The Effects of Wearing a Spring-Loaded Ankle Exoskeleton on Soleus Muscle Mechanics during Two-Legged Hopping in Humans

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Motivation/State of the Art

Assistive exoskeletons have the potential to aid locomotor recovery and restore walking function in neuro-muscularly and musculo-skeletally impaired individuals (e.g. post-stroke or spinal cord injury). They also may be used to augment locomotor performance in healthy individuals by reducing the metabolic cost of locomotion or reducing skeletal loading. Whilst these devices have been shown to be effective in replacing joint moments and powers, little is known about how they influence the underlying muscle function.

Neuro-muscularly intact humans rely on ankle plantar-flexor muscles to provide a considerable proportion of the mechanical work required for locomotion (40-50%)[1]. The main plantar-flexors (Gastrocnemius and Soleus) insert on the calcaneous via the compliant Achilles tendon. The series compliance provided by the Achilles allows these muscles to contract relatively isometrically during most of stance in walking and running, whilst the tendon stores and returns elastic energy [2]. This is an efficient way for the muscle-tendon units to produce force and provide work at the ankle joint. Thus, these mechanisms help to reduce the metabolic energy required for locomotion.

The use of spring-loaded ankle exoskeletons could reduce the required contribution of the plantar-flexors to ankle joint kinetics during cyclic motions but, they might also perturb the 'tuned' interaction of muscle and tendon. The purpose of this study was to investigate the effects of using spring-loaded ankle exoskeletons on soleus muscle mechanics during a cyclic motion (two-legged hopping).

Methods

Seven healthy male participants hopped at a range of frequencies (2.2, 2.5, 2.8 & 3.2 Hz) in 3 conditions: with bilateral spring-loaded ankle exoskeletons (SE); without exoskeletons (NE); & with bilateral spring-less exoskeletons (NS). The exoskeletons consisted of a carbon fiber cuff around the upper calf connected to a carbon fiber foot segment and training shoe by aluminium struts and a freely rotating joint on the medial and lateral sides. When the spring was attached, it connected the heel of the foot segment to the dorsal aspect of the cuff with the resting length set at an ankle angle of 127°. The linear stiffness of the springs was 5 kN/m.

A stationary instrumented treadmill was used to record ground reaction forces (Bertec, 980 Hz). Motion capture (Vicon, 120 Hz) was used to determine kinematics for a four segment (Pelvis, thigh, shank & foot) inertial model of the right leg. These were combined in a typical inverse dynamics analysis to compute ankle, knee and hip joint moments and powers using Visual 3D software (C-motion Inc.). EMG data were also recorded for soleus, gastrocnemius and tibialis anterior.

B-mode ultrasound images of Soleus muscle fascicles were recorded synchronously with the kinematics & kinetics using a linear array 128 element transducer (Telemed, 50 Hz). Manual digitization of these images provided a measurement of soleus fascicle length and pennation angle. Soleus muscle-tendon unit (MTU) lengths were calculated from regression equations using the ankle angle as input. A simple geometric model was then used to calculate series elastic element (SEE, the elastic tendon & aponeurosis in series with soleus) lengths. Forces in the SEE were modeled as the flexion-extension ankle joint moment divided by the Achilles tendon moment arm, multiplied by the relative physiological cross sectional area of soleus within the plantar-flexors. An adjustment of this force for pennation angle yielded the fascicle forces. Fascicle and SEE velocities were multiplied by their respective forces to give fascicle and SEE powers. Powers were integrated to calculate the positive and negative work done by each and this was divided by time to obtain average positive power of the fascicle (P^{+}_{FAS}) and SEE (P^{+}_{SEE}).

Results

The results presented are for hopping at 2.5 Hz only. The use of spring-loaded ankle exoskeletons resulted in reduced force production by soleus and reduced average length of the SEE and MTU (Table 1). This was associated with lesser soleus EMG magnitude just after landing and a reduced positive power contribution from the SEE (Table 1, Fig 1d).

