THE EFFECTS OF ADDED FOOT STIFFNESS ON SOLEUS MUSCLE FASCICLE BEHAVIOR DURING HUMAN WALKING

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INTRODUCTION

Understanding the interplay between foot and ankle structures may help uncover the fundamental principles governing the mechanics and energetics of human locomotion. The structure of the foot, for example, defines the input and output lever arms that set the mechanical advantage of the plantar flexors during push-off in walking and running [1]. The foot and ankle can also interact in a rather unintuitive manner; while the muscles and tendons crossing the ankle do positive work during push-off, the foot may counteract the ankle by absorbing or dissipating energy [2,3]. We explored this functional interplay by adding stiffness to the foot (through footwear) and evaluated ankle plantar flexor (soleus) muscle fascicle behavior and whole-body energy cost during walking.

Prior studies involving footwear have shown that a stiffer shoe increases the gear ratio (the ratio of ground reaction force lever arm to ankle plantar flexor moment arm) and also increases the mechanical energy returned by the foot [4,5]. The effects of altered shoe stiffness on ankle plantar flexor function, however, remain unclear. In theory, increased gear ratio could enhance muscle force production through slower shortening velocity [6]. In addition, increased foot energy return may decrease the mechanical work demands elsewhere (such as from structures crossing the ankle), as net work done by the body is conserved during steady-state locomotion.

We hypothesized that adding stiffness to the foot would increase soleus fascicle force while decreasing the fascicle shortening velocity and positive work. Additionally, we hypothesized that these altered muscle mechanics would decrease the whole-body metabolic energy cost of walking.

METHODS

Kinematic and kinetic gait data were collected from 5 healthy subjects (2 females and 3 males). We fabricated carbon fiber foot insoles with four different thicknesses (0.8, 1.6, 2,4 and 3.2 mm) to vary insole stiffness. Subjects walked at a fixed speed of 1.25 m/s on an instrumented treadmill under six different foot conditions (barefoot, shod, and shod with four different insole thicknesses). The shod and shod+insole conditions corresponded to an added stiffness of 16.3, 24.3, 27.1, 30.8, and 64.1 N/mm relative to barefoot, respectively. We note that the shoe and insoles were intended to *add* stiffness to the anatomical foot, and not necessarily to modify the stiffness of the foot itself.

Soleus muscle fascicle length and pennation angle during walking were estimated using B-mode ultrasound (Telemed, Lithuania), while fascicle velocity was computed by differentiating the length with respect to time. Soleus fascicle force was estimated by dividing the total ankle joint moment (computed from inverse dynamics) by the Achilles tendon moment arm, scaled to cross sectional area of the soleus relative to all plantar flexor muscles, and then corrected for pennation angle. Work done by the soleus muscle fascicle was estimated by integrating the fascicle power (product of fascicle force and velocity) over time.

The effects of different foot conditions were analyzed using a 1-way repeated measures ANOVA for the following variables: (1) peak soleus fascicle force, (2) soleus fascicle velocity at the time of peak force, (3) soleus fascicle positive work, and (4) whole-body net metabolic power (estimated from indirect calorimetry). If a significant main effect ($p < 0.05$) was detected, we used a paired t-test to perform pairwise comparisons. Because of the current low sample size, we opted not to adjust for multiple comparisons to control for Type I errors.

RESULTS AND DISCUSSION

With added foot stiffness, soleus fascicle peak force increased ($p < 0.01$). Furthermore, the fascicle velocity was decreased across several foot conditions ($p < 0.05$), with shod, shod+0.8mm, and shod+1.6mm having slower fascicle shortening velocity (at the time of peak force) compared with barefoot. These preliminary findings are consistent with previous findings that footwear can alter gear ratio [4], increasing plantar flexor force by reducing contraction velocity. Despite these changes in force and velocity profiles, there was no significant change in fascicle positive work ($p = 0.22$). Lastly, added stiffness was found to influence whole-body metabolic cost ($p < 0.05$). The barefoot condition had the least metabolic power (2.80 ± 0.38 W/kg) while the shod+3.2mm (stiffest condition) had the greatest metabolic power (3.08 ± 0.29 W/kg).

CONCLUSION

Our preliminary data indicate altered force-velocity behavior of the soleus muscle fascicle with varied foot stiffness conditions. We are currently collecting data from more subjects to confirm these initial observations.

