Muscle activation timing influences muscle-tendon mechanical performance during cyclic contractions

Gregory S. Sawicki[1] Emanuel Azizi[1] and Thomas J. Roberts[1]

[1]Dept. of Ecology and Evolutionary Biology, Brown University, Providence, RI, USA
E-mail: gsawicki@brown.edu

INTRODUCTION

During cyclic movements (e.g. running, walking) muscle fibers at distal joints can produce force nearly isometrically, performing little mechanical work, while series elastic tendons store and return elastic energy in the interaction with the external environment (Roberts, Ishikawa). The 'tuned' elastic behavior of muscle-tendon likely requires a specific pattern (timing and amplitude) of muscle force output (Ettema). The goal of this study was to determine how the timing of muscle activation onset influences the mechanical performance of the contractile element (CE) in a compliant muscle-tendon (MT) undergoing a fixed sinusoidal length change. We hypothesized that as activation phase advanced from initial MT lengthening (i.e. 0% phase) the CE would shorten more and perform more positive mechanical work.

METHODS

We tested six bullfrog (*Rana catesbeiana*) plantaris-Achilles tendons *in vitro*. For each preparation, we used a muscle ergometer to drive the MT through a fixed sinusoidal length change (± 4mm, 4 Hz) (**Fig. 1**) We set the rest length of the MT to correspond with the onset of passive MT force from an experimentally determined force-length curve. We attached a nerve-cuff to the sciatic nerve and stimulated the muscle using a 4V, 100 ms pulse train (0.2 ms pulses, 100 pps) with activation phases of -12.5%, 0% (onset of MT lengthening),12.5%, 25%, 37.5% and 50% of the cycle period (**Fig. 1**). We also collected a control condition with no muscle stimulation (NS).

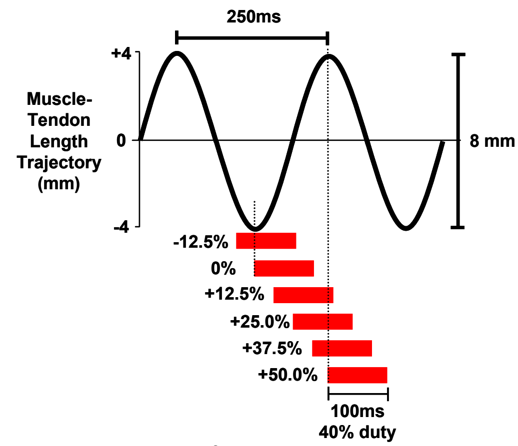

Figure 1. Schematic of experimental conditions. An ergometer maintained a sinusoidal (4Hz; ± 4mm) muscle-tendon length trajectory. We stimulated the muscle for 100 ms with activation phases ranging from -12.5% to 50% of the cycle period (red bars).

We recorded (1) MT force and length from the ergometer and (2) muscle fiber length from surgically implanted sonomicrometry crystals. To calculate CE length change we multiplied muscle fiber length by a gearing factor (~1.6) to account for the effects of muscle pennation. Series elastic element (SEE) length changes were computed as the difference between MT length (from the ergometer) and CE length (from sonomicrometry). Power was calculated as the product of force and velocity for each element. We integrated the positive regions of the power curves and divided by MT mass to obtain mass-specific MT and CE positive work over a cycle. We used a repeated measures ANOVA to determine if there were differences in CE length change over the MT shortening phase, CE positive work, MT peak force and MT peak power between activation phase conditions.

RESULTS

Activation phase had a significant effect on CE length change (ANOVA, p<0.0001). During MT shortening (50%-100% of the contraction cycle), the CE lengthened only slightly in the 0% phase condition (+0.3 ± 0.1 mm (mean ± s.e.)) but shortened considerably (-7.0 ± 0.4 mm) in the 50% phase condition (**Fig. 2C, 2D**). MT peak force was markedly higher (+324%) in the 0% phase condition when compared to the 50% phase condition (ANOVA, p<0.0001) (**Figs. 2A-C**). As a result, CE positive mechanical work increased then decreased as activation timing advanced from 0% to 50% phase (**Fig. 2E**). MT peak power was maximum (497.3 ± 18.6 W/kg) in the 0% phase condition and decreased significantly as phase advanced (ANOVA, p<0.0001) (**Fig. 2F**).

