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In vivo measurement-based estimations of the human Achilles tendon moment arm

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Abstract The aim of the present study was to estimate and compare in vivo measurement-based Achilles tendon moment arm lengths at rest and during isometric plantarflexion maximum voluntary contraction (MVC) using the centre-of-rotation (COR) and the tendon-excursion (TE) methods. Both methods were based on morphometric analysis of sagittal-plane magnetic resonance images of the foot. Using the COR method, moment arms were obtained at ankle angles from 15° of dorsiflexion to 30° of plantarflexion in steps of 15°, digitizing the perpendicular distance from a moving centre of rotation in the tibio-talar joint to the Achilles tendon action line. The TE method was based on measurement of calcaneal displacement along the tibial axis during 15° rotations of the ankle joint, from 30° of dorsiflexion to 45° of plantarflexion. The two methods gave similar estimations at rest varying from 4.3 to 5.6 cm. Using the COR method, the Achilles tendon moment arm during MVC was larger by 1–1.5 cm (22–27%, $P < 0.01$) than the respective resting value. In contrast, no difference ($P > 0.05$) was found between the resting and MVC moment arm estimations of the TE method. The disagreement in moment arms during MVC may be attributed to differences in the assumptions made between the two methods. The TE method has more limitations than the COR method and its estimations during MVC should be treated with caution. Resting Achilles tendon moment arm estimations of the COR method should be multiplied by 1.22–1.27 when maximal isometric plantarflexion joint moments, musculotendon forces and stresses are predicted using modelling.

Key words Achilles tendon moment arm · MRI · Maximum voluntary contraction · In vivo · Tendon excursion

Introduction

Musculoskeletal models simulating the mechanical output of muscle around a joint require information about the tendon moment arm. Estimation of tendon moment arm requires identification of the rotation centre of the joint spanned by the tendon and the orientation of the tendon action line. Any error in these parameters would affect the estimated moment arm. Alternatively, the average moment arm over a joint rotation can be calculated from the tendon excursion-to-joint rotation ratio using the virtual work principle (for review see An et al. 1984). In cadaveric specimens, tendon excursion measurements have been carried out repeatedly (e.g. Klein et al. 1996; Hintermann et al. 1994; Spoor and van Leeuwen 1992; Spoor et al. 1990; An et al. 1979, 1984; Grieve et al. 1978). In vivo tendon excursion measurements in man have been carried out in the past by recording the displacement of injected markers into the musculotendinous junction (Amis et al. 1987; Fellows and Rack 1987). This method enables calculation of moment arms over the studied range of motion but it is highly invasive. Magnetic resonance imaging (MRI) and real-time ultrasonography offer, however, the possibility for non-invasive, in vivo tendon excursion estimations (Maganaris 2000; Ito et al. 1998, 2000; Maganaris and Paul 1999; Fukunaga et al. 1996a; Fukashiro et al. 1995).

Although three-dimensional (3D) methodologies for moment arm estimation have been developed recently (Wilson et al. 1999; Boyd and Ronsky 1998),

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two-dimensional (2D) scan-based methodologies have grown in popularity (Maganaris 2000; Ito et al. 1998, 2000; Maganaris et al. 1998, 1999a; Fukunaga et al. 1996a, b; Rugg et al. 1990). 2D images require short scanning time and may thus allow scanning during high-intensity muscle contractions.

Quantification of differences in moment arm between rest and maximal isometric contraction is important for accurate modelling-based prediction of maximal isometric joint moments, musculotendon forces and stresses (e.g. Fukunaga et al. 1996b; Hoy et al. 1990). The aim of the present study was to estimate and compare in vivo MRI-based Achilles tendon moment arms in the sagittal plane using two different methods: the centre-of-rotation (COR) method, that is measuring the perpendicular distance between the moving centre of rotation in the tibio-talar joint and the Achilles tendon action line, and the tendon-excursion (TE) method, which is based on bone kinematics during ankle plantarflexion-dorsiflexion.

Preliminary results of this work have been presented (Maganaris et al. 1999b, c).

