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Interactive Effects of Joint Angle, Contraction State and Method on Estimates of Achilles Tendon Moment Arms

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The muscle-tendon moment arm is an important input parameter for musculoskeletal models. Moment arms change as a function of joint angle and contraction state and depend on the method being employed. The overall purpose was to gain insights into the interactive effects of joint angle, contraction state and method on the Achilles tendon moment arm using the center of rotation (COR) and the tendon excursion method (TE). Achilles tendon moment arms were obtained at rest (TE_{rest}, COR_{rest}) and during a maximum voluntary contraction (COR_{MVC}) at four angles. We found strong correlations between TE_{rest} and COR_{MVC} for all angles ($.72 \leq r \leq .93$) with Achilles tendon moment arms using COR_{MVC} being 33–36% greater than those obtained from TE_{rest}. The relationship between Achilles tendon moment arms and angle was similar across both methods and both levels of muscular contraction. Finally, Achilles tendon moment arms for COR_{MVC} were 1–8% greater than for COR_{rest}.

Keywords: moment arm, ankle joint, tendon excursion, center of rotation

Muscle-tendon moment arms are important input parameters for musculoskeletal models. Achilles tendon moment arm (MA_{AT}) has been estimated in vivo using both the tendon excursion (TE)[1–3] and the center of rotation (COR) methods.[4,5] Recently, MA_{AT} magnitude was reported to be significantly smaller when the tendon excursion method was used compared with the center of rotation method. However, both methods correlated well across participants for a range of joint angles.[6] Thus, the possibility exists that while MA_{AT} estimates might differ between the methods, the joint-angle dependent changes in MA_{AT} are relatively consistent. Furthermore, MA_{AT} changes with the level of muscle contraction.[4] However, contrary to the center of rotation method, the measurement of MA_{AT} using the tendon excursion method during muscular contraction is associated with severe limitations. The tendon excursion method is based on the principle of virtual work[7,8] and therefore assumes that the work done by an external torque is equivalent to the virtual work done by the muscles and tendons. Implicit in this is the assumption that no energy is lost during a muscle contraction. Given that muscles and tendons store, release and dissipate elastic energy during muscle contractions, the principle of virtual work is violated, and this violation is likely to be more significant when large muscle forces are produced. Using the relationship between moment arms obtained from the tendon excursion method at rest and those obtained using the center of rotation method during a MVC might therefore be a more meaningful way of accounting for contraction-dependent changes in moment arms derived from the tendon excursion method.

Therefore, the overall purpose of this study was to investigate the interactive effects of method, joint angle and contraction level on MA_{AT} estimates. The specific aims were (1) to test the assumption that the MA_{AT} estimated using the tendon excursion method at rest (TE_{rest}) would be related to estimates obtained using the center of rotation method during a maximum voluntary contraction (COR_{MVC}) and (2) to test the assumption that joint angle-related changes in MA_{AT} would be independent of method and contraction state.

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Methods

With institutional ethical approval and after providing written informed consent, six healthy adults (4 men and

2 women) participated in this study (age = 30 ± 6 y, stature = 1.76 ± 0.11 m, mass = 74 ± 14 kg).

MA_{AT} about the right ankle joint was obtained using both the center of rotation (at rest and during MVC) and the tendon excursion (at rest) methods. For the center of rotation method, participants were asked to lie supine in a 3-Tesla magnetic resonance imaging scanner (Siemens Magnetom Trio syngo magnetic resonance 2004A) with their leg straight (ie, knee angle = 0°). The foot was securely fastened with two inelastic Velcro straps. Magnetic resonance images were taken during rest and MVC (sagittal scans, repetition time = 600 [20] ms, echo time = 12 [5] ms, 3 [1] excitations, 300-mm field of view, 2 [3]-mm slice thickness for rest and MVC [ ], respectively) at six different ankle positions (60°–135°, in 15° increments; 90° = foot perpendicular to tibia). Using the magnetic resonance images, the center of rotation of the ankle joint, the line of action (of the Achilles tendon) and consequently the MA_{AT} were determined during rest and MVC at ankle angles of 75°, 90°, 105° and 120° using the Reuleaux method as previously described by others in detail (Figure 1).[4,9]

