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Variation in the human Achilles tendon moment arm during walking

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Abstract

The Achilles tendon (AT) moment arm is an important determinant of ankle moment and power generation during locomotion. Load and depth-dependent variations in the AT moment arm are generally not considered, but may be relevant given the complex triceps surae architecture. We coupled motion analysis and ultrasound imaging to characterize AT moment arms during walking in 10 subjects. Muscle loading during push-off amplified the AT moment arm by 10% relative to heel strike. AT moment arms also varied by 14% over the tendon thickness. In walking, AT moment arms are not strictly dependent on kinematics, but exhibit important load and spatial dependencies.

Keywords

Gait; Plantarflexors; Triceps surae; Ultrasound; Musculoskeletal model

Introduction

The Achilles tendon (AT) moment arm is an important biomechanical measure that converts gastrocnemius and soleus muscle forces into a moment about the ankle, ultimately contributing to the absorption and generation of mechanical power during walking. However, existing *in vivo* measurements of the AT moment arm are made during isolated ankle exercises and are then assumed to apply during walking (Fath et al. 2010; Maganaris 2004; Manal et al. 2013; Olszewski et al. 2015). Moreover, current musculoskeletal modelling approaches based on these measurements presume a kinematic AT moment arm that increases with plantarflexion over the range of motion observed in walking (Arnold et al. 2010). 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 (Olszewski et al. 2015; Fath et al. 2013). Further, anatomical studies have illustrated the complex architecture of the AT, with distinct fascicle bundles extending from the medial

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gastrocnemius, lateral gastrocnemius, and soleus that undergo different elongations during activities such as walking (Franz et al. 2015; Szaro et al. 2009). The moment arms associated with these individual bundles, and thus with the individual triceps surae muscles, may differ across the tendon's depth. These observations suggest that the AT moment arm may not be a strict kinematically-determined variable during gait, but instead may exhibit complex load and depth-dependent behaviour.

Our purpose was to investigate *in vivo* load and depth-dependent variations in the AT moment arm during walking. Our approach used motion capture to co-register dynamic ultrasound images of the Achilles tendon with ankle joint kinematics. We hypothesized that the AT moment arm varies considerably during walking, but not as a strict kinematically-determined function of ankle joint angle.

Methods

Subjects and experimental protocol

Ten healthy adults (age: 23.9 ± 4.0 years, height: 1.76 ± 0.14 m, mass: 70.3 ± 12.0 kg, 6 males and 4 females) completed the study. Subjects first walked barefoot on a dual-belt, force-measuring treadmill for 6 min to pre-condition the Achilles tendon (Hawkins et al. 2009). Subjects then completed 2 min walking trials at 1.25 m/s for data collection. A custom orthotic positioned a 38 mm linear array transducer over the free AT (i.e., calcaneal insertion to soleus muscle-tendon junction) of subjects' right leg, on average ~6 cm superior to the calcaneal insertion (Fig. 1). We recorded ultrasound radiofrequency (RF) data from a longitudinal cross-section of the tendon at 155 frames/s from five strides sampled over each 2 min trial. In synchrony, an 8-camera motion capture system (Motion Analysis, Corp., Santa Rosa, CA) operating at 200 Hz recorded the 3D trajectories of retroreflective markers placed on each subject's pelvis, right and left legs, and the ultrasound orthotic. We also collected electromyographic (EMG) activities of the lateral gastrocnemius and soleus muscles at 2000 Hz using surface electrodes (Delsys, Inc., Natick, MA) positioned on the muscle mid-belly 1/3 and 2/3 of the distance between the lateral fibular head and posterior heel, respectively (Cram and Kasman 1998).

Data Analysis

We manually tracked the superficial and deep AT edges using B-mode images created from the RF data (0.297 mm × 0.019 mm pixels). Specifically, we identified points at each frame corresponding to the superficial and deep edges at three locations, separated by 10 mm, along the length of the imaged tendon (i.e., proximal, middle, and distal). We then defined the superficial and deep tendon edges as the best fit line through their respective points, and the AT midline as the best fit line through points corresponding to the average of the superficial and deep edges.

We filtered marker trajectories using a 4^{th} order low-pass Butterworth filter with a cut-off frequency of 6 Hz. The right ankle joint center was defined as the midpoint of the lateral and medial malleoli markers. Sagittal plane ankle angles were computed using inverse kinematic analysis (Franz and Thelen 2015). We separately established the coordinate transformation between ultrasound images and the three markers defining the position and orientation of the ultrasound orthotic (Franz et al. 2015). Using this transformation, we co-registered the ultrasound, orthotic, and motion capture kinematics into a common 3D reference frame. We then estimated the AT moment arm as the perpendicular distance from the AT midline, as well as from its superficial and deep edges, to the ankle joint center in three-dimensional space (Fig. 1). Finally, a Monte Carlo simulation assessed the sensitivity of AT moment arm estimates to errors in identifying the tendon edges using a standard deviation of ±1 mm around the identified landmarks and 10,000 iterations for each of the proximal, middle, and distal tracking locations.