Methods

Experimental protocol

Sagittal-plane magnetic resonance images (MRIs) (G.E. Signa Advantage 1.5 T/64 MHz, Milwaukee) of the right leg were taken at the level of the ankle in six males [mean age, height and body mass: 28 (SD 4) years, 175 (SD 8) cm and 75 (SD 7) kg, respectively], who had given their written consent to participate in the study. The body was placed in the supine position with the knee of the tested leg flexed at 90°. MRIs were taken at foot positions from −30° (dorsiflexed direction, where 0° indicates the tibia perpendicular to the sole of the foot) to +45° (plantarflexed direction) in rotation steps of 15°. A system of mechanical stops, triangular blocks and Velcro straps was used to secure the subject at the required position (see Fig. 1 in Maganaris et al. 1998). Scans were taken at all six foot positions in the study, first at rest and then during isometric plantarflexion maximum voluntary contraction (MVC). All subjects were instructed to avoid eversion or inversion of the foot during contraction. Scanning was performed using a Fast GRASS sequence at a flip angle of 90° with 15 ms repetition time, 6.7 ms echo time, 24 cm field of view, 1 excitation, 256 × 128 matrix, 5 mm slice thickness and 2 s scanning time. All MRIs were taken at the same sagittal-plane level, based on axial-plane pre-scanning at the level of the malleoli. Typical foot MRIs are presented in Fig. 1.

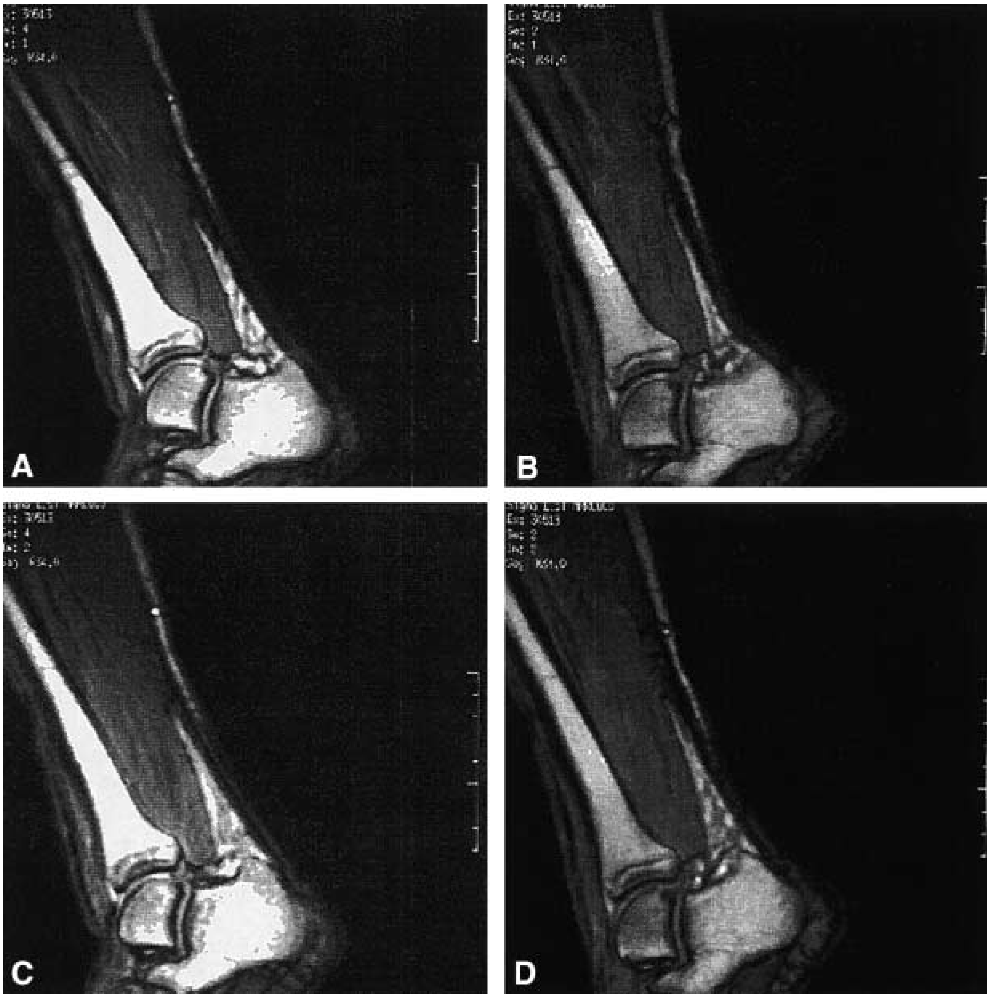

Fig. 1A–D Magnetic resonance images (MRIs). Sagittal-plane MRIs of the right ankle of a subject at foot positions of +15 and +30° at rest (**A** and **B**, respectively) and during plantarflexion maximum voluntary contraction (MVC) (**C** and **D**, respectively)

