XXIV CONGRESS OF THE INTERNATIONAL SOCIETY OF BIOMECHANICS
XV BRAZILIAN CONGRESS OF BIOMECHANICS

TRICEPS SURAE ELASTIC ENERGY UTILIZATION DURING HUMAN RUNNING WITH REARFOOT AND FOREFOOT PATTERNS

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SUMMARY
The forefoot (FF) running footfall pattern has been advocated to improve running economy compared to the rearfoot (RF) footfall pattern as a result of greater elastic energy storage and release. However, this claim has been made without previous investigation of the topic. The purpose of this study was to compare the mechanical work of the triceps surae muscle group between footfall patterns using a musculoskeletal modeling approach. Elastic strain energy was greater in the FF pattern compared to the RF pattern, but active muscle work was also greater in the FF pattern. Greater elastic energy utilization in the FF pattern, without a reduction in muscle fiber work, may not result in lower muscle metabolic energy expenditure in the triceps surae compared to the RF pattern.

INTRODUCTION
The forefoot (FF) running footfall pattern is characterized by the ball of the foot making initial contact with the ground, followed by eccentric contraction of the triceps surae to control the lowering of the heel. It has been suggested that FF running results in greater storage and release of elastic energy in the Achilles tendon [1,2], resulting in a lower metabolic cost [3,4] compared to the rearfoot (RF) footfall pattern. However, these claims have not been directly investigated, nor have previous studies found a difference in running economy between footfall patterns [1,2]. Therefore, the purpose of this study was to compare the mechanical work of the gastrocnemius (GA) and soleus (SOL) between footfall patterns using a musculoskeletal modeling approach. It was hypothesized that: 1) FF running would result in more series elastic element (SEE) mechanical work, whereas: 2) RF running would result in greater contractile element (CE) mechanical work.

METHODS
Ten natural RF runners (7 males, 3 females, age = 28±5 yrs, mass = 70.6±9.8 kg, height = 1.8±0.1 m) and ten natural FF runners (9 males, 1 female, age = 26±8 yrs, mass = 70.5±7.1 kg, height = 1.8±0.1 m) participated after providing informed consent. Participants performed 10 trials of over-ground running (3.5 $m\cdot s^{-1}$±5%) with each footfall pattern. Sagittal plane knee and ankle joint angles and ankle joint moments were averaged over the 10 trials and served as inputs to a musculoskeletal model. A model of GA and SOL muscle-tendon (MT) length and moment arm as a function of joint angle [5] was scaled to each subject. MT length was differentiated with respect to time to determine MT velocity. A two-component Hill muscle model [6] was used to determine GA and SOL muscle forces. MT, CE, and SEE powers were determined by multiplying force by velocity for each element. Mechanical work for each element was determined by integrating power with respect to time. A mixed-factor ANOVA was used to detect a difference in mechanical work of the CE and SEE and muscle force between footfall patterns and groups ($\alpha = 0.05$).

RESULTS AND DISCUSSION
In both muscles, significant group by pattern interactions were only observed for SEE work ($P<0.05$). Post-hoc analysis indicated that the FF pattern resulted in greater SEE positive and negative work in both muscles in both groups ($P<0.05$). All other statistically significant findings were pattern main effects. Thus, the following results were collapsed across groups. In the GA, FF running resulted in 18% greater peak force production ($P<0.05$) than RF running (Figure 1A). CE velocity was lower in FF running during the first half of stance than in RF running (Figure 1B), though CE velocities were similar in FF and RF running for the second half of stance. FF running resulted in greater SEE mechanical work compared to RF running ($P<0.05$) but no differences were found in CE mechanical work between footfall patterns ($P>0.05$) (Figure 1D). Therefore, the first hypothesis was supported with respect to the GA, but the second hypothesis was not. Despite greater elastic energy utilization in the GA during FF running, CE work did not differ between patterns. Thus, the elastic energy mechanism acts to enhance work production in the GA, but may not result in muscle metabolic energy savings.

