The Influence of Midtarsal Joint Stiffness on Walking Metabolic Cost

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Abstract

Walking is a common activity of daily living and is typically metabolically efficient. An evolutionary theory proposes that human foot arch stiffness aids in this efficiency. Many of the computational musculoskeletal models used to examine the metabolic cost of gait have failed to incorporate the complexity of the foot, modeling it as a single rigid segment. This ignores the behavior of joints like the midtarsal joint (i.e., the arch), influences the mechanics of the more commonly studied ankle and knee joints, and hampers our understanding of energetically optimal gait.

PURPOSE: To determine the influence of midtarsal joint stiffness on midtarsal joint energetics and the metabolic cost of simulated walking. **METHODS:** A two-dimensional musculoskeletal model was developed in OpenSim. A torsional spring at the midtarsal joint represented passive tissues and/or differences in shoe/orthotic properties. An optimal control problem was solved to produce muscle excitation time-series that generated walking gait for five different midtarsal joint stiffness conditions. The problem's objective function included terms for minimizing the sum of muscle excitations squared, and the discrepancies with experimental joint angles, joint angular velocities, and ground reaction forces. Midtarsal joint energetics were assessed by estimating the work performed about the joint. The metabolic cost of the stance phase of walking was estimated using modeled muscle behavior. **RESULTS:** The magnitude of positive, negative, and net work performed about the arch and the estimated metabolic cost of stance generally decreased with increasing midtarsal joint stiffness. **CONCLUSION:** Arch stiffness influences the metabolic cost of simulated walking.

1. Introduction

- The stiffness of the human foot's arch is thought to aid in efficient bipedal locomotion [1].
- Models used to study the metabolic cost of walking have traditionally ignored the foot's arch.
- This study examined the role of midtarsal joint (i.e., arch) stiffness on walking metabolic cost of transport.

2. Methods

- An optimal control problem minimized the sum of muscle excitations squared, and discrepancies with joint angles, joint angular velocities, and ground reaction forces from *in vivo* walking data [2].
- The midtarsal joint torsional spring stiffness value was varied to represent a range of experimental values [2].
- The metabolic cost of transport for the support leg muscles during stance was estimated using modeled muscle behavior [3].