For the tendon excursion method, participants were seated on an isokinetic dynamometer (Biodex System 3, Biodex Medical Systems, Inc., NY) with their right knee straight (0°) and a relative hip angle of 85°. The right foot was secured firmly to the dynamometer's footplate with the lateral malleolus aligned with the center of rotation of the dynamometer. The ankle was passively rotated through its range of motion by the dynamometer five consecutive times at $10°\cdot s^{-1}$. For all participants, the range of motion was greater than 75° (dorsiflexion) and 120° (plantar flexion). To determine tendon displacement, a 10-MHz B-mode, 40-mm linear ultrasound probe (Esoate Megas GPX, Genova, Italy) was placed over the muscle-tendon junction of the gastrocnemius medialis. Raw position data (sampled at 1 kHz) from the isokinetic dynamometer were low-pass filtered (4th-order Butterworth, zero-lag, 3.75 Hz cut-off). Ultrasound video data were sampled at 25 Hz. The positions of the muscle-tendon

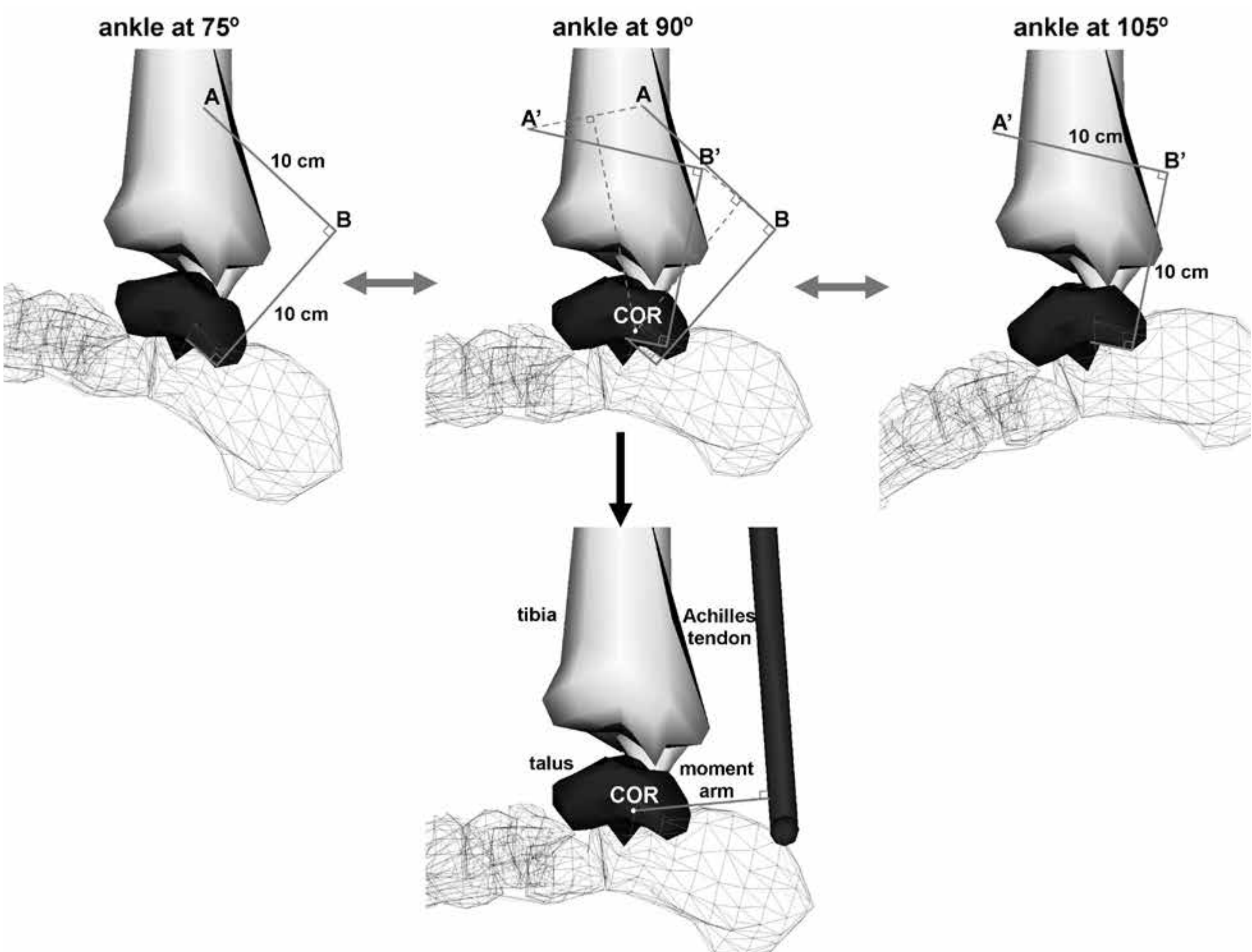

Figure 1 — Schematic illustration of the center of rotation method using the Reuleaux geometrical method to determine Achilles tendon moment arm (Reuleaux, 1875). *Note.* To determine the moment arm at 90°, for example, magnetic resonance scans were taken at 90 ± 15° and the center of rotation of the joint was subsequently determined. The tibia was assumed to be a constant throughout the joint rotation and the talus was the designated as the rotating segment. Achilles tendon moment arm at 90° was defined as the perpendicular distance between the center of rotation of the ankle joint and the line of force (ie, the Achilles tendon).

junction and the Achilles tendon were manually digitized, low-pass filtered (4th-order Butterworth, zero-lag, 2.63 Hz cut-off) and down-sampled to 25 Hz. The tendon and joint angular displacement data were plotted against joint angular displacement over the interval of 75° and 120°, and approximated by fitting a 2nd-order polynomial (mean (±SD) coefficient of determination = 0.996 ± 0.002). To calculate the MA_{AT}, the polynomial was analytically differentiated at the four ankle angles of interest. MA_{AT} measurements were analyzed three times at each angle for each method. The coefficient of variation was smaller than 5% for all conditions. More detailed descriptions of the experimental protocol and the derivation of MA_{AT} are published elsewhere.[6]

