Effect of Waveform Type on Ex Vivo Sheep Tendon Hysteresis

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Summary

In this study, we measured the medial gastrocnemius and plantaris tendon force- and length-time histories during sheep locomotion and replicated the *in vivo* force-time histories during *ex vivo* testing using a material's testing machine. For comparison with the replicated *in vivo* force-time histories, we also used sinusoidal and triangular waveforms, matching the *in vivo* loading range and frequency, to test tendon mechanical properties. The triangular waveform consistently showed lower hysteresis values than the replicated *in vivo* force-time histories and the sinusoidal waveform. Differences in peak loading rates may explain the systematic differences in *ex vivo* tendon hysteresis for the different imposed loading conditions, but cannot explain the differences between hystereses measured *in vivo* and *ex vivo*.

Introduction

Previous studies have reported that tendon hystereses measured *in vivo* were substantially greater than those measured *ex vivo* [1]. *In vivo* hystereses were shown to vary greatly (2-45%) with some values even reaching 55% [2,3]. *Ex vivo* studies consistently report lower hysteresis values, averaging around 10% [4]. *Ex vivo* experiments are typically performed using material's testing machines with sinusoidal or triangular force-time waveforms [5], which do not reflect the muscle/tendon force-time histories obtained during *in vivo* locomotion. Variations in loading rates have been suggested as a potential explanation for the observed differences between hystereses obtained *in vivo* and *ex vivo* [6]. Simulating *in vivo* force-time curves during *ex vivo* testing may provide insight into the discrepancies between results obtained *in vivo* and *ex vivo*. This study was aimed at determining *ex vivo* tendon hystereses when using different force-time waveform conditions. We hypothesized that *ex vivo* hystereses measured by replicating the *in vivo* force-time curves would be greater than the hystereses obtained using sinusoidal and triangular waveforms.

Methods

Ex vivo data were collected from four sheep. Experiments were conducted using an Instron material's testing machine, which measured the force and elongation of the medial gastrocnemius (MG, N = 4) and plantaris (PL, N = 3) tendons. The *in vivo* tendon forces obtained during walking at varying speeds (0.7, 1.3, and 2 m/s) and inclinations (0°, 3°, and 6°) were programmed into the Instron machine to replicate the previously measured forces during free sheep locomotion. Sinusoidal and triangular force profiles matching the *in vivo* peak forces and frequencies were also programmed into the testing machine (Figure 1). Tendon hystereses were calculated from the loading and unloading phases and averaged for three consecutive step cycles. Peak loading rate was determined as the first-time derivative of the force-time histories.

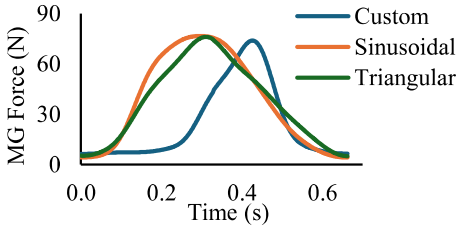

Figure 1: Medial gastrocnemius (MG) tendon force for the *in vivo* (blue), sinusoidal (orange), and triangular (green) waveforms. The example shown is for walking at 2 m/s and 6° of inclination.

Results and Discussion

MG tendon hystereses were lower than PL hystereses. PL forces were greater than MG forces, while tendon strains did not differ between muscles. MG and PL tendons consistently had the smallest hystereses with the triangular waveform (Table 1). The replicated *in vivo* waveform had greater peak loading rates than the sinusoidal and triangular waveforms. Differences in peak loading rates between waveforms may account for variations in hystereses.

	In vivo	Sinusoidal	Triangular
MG	15±3%	14±3%	12±3%
PL	18±2%	17±1%	14±1%

Table 1: MG and PL *ex vivo* tendon hystereses for the *in vivo* loading condition, sinusoidal, and triangular waveforms.

Conclusions

We conclude from the results of this study that force-time waveforms affect *ex vivo* hystereses in a systematic manner.

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