COR method

Instant CORs in the tibio-talar joint, and Achilles tendon action lines and moment arms, were identified at foot positions of −15, 0, +15 and +30°, both at rest and during MVC as described elsewhere (Maganaris et al. 1998). CORs were identified from the foot rotations −30° → 0°, −15° → +15°, 0° → +30° and +15° → +45° using the Reuleaux graphical analysis (Reuleaux 1875). The tibia was considered to represent the stationary segment and the talus the whole rotating foot. The two markers required for the Reuleaux analysis were placed about 10 cm away from the centre of the talus, over two straight lines subtending an angle of 90°. A straight line drawn through the middle of Achilles tendon was considered to represent the tendon action line. The distance between the moving centre of rotation and the Achilles tendon action line, i.e. the Achilles tendon moment arm, was measured using a sonic digitizer (TDS, Blackburn).

TE method

Average moment arm values over the foot rotations −30° → −15°, −15° → 0°, 0° → +15°, +15° → +30° and +30° → +45° were calculated both at rest and during MVC. Tracings were drawn on a transparency of the outline of the tibia and calcaneus including the attachment point of Achilles tendon on the calcaneus and the Achilles tendon action line at all six foot positions in the study. The tibia was considered to represent the stationary segment and the calcaneus the whole rotating foot. The parallel to the axis of the tibia distance between the locations of the attachment point of Achilles tendon on the calcaneus at the initial and final foot positions in the above five rotations was digitized and considered to represent the Achilles tendon excursion $\mathrm{d}L$ (Fig. 2A and C). Although foot rotation was set in steps of 15°, ligament loading during MVC could result in changes in ankle joint geometry (Maganaris et al. 1998, 1999a; van den Bogert et al. 1994; Lundberg and Svensson 1993; Lundberg et al. 1989), introducing errors when assuming that the foot rotation performed in each step was always 15°. Thus, morphometric analysis of the MRIs with respect to ankle joint rotation was performed both at rest and during MVC. Ankle joint rotation measurements were based on tracings drawn on a transparency of the outline of the tibia and calcaneus at all foot positions. The tibia was considered to represent the rotating segment and the calcaneus the stationary segment. The angle between the longitudinal axis of the tibia at the initial and final foot positions in the five rotations studied was digitized and considered to be the ankle joint rotation $\mathrm{d}\varphi$ (Fig. 2B and D). For any given foot rotation step of 15°, the Achilles tendon moment arm was calculated as the quotient $\mathrm{d}L/\mathrm{d}\varphi$.

All morphometric analyses in either method were performed three times by the same investigator and mean values were used for further analysis.

Statistics

Values are presented as means (SD). For each method, differences in the Achilles tendon moment arm between rest and MVC and between different foot positions were tested using two-way ANOVA (2 × 4 for the COR method and 2 × 5 for the TE method). Simple effects tests were used to identify where interaction effects occurred and Tukey's analysis was used to determine significant difference between mean values. $P < 0.05$ was considered significant.

Results

COR method

As the foot position changed from −15 to +30° at rest, the Achilles tendon moment arm increased from 4.4 (SD 0.3) to 5.5 (SD 0.3) cm ($P < 0.01$). During MVC, as the foot position changed from −15 to +30° the Achilles tendon moment arm increased from 5.4 (SD 0.4) to 7.0 (SD 0.4) cm ($P < 0.01$). At any given foot position, the Achilles tendon moment arm during MVC increased by between 1 (SD 0.2) and 1.5 (SD 0.3) cm (22–27%, $P < 0.01$) compared with rest (Fig. 3).