To determine the relationship between TE_{rest} and COR_{MVC}, four Pearson's product-moment correlations were performed (one at each angle). To test if MA_{AT} obtained using TE_{rest}, COR_{rest} and COR_{MVC} would change similarly as a function of ankle angle, and, to determine if this change was independent of muscular contraction level, a repeated-measures ANOVA (3 × 3, TE_{rest}, COR_{rest}, COR_{MVC} at ankle angles of 75°, 90° and 105°) was performed. Here, we tested for a method × angle interaction. To test this effect independent of differences in MA_{AT} magnitude, all MA_{AT} values were normalized by the MA_{AT} obtained at 120° for the corresponding condition. To further illustrate the changes of MA_{AT} across angles and method, we quantified the correlations between MA_{AT} and ankle angle for each participant and each method. To provide more specific information about the COR_{rest}–COR_{MVC} comparison, we also report percentage differences for all angles. Statistical significance was accepted at an alpha of .05.

Results

The correlation coefficients quantifying the relationship between TE_{rest}–COR_{MVC} ranged between .72 and .93 (Table 1). The repeated-measures ANOVA revealed no method × angle interaction ($F(4, 20) = 0.769$; $P = .558$) (Figure 2). The mean correlations between MA_{AT} and ankle angle were 1 ± 0.00, .91 ± 0.10 and 0.95 ± 0.08 for TE_{rest}, COR_{rest} and COR_{MVC}, respectively. MA_{AT} magnitudes were larger at the 120° than the 75° ankle angle with mean differences of 24.5 ± 12.2%, 19.9 ± 6.3% and 24.3 ± 7.3% for TE_{rest}, COR_{rest} and COR_{MVC}, respectively. When comparing COR_{rest} and COR_{MVC}, the percentage differences in MA_{AT} (±SD) were 0.8 ± 6.5%, 3.7 ± 2.8%, 5.5 ± 6.4% and 7.9 ± 6% at ankle angles of 75°, 90°, 105° and 120°, respectively.

Discussion

The first aim of this study was to directly compare MA_{AT} obtained from TE_{rest} and COR_{MVC}. We found strong correlations between MA_{AT} obtained from TE_{rest} and COR_{MVC} across a range of ankle angles with MA_{AT} values obtained from TA_{rest} being significantly smaller. These results extend previous findings by demonstrating that MA_{AT} obtained using the center of rotation method at MVC and tendon excursion method at rest are well correlated and therefore independent of contraction state.[6] The significantly smaller MA_{AT}'s obtained from the tendon excursion method can be explained by the viscoelastic nature of the tendon. As the Achilles tendon becomes more slack during the passive plantar flexion rotation, the displacement of muscle tendon junction for a given joint rotation is reduced which leads to an underestimation of MA_{AT}. The second aim was to test the hypothesis that MA_{AT} would change as a function of ankle angle independently of the method of MA_{AT} estimation. In conformity with this hypothesis, we found (1) no angle × method interaction and (2) similar moment arm-joint angle correlations for all experimental conditions (Figure 2). Our results extend previous findings by demonstrating that the relationship between MA_{AT} and joint angle is not only independent of muscular contraction level but also of the method used.

