

SPRING-LOADED ANKLE EXOSKELETONS REDUCE METABOLIC COST AND ALTER GASTROCNEMIUS FASCICLE BEHAVIOUR IN HUMAN HOPPING

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INTRODUCTION

The metabolic cost of hopping is reduced with the assistance of an exoskeleton that places a spring in parallel with the entire leg [1]. Energy stored and returned by the spring replaces work that otherwise would be done by muscle-tendon units (MTU). Similarly, exoskeletons bridging only the ankle joint can replace work from ankle plantar-flexors [2]. Therefore, the first aim of this study was to test if a spring-loaded ankle exoskeleton could reduce the rate of metabolic energy consumption during hopping. It was hypothesized that net metabolic power would be reduced when an ankle exoskeleton with a spring assisting plantar-flexion was used due to less work being done by the plantar-flexor muscles.

However, an alteration in joint level mechanics due to an exoskeleton could affect muscle fascicle and series elastic element (SEE) behavior in the plantar-flexors. The interaction between fascicles and SEE in the gastrocnemius (GM) has been shown, using ultrasound (US) imaging, to result in largely isometric behavior of fascicles during the stance phase of running [3]. This is beneficial for reducing the energetic cost of muscle contraction and promotes storage and return of elastic energy in the SEE. The use of an exoskeleton could perturb this optimal fascicle-SEE interaction. By reducing the required contribution of the plantar-flexors to joint moments, the exoskeleton might lower force across the GM MTU. With less force acting through the SEE, the SEE length change pattern and thus, the fascicle length change pattern, may be altered, resulting in a sub-optimal interaction between the two. Two possible scenarios were considered for reduced force across the SEE: 1) muscle activation is unaltered causing fascicles to shorten and do work 2) Activation is reduced allowing isometric behavior at longer fascicle lengths.

The primary aim of this study was to assess the effects of a spring loaded ankle exoskeleton on gastrocnemius muscle fascicle and SEE behavior

during hopping. It was hypothesized that in naïve subjects, muscle activation would not be adjusted, causing fascicles to shorten and do work.

METHODS

At present, preliminary data from one subject (male, age = 32 yrs, height = 1.7 m, mass = 63 kg) has been collected. The subject performed bilateral hops at a frequency of 2.2 Hz for four minutes wearing bilateral ankle exoskeletons. In one condition the exoskeletons had a linear spring of stiffness $5.1 \text{ kN}\cdot\text{m}^{-1}$, fitted in parallel with the ankle plantar-flexors and with a moment arm about the ankle joint of 0.14 m. This produced a torsional stiffness of $1.75 \text{ Nm}\cdot\text{deg}^{-1}$.

Ground reaction force data were recorded (1080 Hz) from two force platforms (BERTEC, USA) synchronously with kinematic data (120 Hz, VICON, USA) and longitudinal US images (50 Hz) of medial gastrocnemius muscle fascicles [3]. US images were captured using a 128 element linear array probe operating in B-mode at 8.0 MHz (TELEMED, Lithuania).

Inverse dynamic analyses were performed to compute ankle joint moments and powers. The force in the spring was measured with a tension load cell and converted to an ankle moment by multiplication by the moment arm. GM fascicle lengths were determined by manually digitizing the end points of a fascicle in the sequences of US images. Fascicle pennation angle was determined as the angle between the fascicle and the superficial aponeurosis of the GM. Whole GM MTU length was determined from kinematics and the SEE length was then calculated as the MTU length minus the fascicle length after it had been corrected for pennation angle [3].

Oxygen consumption ($\dot{V}O_2$) was measured during standing and hopping trials using a portable metabolic system (VIASYS, Germany). $\dot{V}O_2$ was averaged over 30 s intervals and net metabolic powers were computed for hopping trials.

RESULTS

These preliminary results indicate that springs in parallel with the ankle joints can reduce the average positive mechanical power output required of the plantar-flexor MTU's by 58%. Also, they reduced net metabolic power by 14% (Figure 1). Figure 2 shows that GM fascicle length change demonstrated isometric behavior without the spring and a pattern of shortening and re-lengthening with the spring. The average fascicle length was 25 mm without the spring and 28 mm with the spring.

DISCUSSION

As hypothesized, there was a reduction in net metabolic power when a spring was added to assist plantar-flexion. This appeared to be a result of the exoskeleton contributing to average power output at the ankle and thus, reducing the contribution of the plantar-flexor muscles.

Furthermore, the addition of the spring altered the length change trajectories of the GM MTU, SEE and fascicles. Shortening and re-lengthening of the fascicles was observed in the spring condition. As hypothesized this could be a result of reduced force across the MTU (due to some of the load being borne by the spring) whilst muscle activation remained unaltered. This situation is undesirable as the muscle fascicles appear to be doing work which is metabolically more expensive and thus the maximum potential benefit of the exoskeleton might not be achieved. However, despite sub-optimal fascicle behavior in the GM there was a large reduction in net metabolic power. Therefore, further analysis will include the knee and hip joint mechanics in an attempt to further explain these results.