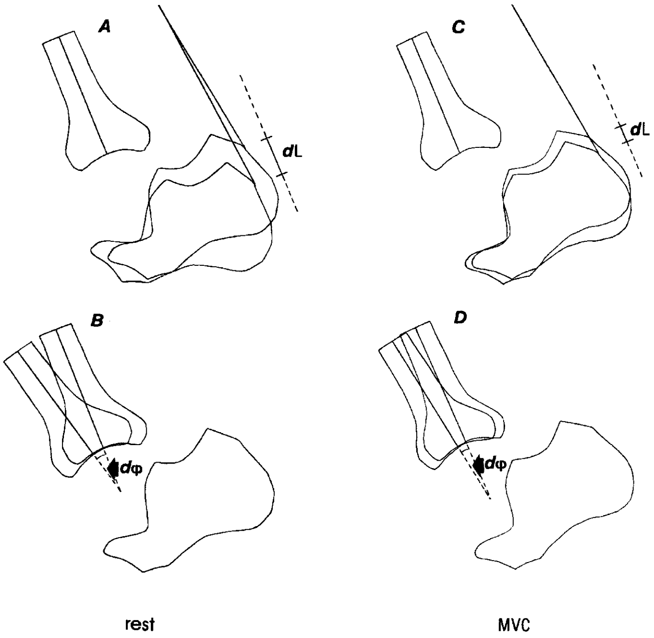

Fig. 2A–D Tendon excursion and joint rotation measurements. **A**, **C** Achilles tendon excursion measurements; **B** and **D** ankle joint rotation measurements as performed in the study. The *drawings* show the structures of the foot illustrated in Fig. 1. **A**, **B** MRIs taken at rest, **C** and **D** MRIs taken during MVC. In **A** and **C**, the Achilles tendon action line at each foot position is presented as a straight line at the upper right part of the calcaneus (the attachment point of Achilles tendon on the calcaneus). Notice the negligible magnitude of the angle between the Achilles tendon action lines at the different foot positions. The displacement $\mathrm{d}L$ of the attachment point of Achilles tendon in the transition +15° → +30° was considered to represent the Achilles tendon excursion over this foot rotation. The distance $\mathrm{d}L$ is marked over a straight line, parallel to the longitudinal axis of the tibia. In **B** and **D**, the angle between the longitudinal axis of the tibia at angles of +15 and +30° was taken as the ankle joint rotation ($\mathrm{d}\varphi$) for the foot rotation step +15° → +30°. Notice that both excursion of Achilles tendon and ankle joint rotation are smaller during MVC compared with rest

TE method

The Achilles tendon moment arm varied from 4.3 (SD 0.4) to 5.6 (SD 0.4) cm at rest ($P < 0.01$) and from 4.2 (SD 0.4) to 5.7 (SD 0.4) cm during MVC ($P < 0.01$). In contrast with the COR method, no difference ($P > 0.05$) was found when comparing the Achilles tendon moment arm estimations of the TE method between rest and MVC over any given foot rotation step (Fig. 3).

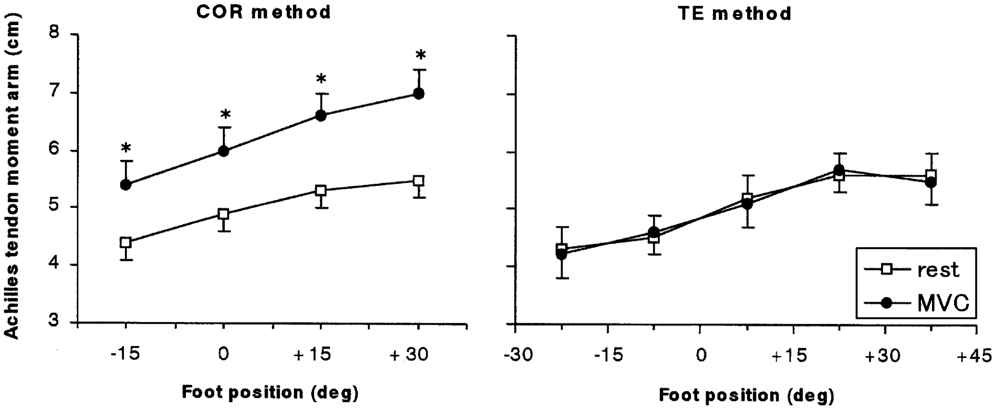

Fig. 3 Achilles tendon moment arm estimations at rest and during MVC. Means, *error bars* show SD ($n = 6$). $^*P < 0.01$ between measurements at a given foot position for a given method

