, which was then used to control ergometer position. Nine simulated loads were tested, ranging from a normalized weight (W) of ~0 to 1.0*MT F_{max}. We recorded MT force and length from the ergometer and muscle fiber length from surgically implanted sonomicrometry crystals. To calculate contractile element (CE) length we multiplied muscle fiber length by a gearing factor (~1.5) to account for the effects of muscle pennation. Power was calculated as the product of force and velocity. We integrated the positive regions of the power curves and divided by muscle mass to obtain mass-specific MT and CE positive work. Peak isotonic power was calculated from an experimentally determined force-velocity curve using a standard “after-load” protocol. We computed a power amplification ratio by dividing the peak MT power from each contraction on a simulated load by the peak isotonic power.

RESULTS AND DISCUSSION

Both the power ratio and positive work output varied significantly within the range of inertial loads explored ($p<0.0001$). A peak power ratio of 1.81 ± 0.19 (unitless) was achieved at W = 0.5 (**Figure 2, black)**. The peak isotonic power of the muscle alone was 235 ± 5.5 W/kg. Total positive work output was also greatest at this intermediate load (W = 0.5) and was 20.8 ± 2.9 J/kg (**Figure 2, red**).

The sample contraction (W = 0.5) shown in **Figure 3** illustrates the mechanism of power amplification. Energy storage can be visualized by comparing CE and load power traces (**Figure 3, C**). In the first half of the contraction, the CE produces power before any movement of the load (**Figure 3, B**). This work is stored as elastic strain energy within the stretched tendon. In the second half of the contraction, elastic strain energy is released, allowing power delivered to the load to exceed power produced by the muscle CE.

CONCLUSIONS

These results indicate that during the acceleration of an inertial load, compliant muscle-tendon systems can produce power outputs that exceed the muscle’s peak isotonic power. Additionally, this capacity for power amplification is load dependent. There is an optimal inertial load for maximally exploiting muscle-tendon compliance. At W = 0.5, a balance between the tendon’s ability to absorb muscular work and release this work to the load is achieved. This load not only resulted in the peak power ratio, but also the maximal positive work output by the muscle. Further studies might examine real-world behaviors where such power amplification is seen, such as frog jumping, to see if systems in nature have evolved to operate near optimal inertial loads.

REFERENCES

1. Roberts, T.J. et al. *J Exp Biol* **206**, 2567-2580, 2003.
2. Galantis, A. et al. *Proc. R. Soc. Lond. B* **270**, 1493-1498, 2003

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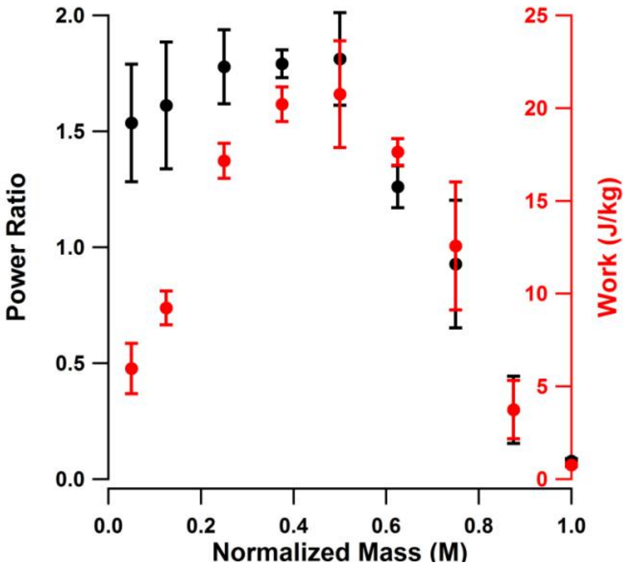

Figure 2. The mean ± SD of power ratio (black) and positive work output (red) for each of the inertial loads from the four preparations.

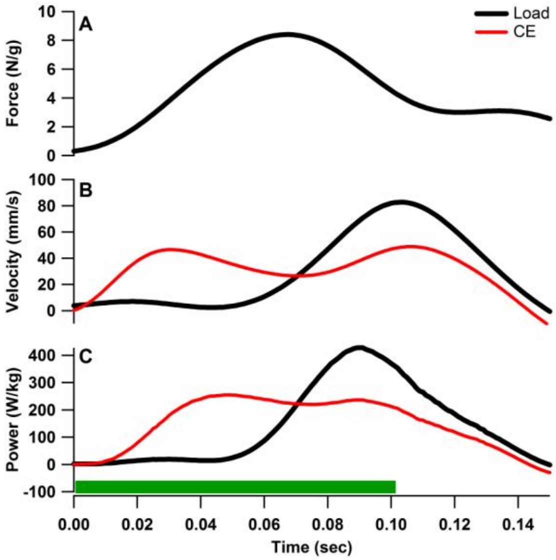

Figure 3. Representative (**A**) force (N/g), (**B**) load and CE velocity (mm/s), and (**C**) load and CE power (W/kg) versus time (sec) curves for ideal inertial load conditions (W = 0.5). The green bar represents the duration of muscle stimulation.