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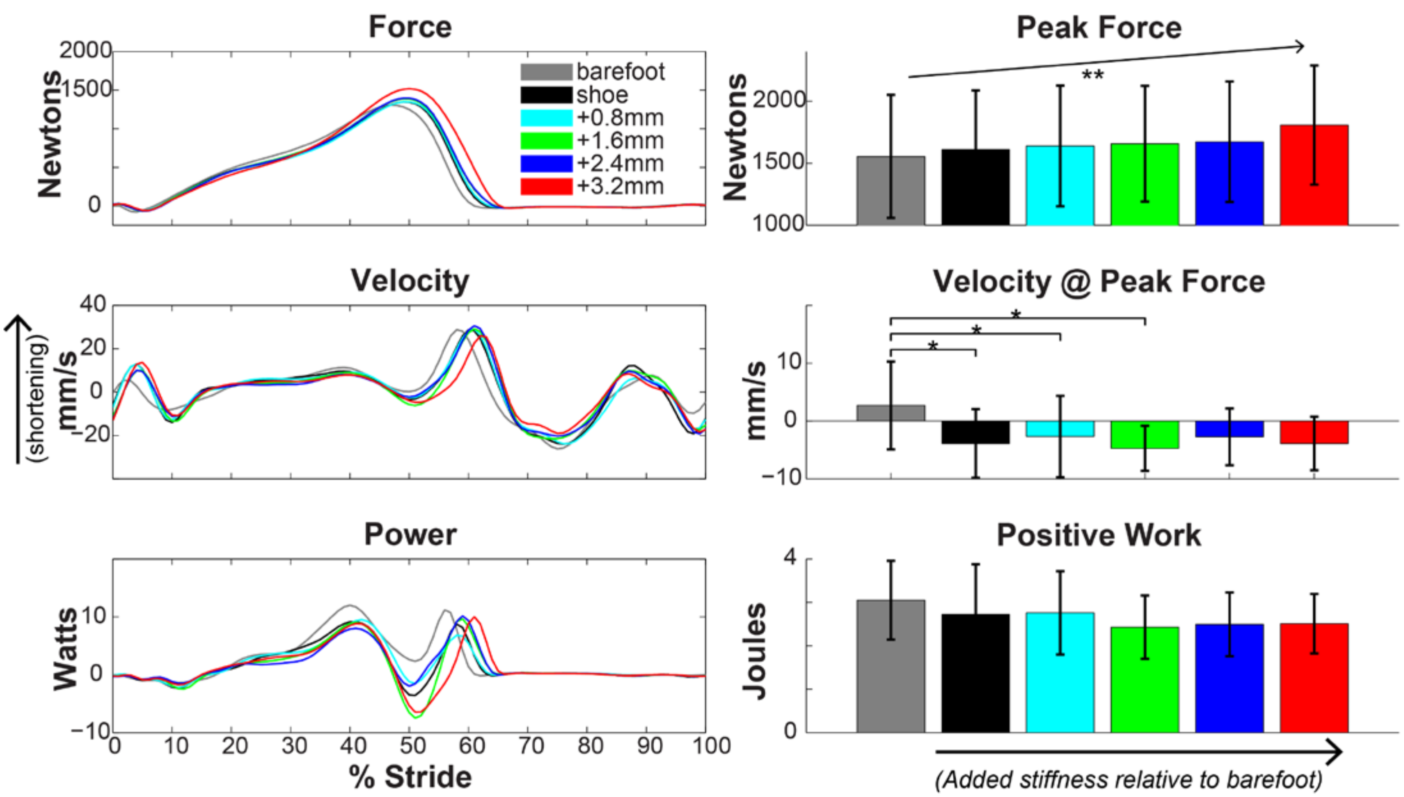

Figure: Averaged soleus muscle fascicle data (N=5) of force, velocity, and power (time-normalized to stride cycle) and magnitudes (mean ± SD) of peak force, velocity at the time of peak force, and positive work. There was a significant effect of added foot stiffness on peak force ($p < 0.01$, denoted by **), and velocity at the time of peak force ($p < 0.05$, with significant pair-wise comparisons denoted by *), but there was no significant effect on positive work ($p = 0.22$).