INTRODUCTION

The Achilles tendon (AT) moment arm is an important biomechanical measure that converts gastrocnemius and soleus muscle forces into a joint moment at the ankle, ultimately contributing to the generation of mechanical power during walking. However, existing measurements of the AT moment arm are limited to isolated ankle exercises, which are then assumed to apply during walking [1-4]. For example, current modeling approaches presume a kinematic AT moment arm that increases with plantarflexion over the range of motion observed in walking. Yet, recent evidence suggests that the relation between AT moment arm and ankle joint rotation is load dependent and varies significantly from rest with increasing muscle activity [2]. Thus, the AT moment arm may vary in a complex manner during gait, reflecting considerable and compound changes in joint angle and muscle forces.

Our purpose was to couple ultrasound imaging and quantitative motion capture to dynamically estimate the AT moment arm in vivo during walking. We hypothesized that the AT moment arm varies considerably during walking, but not as a strict kinematic function of ankle joint angle.

METHODS

Ten healthy, young adults (age: 23.9 ± 4.0 years; 6 males and 4 females) walked barefoot at 1.25 m/s on a dual-belt, force measuring treadmill. A custom orthotic positioned a 38 mm linear array transducer over the free AT of subjects’ right leg, on average ~6 cm superior to the calcaneal insertion (Fig. 1). For each subject, we recorded ultrasound radiofrequency (RF) data at 155 frames/s over five strides. In synchrony, an 8-camera motion capture system (Motion Analysis, Corp., Santa Rosa, CA) recorded the 3D trajectories of retroreflective markers placed on subjects’ pelvis, right and left legs, and the ultrasound orthotic. We also collected electromyographic (EMG) activities of the lateral gastrocnemius and soleus.

We manually tracked the superficial and deep edges of the AT at three locations (proximal, middle, and distal) using down-sampled (2x) B-mode images created from the RF data. We defined the AT midline as the best fit line through the average of the superficial and deep tendon edges. We defined the right ankle joint center as the midpoint of the lateral and medial malleoli markers. Finally, by transforming the ultrasound, orthotic, and motion capture kinematics into a common reference frame, we estimated the AT moment arm over the gait cycle as the perpendicular distance from AT midline to the ankle joint center (Fig. 1). A repeated measures ANOVA tested for significant (p<0.05) main effects of gait cycle phase (20% bins) on estimates of the AT moment arm.
RESULTS AND DISCUSSION

We found that the AT moment arm varied considerably during walking, increasing significantly and progressively from initial contact until after toe-off (Fig. 2B) \((p<0.001)\). The progressive increase in AT moment arm during stance corresponded with increasing plantarflexor muscle activity (Fig. 2A). In addition, the AT moment arm reached its maximum near the instant of peak plantarflexion. However, as hypothesized, and in contrast to current musculoskeletal modeling approaches, the AT moment arm during walking could not be expressed as a strict function of ankle joint angle (Fig. 2C). Our results imply that the AT moment arm varies with load during gait, presumably arising from a co-interaction between gastrocnemius and soleus forces and ankle angle.

Interestingly, we do observe some similarities between the AT moment arm measured during walking and that during isolated ankle exercises. For example, the AT moment arm immediately after initial contact, an instant of negligible muscle force \([5]\), coincides with that previously reported at rest for the same joint angle (Fig. 2C) \([1]\). Additionally, the AT moment arm during late stance, when the AT is maximally loaded \([5]\), corresponds to that reported during MVC at the same joint angle \([1]\).

By measuring the AT moment arm \textit{in vivo} during gait, we might better elucidate the relation between muscle-tendon architecture and performance. For example, the AT moment arm is modestly correlated with walking speed in slower old adults \([6]\), a change that may contribute to diminished ankle power output seen in this population. This potential link between musculoskeletal geometry and performance can be directly tested using the proposed \textit{in vivo} measurements during gait.

CONCLUSIONS

We provide evidence that the AT moment arm during walking is load dependent, likely reflecting compound changes in joint angle and muscle forces. Our results have important implications for the development of musculoskeletal models, suggesting that the AT moment arm measured during isolated ankle exercises may not accurately predict that during walking. Moreover, measuring the AT moment arm \textit{in vivo} during walking has the potential to provide new and mechanistic insight into triceps surae muscle-tendon performance.

REFERENCES


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\textbf{Figure 2}: (A) Group mean EMG profiles of the lateral gastrocnemius (LG) and soleus (SOL) muscles and (B) group mean (standard error) AT moment arm over an average gait cycle. Asterisks (*) indicate significantly different from preceding 20% gait cycle \((p<0.05)\). (C) Group mean AT moment arm versus ankle joint angle compared to previous values during maximum voluntary contraction (MVC) and at rest from isolated ankle exercises \([1]\).