In the SOL, forces, velocities, powers and work were greater during FF running compared to RF running (Figure 1). SOL peak force production was 18% greater during FF running compared to RF running ($P<0.05$) (Figure 1A). The SOL CE acted eccentrically through mid-stance of FF running, but was nearly isometric for much of the first 75% of stance in RF running (Figure 1B). CE shortening velocity in late stance was greater in FF running than RF running. FF running resulted in greater SOL SEE and CE mechanical work compared to RF running ($P<0.05$) (Figure 1D). As with the GA, the first hypothesis was supported for the SOL, but the second hypothesis was not. The SEE and CE

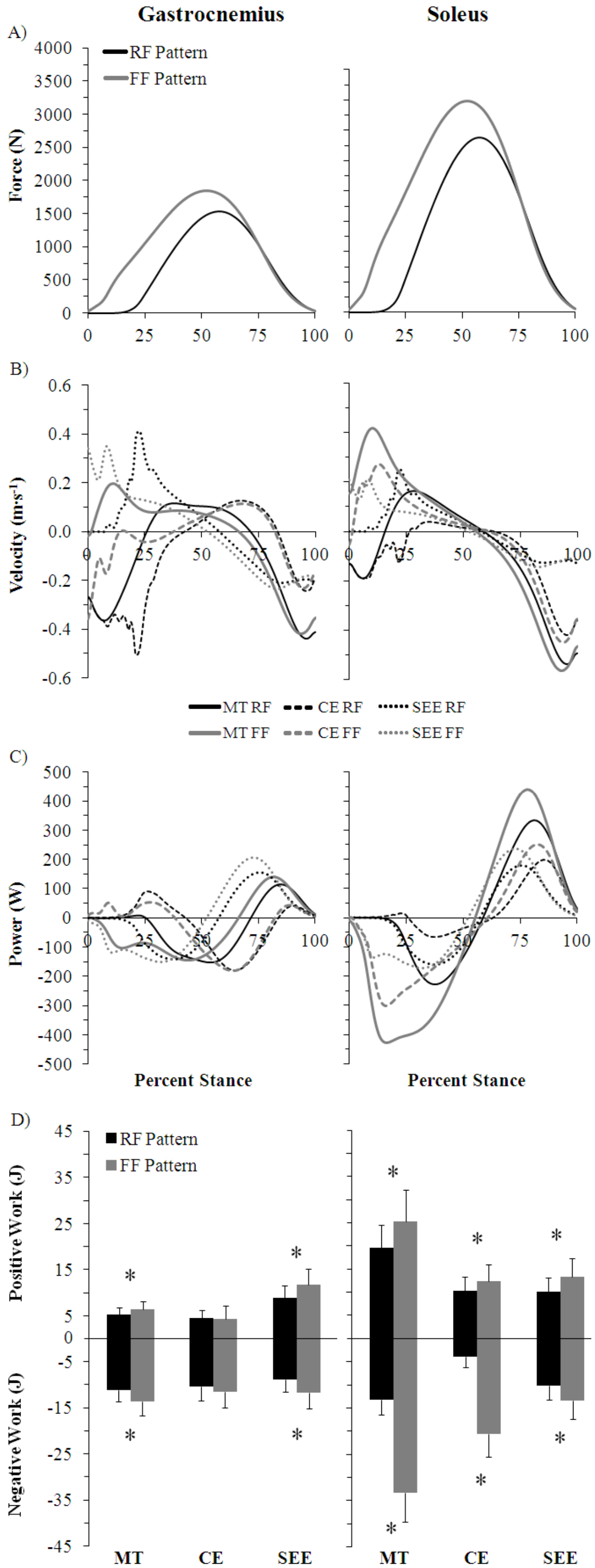

Figure 1: A) Force, B) velocity, C) mechanical power, and D) mechanical work of the muscle-tendon complex (MT), contractile element (CE), and series elastic element (SEE) in the gastrocnemius (GA) and soleus (SOL) during rearfoot and forefoot running collapsed across groups. * indicates a significant difference between footfall patterns (P<0.05).

contributed approximately equally to the greater positive SOL MT work in FF running compared to RF running. FF running also resulted in substantial negative work being done on the SOL, but more is dissipated in the CE than stored in the SEE (Figure 1D). The greater CE work in FF running suggests a greater muscle metabolic cost than in RF running, despite greater storage and release of elastic energy in the FF pattern.

CONCLUSIONS

Effective storage and release of elastic strain energy will reduce muscle fiber mechanical work if the CE operates at low contraction velocities. As a result of low fiber contractile velocities, force may be produced at a lower rate of ATP consumption [7]. Previous claims that FF running results in greater elastic energy utilization than RF running [1,2,3,4] were supported by the present study. In the GA, SEE work increased without a change is CE work during FF running compared to RF. However, in the SOL, greater SEE work in FF running was accompanied by greater CE work compared to RF running. Thus, the elastic energy mechanism serves to augment the mechanical output of the GA and SOL in the FF running pattern, but may not result in a lower metabolic cost compared to the RF pattern.

ACKNOWLEDGEMENTS

We would like to thank Ross Miller and Lex Gidley for their assistance with this study.

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