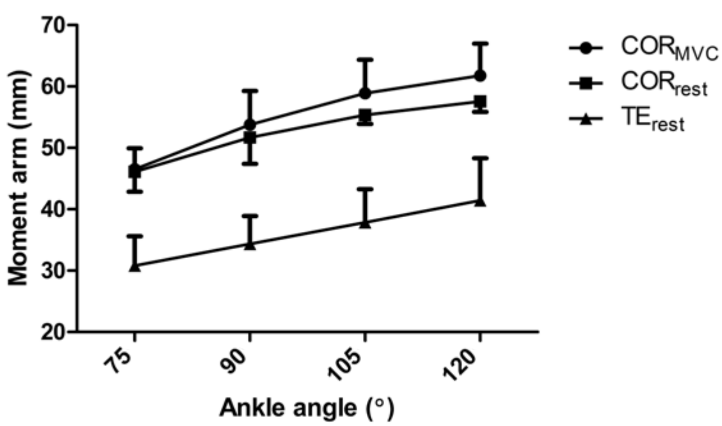

Figure 2 — Achilles tendon moment arm measurements (mean ± SD) at four different ankle angles obtained from the tendon excursion method at rest (TE_{rest}) and from the center of rotations method at both rest (COR_{rest}) and during a maximum isometric contraction (COR_{MVC}). *Note.* 90° ankle angle refers to the foot being perpendicular to the tibia.

Table 1 Achilles tendon moment arm comparison at four different ankle angles obtained using the tendon excursion method at rest (TE_{rest}) and the center of rotation method during a maximum isometric contraction (COR_{MVC})

		Moment arm (mm; mean ± SD)		TE_{rest}–COR_{MVC}		
Ankle Angle	TE_{rest}	COR_{rest}	COR_{MVC}	r	R^2	P
75°	30.8 ± 6.7	46.1 ± 3.3	46.5 ± 3.4	.72	.51	.11
90°	34.3 ± 4.5	51.7 ± 4.3	53.8 ± 5.5	.93	.86	.01
105°	37.9 ± 5.4	55.4 ± 1.5	58.5 ± 5.5	.77	.59	.07
120°	41.1 ± 6.9	56.7 ± 2.4	61.8 ± 5.2	.78	.61	.06

Another interesting aspect of our data is the difference in MA_{AT} between COR_{rest} and COR_{MVC}. This difference ranged between 1 and 8%, which is considerably smaller than that reported by Maganaris et al,[4] who found differences between 22 and 27%. This discrepancy can potentially be explained by the different knee angle used by Maganaris et al (90°) compared with the present investigation (0°). We adopted a knee angle of 0° in an attempt to minimize the influence of tendon slack, which has the potential to introduce errors into the MA_{AT} estimation when using the tendon excursion method.[7] The increase in MA_{AT} during MVC compared with rest can be explained by a shift of the Achilles tendon away from the joint center, due to a thickening of the plantar flexor muscles.[4] This shift is possibly smaller in magnitude when the knee is fully extended compared with a more flexed position. Support for this speculation comes from Riemann et al,[10] who demonstrated that muscle stiffness of the gastrocnemius medialis is greater during full knee extension compared with more flexed positions. A direct consequence of the greater stiffness could be a reduction of Achilles tendon movement during MVC and therefore a reduced increase in MA_{AT} during MVC when compared with rest. Our results, in combination with those of Maganaris et al,[4] let us speculate that there is an interaction between knee angle, MA_{AT} and plantar flexor contraction level. Future research should be conducted to specifically test this hypothesis.

The present findings have specific implications for musculoskeletal modeling. Our descriptive results can be used as guidance for modelers to account for the dependence of MA_{AT} on ankle angle and contraction level. However, it is important to consider the within-group variability observed in our participants. The somewhat large standard deviations reported here indicate that the interaction between ankle angle, muscular contraction level and MA_{AT} can differ between individuals. This variability should be taken into consideration by performing appropriate sensitivity analyses.

Acknowledgments

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