Discussion

When hopping in assistive spring-loaded ankle exoskeletons, participants reduced the contribution of the soleus MTU to overall power production by reducing muscle activation in the early part of ground contact and thus reducing muscle force production. This limited the absolute lengths to which the SEE could be stretched (less force equates to less stretch) and thus limited the storage and return of elastic energy in the SEE and the overall length of the MTU. With less energy stored and returned by the SEE, the fascicles were able to maintain a similar power output across conditions by balancing their length change and force production. It should be noted that the relative length change of the SEE was similar between conditions, indicating that the shortening of the SEE with assistance may have taken it to a non-linear region of its length-tension relationship.

The use of spring-loaded ankle exoskeletons may reduce the overall work required of the soleus MTU but it does so by reducing SEE energy storage rather than fascicle work.

[1] Farris DJ & Sawicki GS. (2012). J. R. Soc. Interface. 9: 110-118.

[2] Lichtwark et al. (2007). J. Biomech. 40: 157-164

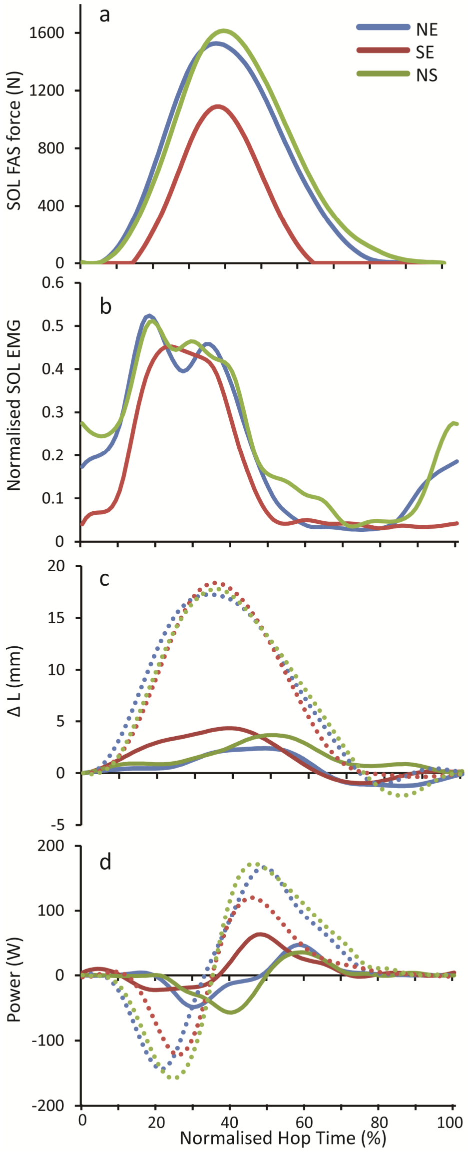

Fig 1. Soleus fascicle force (a); soleus root mean squared EMG (b); fascicle (solid) & SEE (dotted) length change (c) and power (d) over a hop. Data are group means.

Table 1. Group mean (sd) maximum soleus force; total excursion of soleus (ΔL); average length of soleus (L) and average positive power output of soleus (P^+). The latter three are broken down into fascicle (FAS), SEE and MTU.

	Max SOL Force (N)	**ΔL (mm)**			**$\bar{L}$ (mm)**			**$\bar{P}^+$ (W)**		
		FAS	SEE	MTU	FAS	SEE	MTU	FAS	SEE	MTU
NE	1623 (187)*	10 (2)	38 (11)	42 (1)	39 (3)	253 (9)*	291 (8)*	14 (2)	40 (5)*	40 (4)*
SE	1166 (194)	15 (2)	39 (6)	48 (1)	38 (4)	237 (7)	272 (6)	15 (3)	25 (3)	30 (4)
NS	1667 (119)*	9 (2)*	39 (8)	42 (2)	41 (4)	246 (8)*	285 (8)*	13 (2)	45 (4)*	40 (4)*

*Indicates significant difference from the SE condition ($P<0.05$, paired t-test)