Statistical Analysis

We calculated for each subject the average midline AT moment arm across five bins representing 20% phases of the gait cycle. A repeated measures ANOVA tested for significant ($p<0.05$) main effects of gait cycle phase on the magnitude of the AT moment arm. To assess whether this variation was a function of ankle angle alone, we performed a pairwise comparison of the AT moment arm at heel strike with that at the instant the ankle passed through the same angle during push-off. We also report the magnitude of spatial variations in peak AT moment arm across the three tendon depths.

Results

The AT moment arm varied considerably during walking, increasing significantly from initial contact until after toe-off (phase main effect, $p<0.001$) (Fig. 2A). The increase during stance corresponded with increasing plantarflexor muscle activity (Fig. 2A). However, the AT moment arm increased further following toe-off, reaching its maximum near the instant of peak plantarflexion. On average, the AT moment arm was 3.8 ± 1.7 mm (i.e., ~10%) larger during push-off than at heel strike for the same ankle angle ($p<0.001$) (Fig. 2B). These variations were much larger than simulated predictions of those due to errors in manually tracking the tendon edges (i.e., 1.6%). Finally, AT moment arm measured to the superficial tendon edge was up to 14% larger than that measured to the deep tendon edge (Fig. 2A).

Discussion

The AT moment arm is often presumed to be reasonably well-predicted from ankle kinematics (Arnold et al. 2010). We investigated the validity of this assumption by developing a novel technique to characterize the *in vivo* Achilles tendon moment arm during walking. Consistent with kinematic predictions, peak AT moment arm occurred shortly after toe-off, near the time of maximum plantarflexion. However, we observed clear evidence for load-dependence in the AT moment arm during walking. For the same ankle angle, the AT moment arm was significantly larger when loaded during push-off than at heel strike, an instant of relatively negligible muscle force (Finni et al. 1998). Further, and also not generally considered, the AT moment arm varied across the tendon's thickness, and thus across the distinct fascicle bundles comprising the AT. Hence, as hypothesized, the AT moment arm cannot be expressed strictly as a scalar kinematic function, and exhibits both load- and depth-dependence that may be relevant to understanding plantarflexor performance.

We do observe similarities between our results and those measured during isolated ankle exercises. Prior work (Maganaris 2004; Fath et al. 2010; Leardini and O'Connor 2002; Manal et al. 2013; Olszewski et al. 2015) reports AT moment arms between 35 mm and 60 mm and, for constant loads, these values generally increase with plantarflexion angle (Fig. 3). Part of this variability seems to arise from the method used. For example, when directly compared in the same subjects, moment arms calculated from tendon excursion methods (Fath et al. 2010; Maganaris 2004), which assume invariant tendon force and muscle thickness, are generally smaller than those obtained using geometric measures of the perpendicular distance of the AT to the ankle rotation axis (Fath et al. 2010; Maganaris 2004). Regarding its load-dependent behaviour, Olszewski et al. (2015) reported that AT moment arms decreased with decreasing plantarflexion at rest but increased with decreasing plantarflexion at 30% maximum contraction. We too found that the AT moment arm increased with decreasing plantarflexion in a manner consistent with Olszewski, most prominently as the triceps surae become more active from heel strike to midstance. Fath et al. (2013) also found evidence for load-dependence of the AT moment arm, which was up to 8% larger with maximal contraction than at rest. Similarly, we found ~10% larger AT moment arms with muscle load at push-off compared to heel strike for the same ankle angle. Triceps surae muscle bulging during force-generation is one possible explanation for this load-dependence and may act to enhance the mechanical advantage of force transmission during push-off.

Our results have important implications for the development and use of musculoskeletal models of walking. First, the AT moment arm measured during isolated ankle exercises may not accurately predict the dynamic changes evident in that during walking. Future modelling efforts may benefit from moment arms estimated using a combination of ankle flexion and predicted triceps surae muscle force. However, further experimental evidence, for example from a range of walking speeds, is needed to inform those moment arm predictions. Second, we found up to a 14% difference in AT moment arm between the superficial and deep edges of the tendon, presumably corresponding to tendon thickness but also associated with regions of the tendon thought to arise from different muscles. Anatomically, the AT consists of distinct bundles of tendon fascicles arising from the individual triceps surae muscles which merge and twist down to the calcaneal insertion. It is not clear how triceps surae force is transmitted through the AT to produce a moment about the ankle. Evidence of heterogeneous loading within the AT suggests that this force transmission may be complex (Bojsen-Møller and Magnusson 2015). In addition, Zifchock and Piazza (2004) found that variations in AT insertion architecture significantly affected model-predicted moment arms. A better understanding of this complex anatomy together with *in vivo* estimates of the AT moment arm in walking may lead to more accurate model predictions of triceps surae muscle-tendon dynamics.