CONCLUSIONS

These results indicate that muscle activation timing is critical for exploiting the mechanical and energetic benefits of tendon elasticity. In a ‘tuned’ MT (i.e. 0% activation phase) effective tendon recoil allows maximum MT peak mechanical power to be achieved with very little CE mechanical work. These findings could be applied to improve the neuromechanical design of artificial muscle-tendon actuators for lower-limb powered orthoses and prostheses.

REFERENCES

Roberts, T.J. et al. (1997). *Science*, 275(5303):1113-1115.

Ishikawa, M. et al. (2005). *J Appl Physiol*, 99(2):603-608.

Ettema, G.J.C. (1996). *J Exp Biol*, 199(Pt. 9):1983-1997.

ACKNOWLEDGEMENTS

Supported by NSF 0642428 to *TJR*.

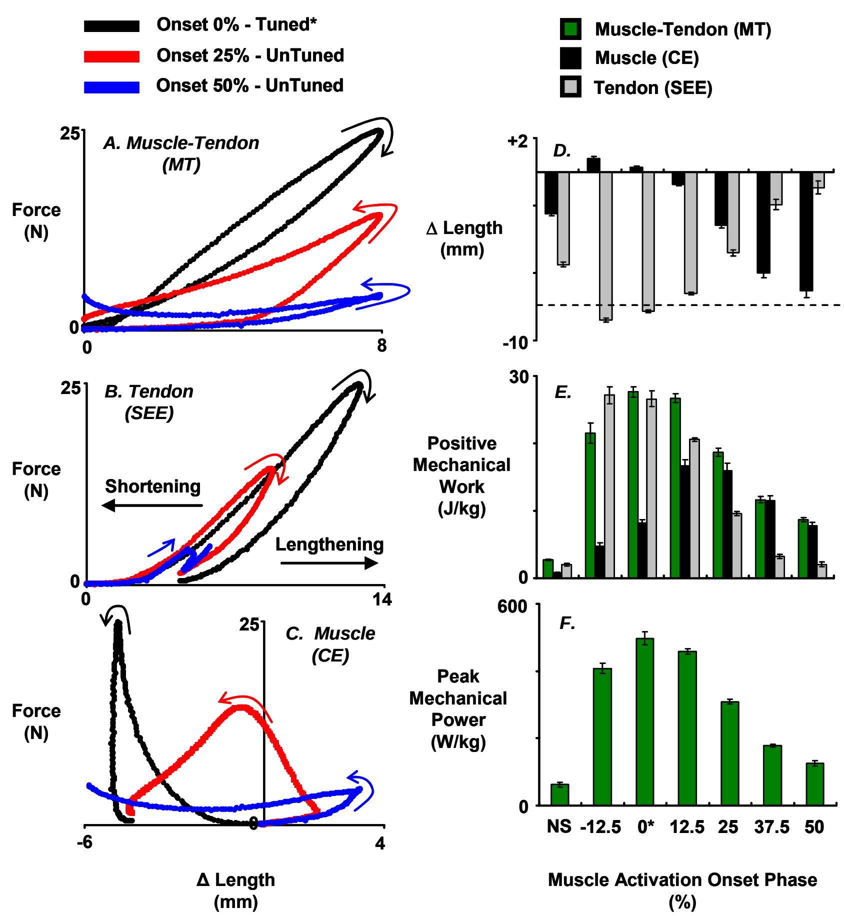

Figure 2. (**Left Panel**) Force (N) versus length (mm) plots for the (**A**) muscle-tendon (MT) (**B**) tendon (SEE) and (**C**) muscle (CE) during one sinusoidal contractile cycle (0%-100%). Three activation phases (black=0%; red=25%, blue=50%) are plotted for a single *in vitro* muscle-tendon preparation. Negative length changes indicate shortening. Colored arrows indicate the time evolution of force-length state. Counter-clockwise loops indicate net positive work. (**Right Panel**) (**D**) Length change over 50%-100% of the MT length change cycle for the CE (black) and SEE (gray). Negative values indicate net shortening. Dashed horizontal line indicates MT length change (-8mm). (**E**) Mass specific positive mechanical work (J/kg) over 0%-100% of the MT length change cycle for the MT (green), CE (black) and SEE (gray). (**F**) Mass-specific (W/kg) peak mechanical power over 0%-100% of the MT length change cycle. In all subplots bars are mean ± standard error for six preparations for each muscle activation onset condition (-12.5%-50% phase) and the control (NS) condition. In the 0% phase condition the muscle stimulation onset coincides with initial MT lengthening (see Fig. 1).