3. Model

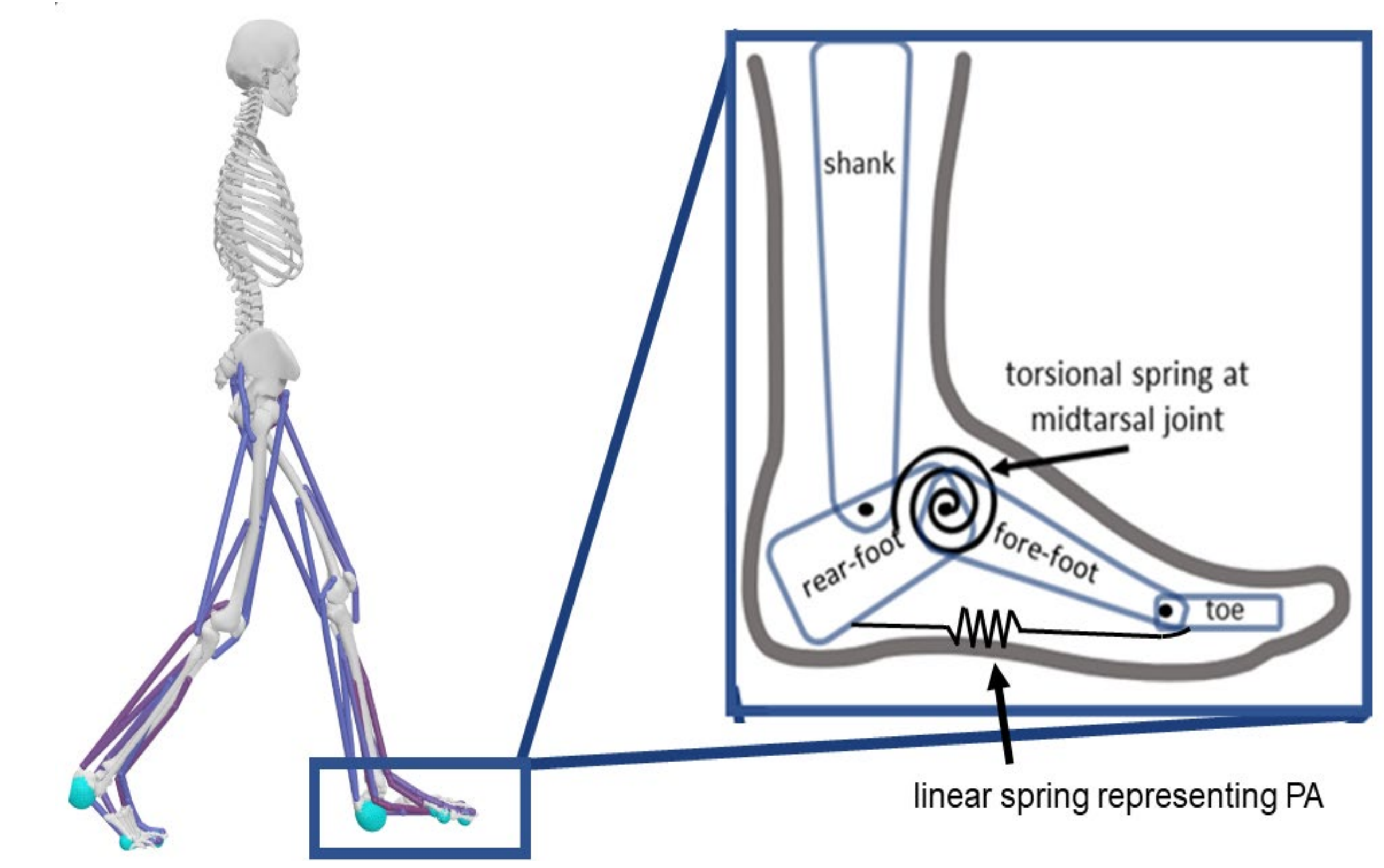

Fig 1. Two-dimensional musculoskeletal model [4] actuated by 26 Hill-type muscles. Each foot is modeled using three-components. The plantar aponeurosis (PA) is represented by a linear spring, and other passive tissues are represented by a torsional spring at the midtarsal joint.