We acknowledge several limitations in our proposed method to measure the AT moment arm during walking. First, we estimated the ankle joint center based on anatomical landmarks, similar to prior techniques during isolated ankle tasks (Manal et al. 2010). Using anatomical landmarks is sensitive to marker placement and may simplify the complex nature of ankle rotation. Relative motion between the malleoli markers and the ankle joint center may represent a source of error that requires further study. Second, a single investigator manually identified edges of the AT from B-mode ultrasound images. Thus, while preserving internal consistency of the identification approach, we cannot report on inter-rater reliability. We can, however, note that simulated variations in the AT moment arm due to errors in manual tracking were more than four times smaller than the average variation in the AT moment arm during walking. In addition, our custom orthotic limited a potential source of error, axial rotation of the probe relative to the leg, to values (i.e., 6.3 ± 1.8°) less than those previously published for techniques coupling ultrasound imaging and motion capture (Lichtwark and Wilson 2006). Finally, although we resolved our moment arms in part using 3D measurements, we used 2D ultrasound imaging which does not capture out of plane tissue motion. Some work has suggested that AT moment arms calculated in 2D overestimate those resolved in 3D (Sheehan 2012).

In summary, our findings reveal that the AT moment arm varies considerably during walking, representing compound effects of kinematics, muscle loading, and spatial location. Measuring the AT moment arm *in vivo* during walking has the potential to provide new and mechanistic insight into triceps surae muscle-tendon performance and changes thereof due to age, injury, or disease.

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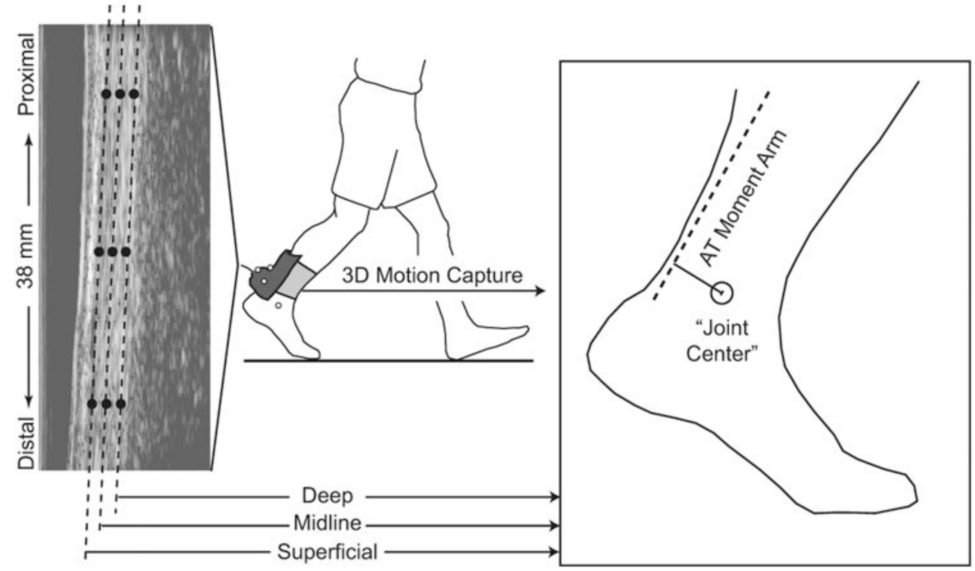

Fig. 1.
We used ultrasound imaging and quantitative motion capture analysis during walking to measure the AT moment arm from the superficial, midline, and deep edges of the tendon. We defined the ankle "joint center" during walking as the instantaneous transmalleolar midpoint.