Reproducibility of measurements

Coefficient of variation values for fifteen repeated estimations of the Achilles tendon moment arm using the COR method for the foot rotation 0° → +30° and the TE method over the foot rotation 0° → +15° in one subject, were 5.1 and 4.7%, respectively, at rest and 4.2 and 5.9%, respectively, during MVC. In the same subject, three images were additionally taken during MVC at foot positions of −15, 0 and +15°. The coefficient of variation for repeated digitizing of the Achilles tendon moment arm at 0° using the COR method was 7.9%. The respective value using the TE method for the foot rotation 0° → +15° was 6.5%. To obtain an estimate of inter-observer variability for the two methods, four different observers calculated the Achilles tendon moment arm over the same foot rotation in a given subject; the rotation 0° → +30° was analysed using the COR method and the rotation 0° → +15° was analysed using the TE method. The values for coefficient of variation for repeat measures were 7.9 and 6.1% at rest and during MVC, respectively, using the COR method, and 7.1 and 8.2% at rest and during MVC, respectively, using the TE method.

Discussion

In the present study, we derived estimations of the Achilles tendon moment arm from 2D-scan morphometrics. However, realistic moment arm estimates would require 3D methodologies. Wilson et al. (1999) estimated the moment arm of the human flexor digitorum profundus tendon at rest from 3D MRIs obtained over about 10 min. Clearly, such long scanning times do not allow continuous application of high contractile forces during scanning.

The assumption made when using in vivo 2D scanning methods for studying musculoskeletal mechanics is that the scanned anatomical structures operate exclusively in the studied plane. Based on this assumption, ankle plantarflexion-dorsiflexion has been treated often as a planar mechanism (Maganaris 2000; Ito et al. 1998, 2000; Maganaris and Paul 1999; Maganaris et al. 1998, 1999a; Fukunaga et al. 1996a, b; Rugg et al. 1990; Sammarco et al. 1973). The tibio-talar joint is a single-degree-of-freedom mechanism (Leardini et al. 1999a, b). Its anatomical axis, however, is not perpendicular to the sagittal plane and its angulation changes during ankle plantarflexion-dorsiflexion (Leardini et al. 1999a; van den Bogert et al. 1994; Lundberg and Svensson 1993; Lundberg et al. 1989; Isman and Inman 1969; Hicks 1953). The assumption that the tibio-talar joint axis is perpendicular to the sagittal plane would therefore result in a measurement error when using the COR method, with size proportional to the angulation α of the tibio-talar joint axis. The actual or "effective" (see Spoor et al. 1990) moment arm would be the product of the estimated moment arm in the present study and $\cos\alpha$. In vivo and cadaver-based studies suggest that α at the neutral ankle position at rest is about 10° (van den Bogert et al. 1994; Isman and Inman 1969). Correction of the respective moment arm estimate for this deviation indicated that the COR method overestimated by some 2% the "effective" moment arm value. Larger deviations of the tibio-talar joint axis could be expected towards end-range positions at rest and during MVC (van den Bogert et al. 1994; Lundberg and Svensson 1993; Lundberg et al. 1989; Hicks 1953).

The talar bone is part of two joints: the tibio-talar joint that allows plantarflexion-dorsiflexion and the talo-calcaneo-navicular joint that allows inversion-eversion. The axes of these joints are not perpendicular to each other, nor are they in anatomical planes (van den Bogert et al. 1994; Lundberg and Svensson 1993; Lundberg et al. 1989; Isman and Inman 1969; Hicks 1953). A shift of the talo-calcaneo-navicular joint axis in the transition from rest to MVC may occur due to ligament compliance and this would result in a talus shift in the frontal plane and a deviation from the talar bone path during plantarflexion-dorsiflexion at rest (Leardini et al. 1999a; van den Bogert et al. 1994; Lundberg and Svensson 1993; Lundberg et al. 1989). Moreover, the talo-calcaneo-navicular joint axis lies slightly laterally with respect to the Achilles tendon insertion point on the calcaneus, suggesting that Achilles tendon loading might result in a slight inversion of the talus. Both of the above effects, however, cannot be identified when using the Reuleaux and COR methods and this might introduce measurement errors during MVC.