4. Results

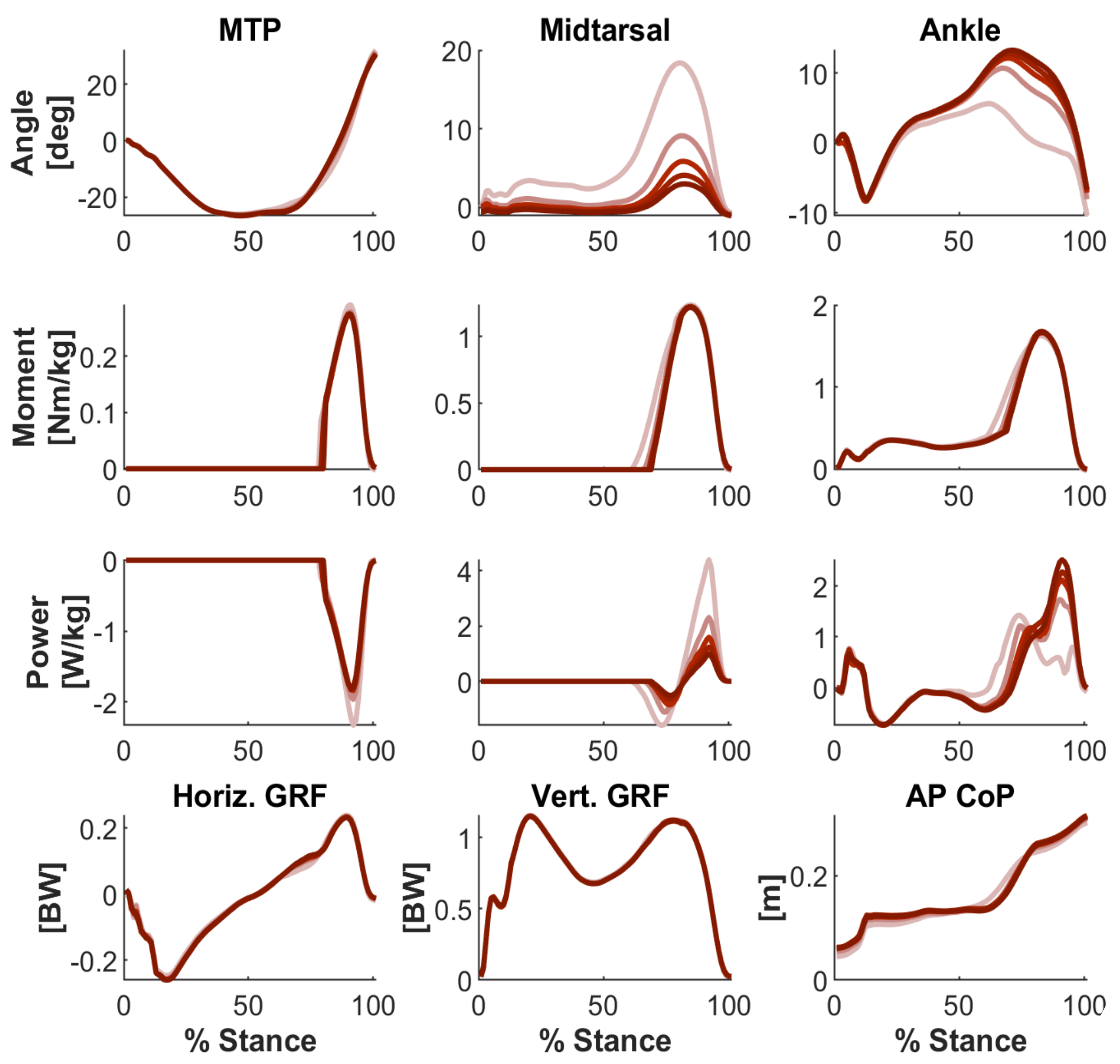

Fig 2. Metatarsophalangeal (MTP), midtarsal, and ankle joint angles, moments, and powers along with ground reaction forces (GRF) and anteroposterior (AP) center of pressure (CoP) with increasing midtarsal joint stiffness.