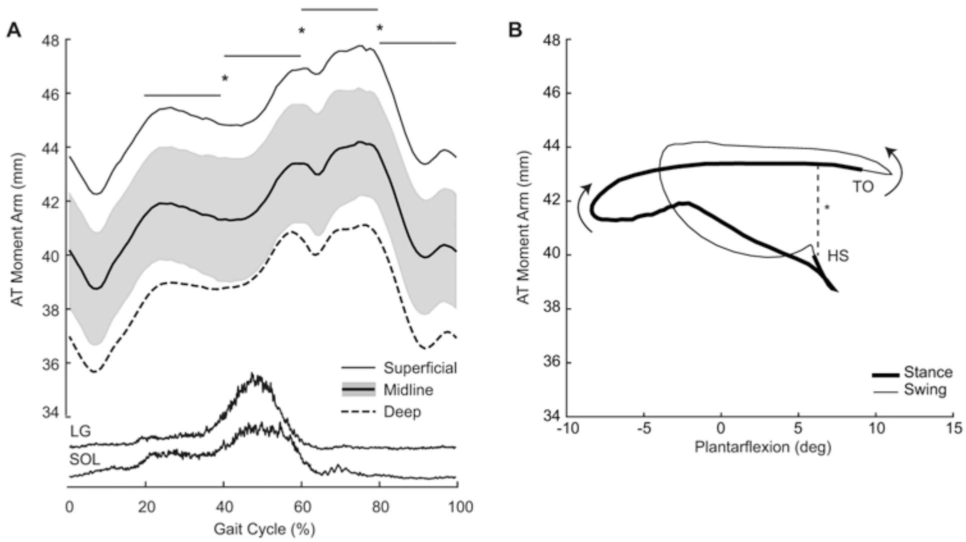

Fig 2.
A: Group mean (standard error) AT moment arm over an average gait cycle and group mean EMG profiles of the lateral gastrocnemius (LG) and soleus (SOL) muscles. Asterisks (*) indicate significantly different from preceding 20% gait cycle ($p<0.001$). B: Group mean AT moment arm versus ankle joint angle. Heel strikes (HS) and toe-offs (TO) were identified from each subject's curves using a 10% threshold of the vertical ground reaction force. The events shown here represent the group average instants of HS and TO. Asterisk (*) indicates a significant increase in AT moment arm during push-off compared to heel strike ($p<0.001$).

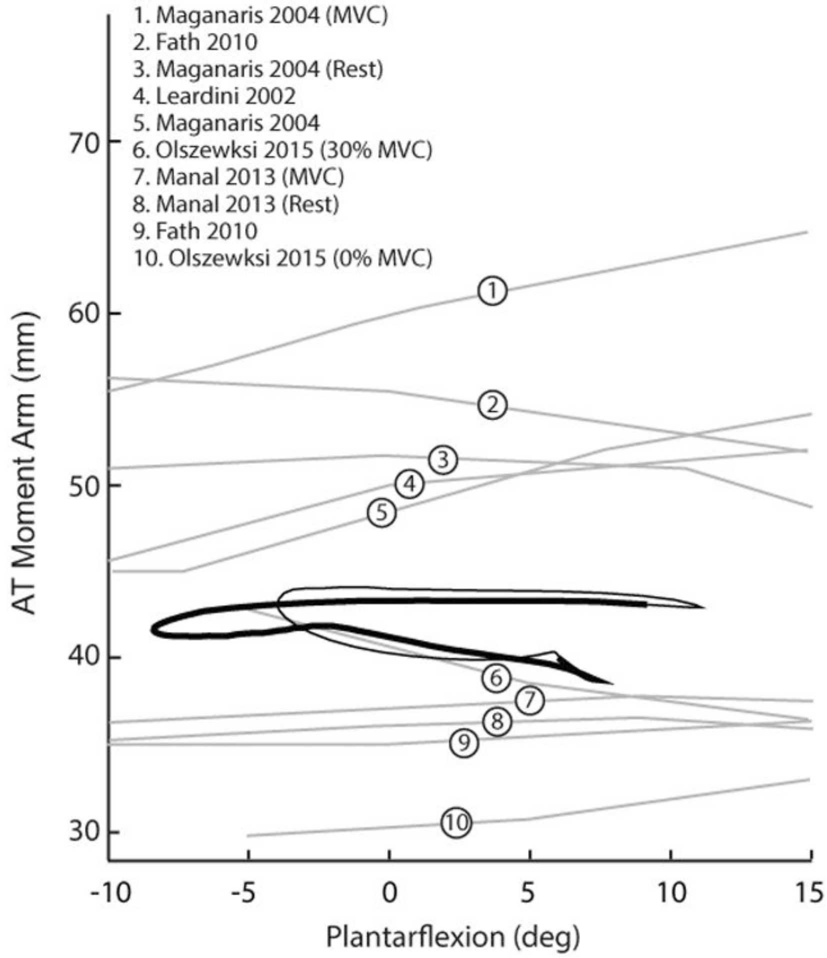

Fig 3.

Comparison of AT moment arm values versus plantarflexion angle estimated during walking to previous literature across a variety of techniques and conditions. Center of Rotation (CoR): 1-3; Model Prediction: 4; Tendon Excursion (TE): 5,6,8,10; Hybrid technique: 6,7. MVC: maximum voluntary contraction.