In the present study, the TE method was based on the assumption that the whole musculotendon complex operates over a straight line. Thereafter excursion values were derived from measurements of the displacement of the Achilles tendon insertion point at the distal end, inside the imaged area which is approximately defined by the circle in Fig. 4. dL over any 15°-foot rotation step was defined as the distance between the locations of the insertion point at the initial and final foot positions, projected on a line parallel to the tibial axis. It is evident, however, that dL as measured in the study is an approximation of the musculotendon excursion PI_1–PI_2 and the error introduced by assuming that d$L = PI_1$–PI_2 will be proportional to 1–the cosine of the angle between PI_1 and PI_2 (see Fig. 4). Morphometric analysis revealed that this angle was 0–4°. However, larger and more substantial errors may have been introduced by assuming that the whole complex has a straight-line orientation. Recently, we have reported that the gastrocnemius lateralis and soleus muscles thicken by up to 45% during plantarflexion contraction compared with rest (Maganaris et al. 1998). This would imply that, during MVC, the orientation of the triceps surae muscle-Achilles tendon is curved rather than straight and thus excursion measurements should be taken along the curved path of the musculotendon complex. Such measurements could be taken by recording the excursion of reference landmarks in the musculotendon complex during joint rotation. Real-time ultasonography allows this possibility and offers promise for improvement in TE method-based estimations of in vivo "effective" moment arms (see Maganaris 2000; Ito et al. 1998, 2000; Maganaris and Paul 1999). Additional errors may have been introduced in the TE method estimations by assuming that the ankle joint axis of rotation is perpendicular to the scanning plane. Sagittal-plane scanning allowed measurement of the projected ankle rotation instead of the true rotation, which implies that underestimated ankle rotation and overestimated moment arm values may have been obtained (Klein et al. 1996). Errors may have also been introduced due to the bi-articular nature of Achilles tendon. Application of the virtual work principle around the tibio-talar joint would require fixation of the talo-calcaneo-navicular joint, which is not applicable under in vivo conditions. Interestingly, however, cadaver-based studies have suggested that there is no substantial effect of talo-calcaneo-navicular joint fixation on the Achilles tendon moment arm around the tibio-talar joint (Klein et al. 1996; Spoor et al. 1990).

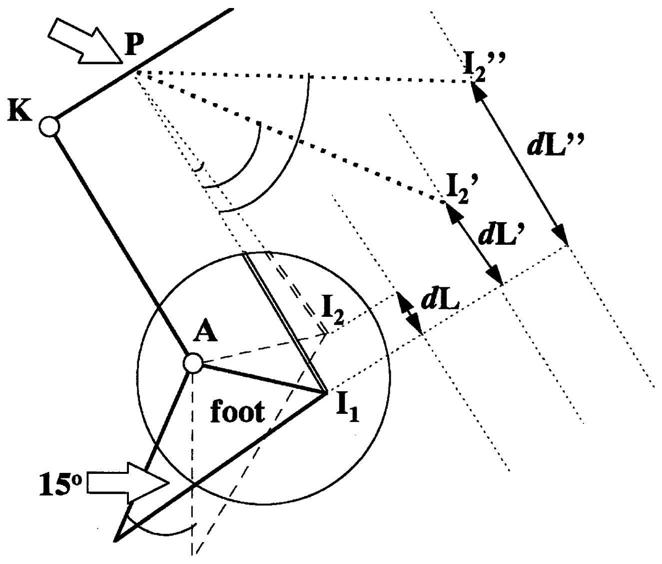

Fig. 4 Representation of the actual musculotendon excursion. In the planar model shown, K is the knee joint, A is the ankle joint, and I_1 and I_2 are the initial and final positions, respectively, of the insertion point of Achilles tendon on the calcaneus over the presented foot rotation step of 15°. P is the proximal end of the triceps surae complex, considering the complex as a single-belly muscle. The *circle* encloses the scanned part of the foot in the MRI. The intersection point of the Achilles tendon action lines (presented as *straight double solid* and *dotted lines*) at the initial and final foot positions (presented as *solid* and *dotted outlines* respectively) determines the point P position. For a constant position in point P, the actual tendon excursion is equal to the musculotendon complex excursion PI_1–PI_2. In the present study, the distance dL over a parallel line to the tibia was considered to represent the Achilles tendon excursion. Notice that, for a given actual musculotendon complex excursion over different positions of the Achilles tendon action line (presented as *thick dotted lines*, $PI_2 = PI_2' = PI_2''$), the larger the angle between the initial and the final Achilles tendon action line positions, the greater the overestimation of the distance dL (d$L'' >$ d$L' >$ dL)