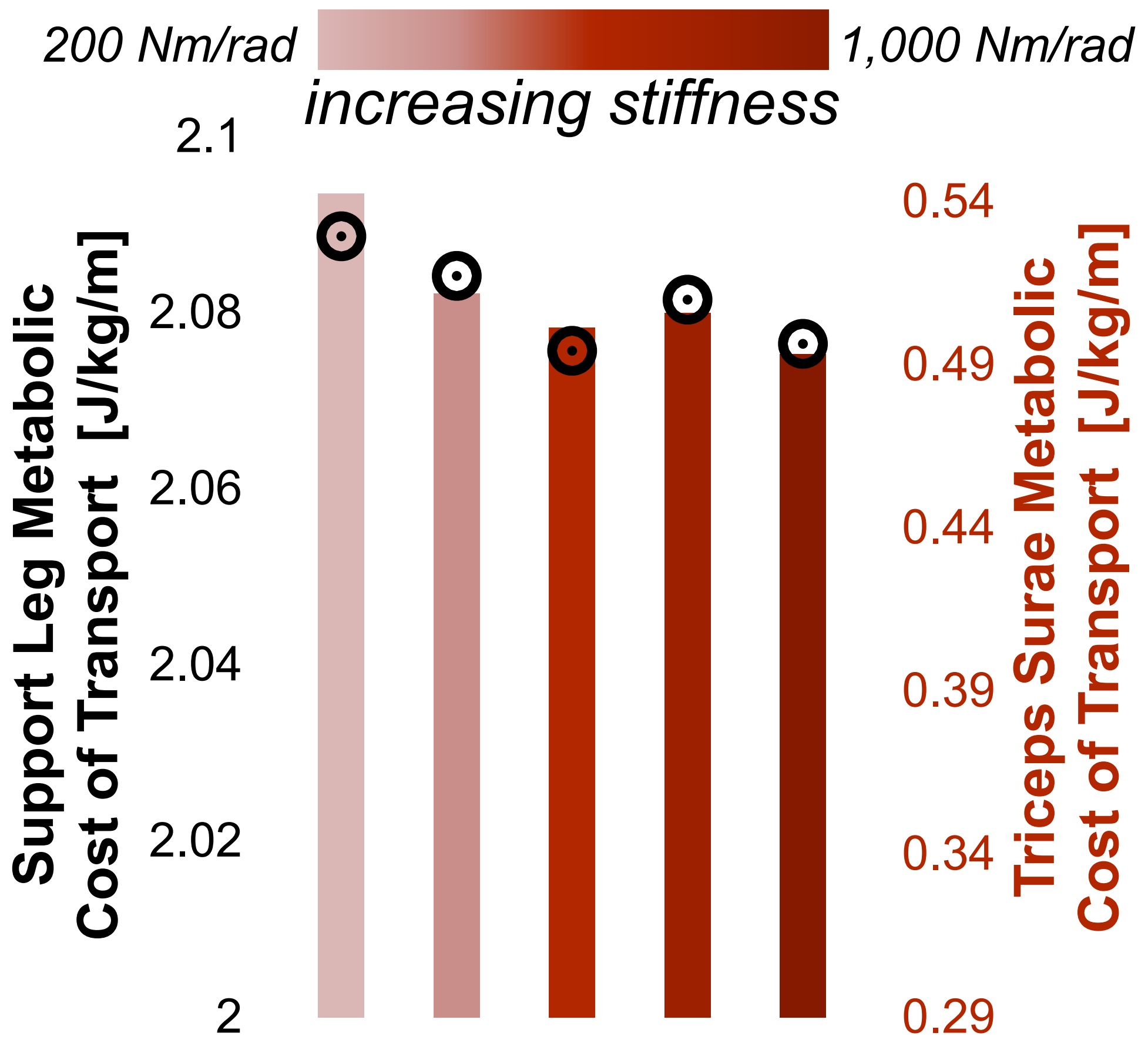

Fig 3. Metabolic cost of transport for the support leg muscles (left axis, black circles) and the triceps surae (right axis, vertical bars) with increasing midtarsal joint stiffness.