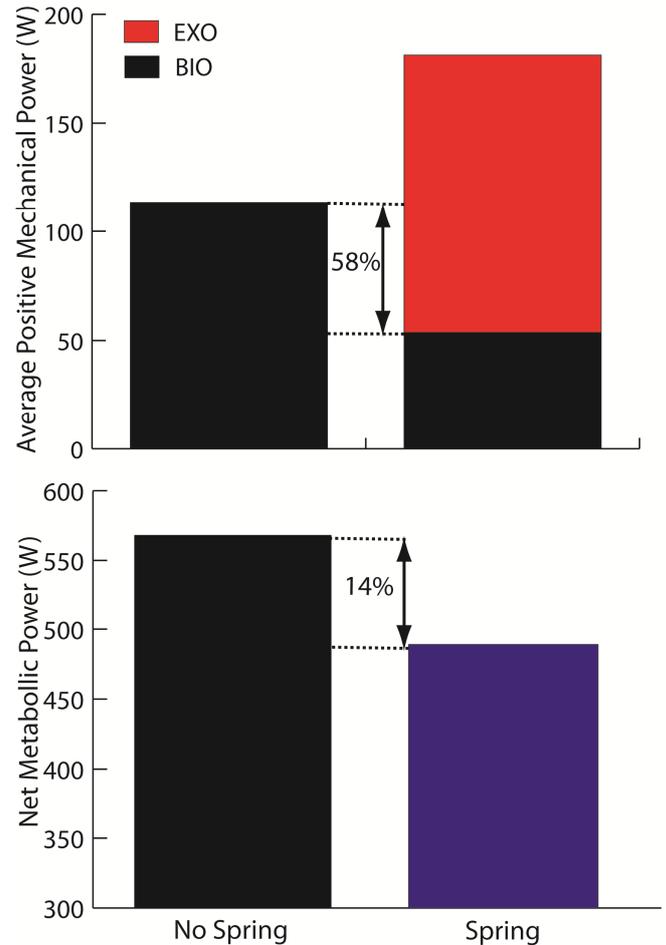


Fig 1. Average mechanical ankle power and net metabolic powers for the two conditions. EXO is the contribution of the spring and BIO shows the biological ankle muscle contribution.

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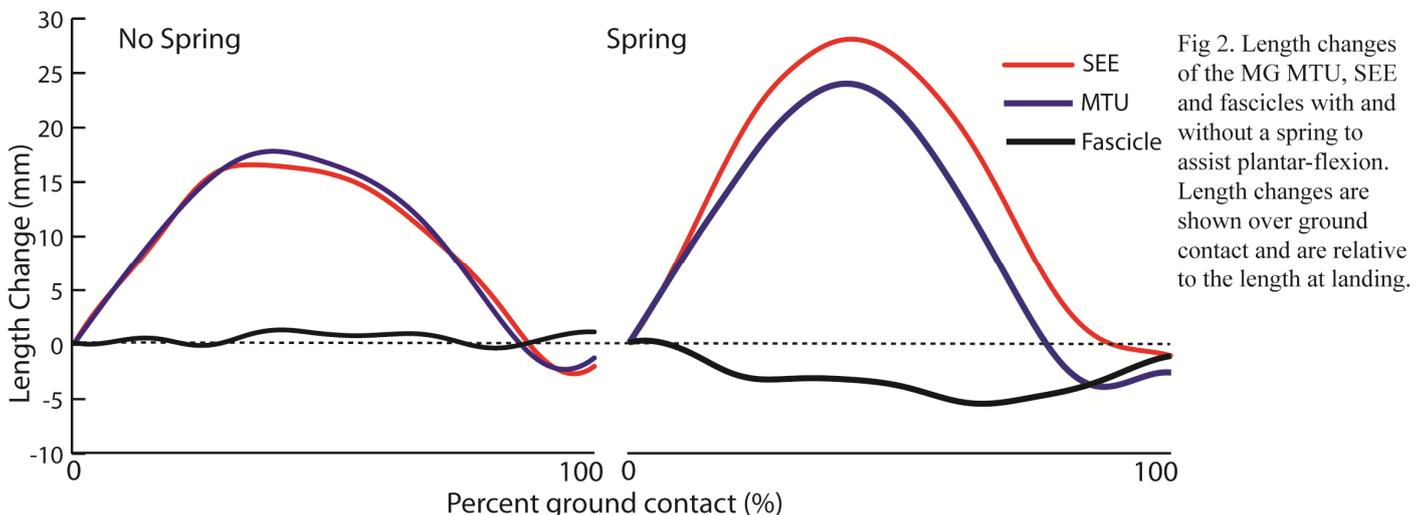


Fig 2. Length changes of the MG MTU, SEE and fascicles with and without a spring to assist plantar-flexion. Length changes are shown over ground contact and are relative to the length at landing.