Employing the COR method, the Achilles tendon moment arm during MVC was 1.22–1.27 times the respective value at rest. When using the COR method, moment arms during isometric contraction may increase compared with rest for three reasons. First, because of an increased muscle thickness that results in a tendon shift (Maganaris et al. 1998); second, because of a displacement in the joint rotation centre (Maganaris et al. 1998, 1999a; Sammarco et al. 1973) and third, because of a deformation in the collagenous sheaths that may surround the tendon studied (Maganaris 2000; Maganaris et al. 1999a; Rugg et al. 1990). In the present study, all precautions were taken when applying the Reuleaux method as to the rotation angles chosen and placement of the two reference markers required to reduce measurement errors (Panjabi and Goel 1982; Panjabi 1979). A detailed analysis of the factors accounting for the change in the Achilles tendon moment arm between rest and MVC revealed that both the Achilles tendon action line and all instant centres of rotation shifted distally during contraction relative to their resting positions. Placement of markers on the Achilles tendon action line revealed that a displacement of the tendon could account for 0.6–1.1 cm, while the instant centres of rotation shifted by 0.3–0.4 cm only (Maganaris et al. 1998).

In contrast with the COR method, the TE method did not show any difference between contracting conditions (Fig. 3). This was attributed to the fact that, although both dL and dφ were altered during MVC compared with rest at any given foot rotation step (see Fig. 2), their ratio, which determines the magnitude of the moment arm value, remained constant between contracting conditions.

Although a direct comparison between the two method estimations is not possible due to differences in the ankle angles studied, it is evident from Fig. 3 that the resting estimations of the two methods are in agreement. This finding is consistent with previous in vivo and in vitro measurement-based reports (Maganaris 2000; Boyd and Ronsky 1998; Spoor and van Leeuwen 1992). The increase in the Achilles tendon moment from dorsiflexion to plantarflexion is also in line with several previous studies (Klein et al. 1996; Hintermann et al. 1994; Rugg et al. 1990; Grieve et al. 1978). Spoor et al. (1990), however, have observed a decrease in the Achilles tendon moment arm in the transition from neutral to plantarflexion angles in cadaver TE method-based measurements. This difference might be associated with inter-subject differences in the mechanical properties of the ankle joint ligaments. Near end-range positions these ligaments are subjected to loading (Leardini et al. 1999a, b) and therefore undergo visco-elastic deformations. The deformation level would depend on the ligament structural and material characteristics, which may vary as a function of age, chronic physical activity and disuse, and specimen condition before testing (e.g. fresh or preserved) (for review see Butler et al. 1978). The relative position of the tibio-talar and talo-calcaneo-navicular joints (and their axes) may thus vary towards end-range positions across subjects (Spoor et al. 1990; Lundberg and Svensson 1993; Lundberg et al. 1989), and this would affect the moment arm lengths of the tendons involved.

The two method estimations during MVC were in striking disagreement. Differences in the assumptions and limitations between the two methods might account for this disagreement. Errors in the COR method estimations would be associated with errors in the joint axis location. A misplacement of the ankle joint axis, however, would not affect the position of the Achilles tendon action line whose shift in the transition from rest to MVC was the major contributor to the differences between resting moment arms and those measured during MVC (see Maganaris et al. 1998). In contrast, errors in the TE method estimations would be associated with errors in both estimation of musculotendon excursion and measurement of joint rotation. Differences could also be attributed to the fact that in the COR method the talus was used to locate the instant CORs whereas in the TE method the calcaneus was used to measure joint rotation. Additional measurements, however, showed that use of talar rotation instead of calcaneal rotation had no effect on the moment arm values obtained using the TE method.

It must be realized that there is no "golden standard" for in vivo 2D moment arm estimations and therefore it is not clear which of the two methods employed in the study gives more accurate estimations. It seems, however, that the TE method as applied in the present study involves more limitations and assumptions than the COR method in which measurement errors are likely to be small. Thus, the TE method should be considered carefully, especially during MVC. The COR method has been often applied at rest when estimating musculotendon forces and stresses during plantarflexion MVC (e.g. Ito et al. 1998; Fukunaga et al. 1996b; Fukashiro et al. 1995). The present findings suggest that there is a contraction effect upon the COR method Achilles tendon moment arm estimations and that resting values should be multiplied by a factor of 1.22–1.27 to obtain respective values during MVC.

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