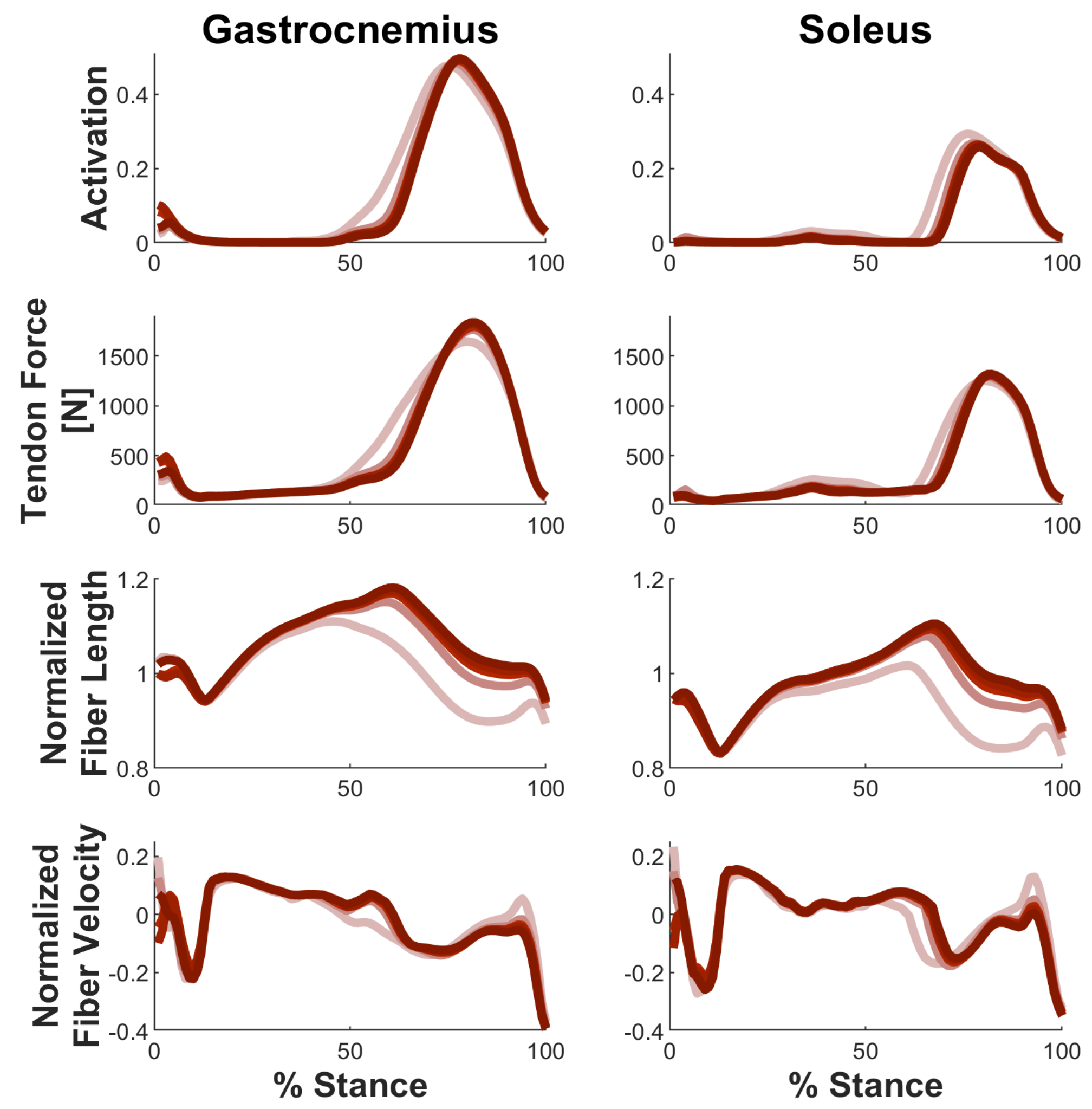

Fig 4. Gastrocnemius and soleus activation, tendon force, normalized fiber length, and normalized fiber velocity with increasing midtarsal joint stiffness.

5. Conclusions

- Increased midtarsal joint stiffness reduced the support leg metabolic cost during the stance phase of walking, primarily due to changes in triceps surae function.
- These differences in walking metabolic cost have important implications for changes in foot properties with injury and aging, the appropriate design of shoes, and future musculoskeletal models endeavoring to estimate the metabolic needs of human gait.

References: [1] Hicks, (1954). *J Anatomy, 88*(Pt.1): 25-31. [2] Davis & Challis (2023). *PLoS ONE*, **17**(9): e0274141. [3] Koelewijn et al., (2018). *Comp Methods Biomech Biomed Engin*, **21**(8): 521-531. [4] Delp et al., (2007). *IEEE Trans Biomed Eng*, **54**(11): 1940 -1950.