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The effect of foot type on the Achilles tendon moment arm and biomechanics

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A R T I C L E I N F O

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A B S T R A C T

Background: The aim was to calculate the Achilles tendon moment arm in different degrees of plantarflexion for pes planus, pes cavus and normal arched feet.

Methods: 99 patients (99 radiographs; 40 males, 59 females; mean age 49 years, SD 15) with a healthy ankle joint and a preoperative weightbearing lateral radiograph of the foot were included. Three groups (pes planus, pes cavus and normal-arched feet) with equal sample sizes ($n = 33$) were formed. On radiographs, the angle formed between a horizontal line and the line connecting the insertion of the Achilles tendon with the center of rotation of the ankle, was measured. The interrater reliabilities (ICC) of the angle alpha were compared on radiographs and on MRIs. Using the angle alpha, the Achilles tendon moment arm was calculated in different plantarflexion positions.

Results: The ICC of alpha was higher on radiographs (0.84, [0.73–0.91]) than on MRIs (0.61, [0.27–0.81]). The average alpha was statistically significantly different (normal arched foot 31 degrees (°), pes planus 24°, pes cavus 36°, $p = 0.021$), resulting in a significant shorter Achilles tendon moment arm for pes cavus than for pes planus ($p < 0.0001$) and normal arched feet ($p = 0.006$) in neutral position.

Conclusion: The data suggests that it is feasible to use radiographs to measure the Achilles tendon moment arm. The maximum Achilles tendon moment arm is reached at different angles of ankle flexion for pes cavus, pes planus and normal-arched feet. This has to be taken into consideration when planning surgeries.

1. Introduction

During locomotion, propulsion is based on the ability to transmit forces to the forefoot. In a simple, quasistatic model, the ground reaction force is balanced by an internally generated muscle force, the pull of the triceps surae complex. This force is then transferred through the Achilles tendon to the calcaneus and subsequently to the metatarsal heads. During the gait cycle, the moment arm of the ground reaction force increases. It extends from under the heel, to the midfoot, to the metatarsal heads at takeoff. This increased moment arm is in return balanced by the generated moment of the force in the Achilles tendon/triceps surae [1,2]. The Achilles tendon moment arm can be determined using different methods. Two out of these methods which are often used are the center of rotation (COR) method and the tendon excursion (TE) method [3]. For the COR method, sagittal two-dimensional images of the ankle are needed. On the images, the COR of the ankle joint has to be determined. The perpendicular distance between the COR and the Achilles tendon forms the Achilles tendon moment arm. For the TE method the tendon displacement is measured for different angular joint excursions. The ratio of the tendon excursion to the angle equals the Achilles tendon moment arm [3,4]. Both methods have their strengths and limitations. For the COR method, MRI are frequently used, increasing the costs while for the TE method, ultrasonography is usually used [3]. An advantage of the MRI however is that the different anatomic structures are highly visible. Limitations include that the determination of the COR and the line of action of the tendon force may contain inaccuracies. While for the TE method, the assumption is made that the tendon tension/stretch is constant [5]. The Achilles tendon moment arm obtained with the TE method was smaller in one study than the value obtained with the COR method [3]. In another study the Achilles tendon moment arm, obtained with the COR and the TE method, were similar [6]. A strong relationship between the values

Abbreviations: alpha, Angle between L and L'; ATI, Calcaneal insertion point of the Achilles tendon; CI, Calcaneal inclination angle; COR, Center of rotation of the ankle; FL, Foot length; ICC, Intraclass correlation coefficients; L, Line connecting ATI with COR; L', Moment arm of the Achilles tendon; $L'_{calculated}$, Calculated moment arm of the Achilles tendon; ML, First metatarsal bone; MRI, Magnetic resonance imaging; SD, Standard deviation

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seems to exist. The moment arm of the Achilles tendon however, is controversially discussed. A lot of authors measured the Achilles tendon moment arm using MRI [7,8] or ultrasonography [9,10], some showing a change in moment arm length across various ankle positions [10,11] while others see no significant change [7,10]. There is evidence however, that the Achilles tendon moment arm is load dependent [12], which is usually not considered with MRI and ultrasonography measurements, but is considered when using weightbearing radiographs.

When planning secondary reconstruction of the Achilles tendon, the surgeon is faced with challenging questions, in particular how he or she will be able to restore the original pull of Achilles tendon about the axis of rotation of the ankle joint. Restoration of continuity and tension of the heel cord may meet the primary goal to obtain flexion power of the foot. Gained function and strength will mainly depend on to which extent the biomechanics have been restored, as basically defined by the Achilles tendon moment arm. If the Achilles tendon moment arm remains small, resulting power will be limited. A further aspect that needs to be considered in the clinic, are influences on the Achilles tendon moment arm through differences in the morphology of the bone, anatomical position of the bone and soft tissue, found for example in cavus and planus feet when compared to normal feet [13–16].

The aim of this study was to calculate the Achilles tendon moment arm with the foot in different degrees of dorsi- and plantarflexion for three foot types (pes planus, pes cavus and normal-arched feet).

2. Methods

This retrospective analysis was conducted according to the Declaration of Helsinki and the guidelines for Good Clinical Practice. The study protocol was approved by the local ethics committee.

2.1. Data source and study population

99 patients (99 radiographs; 40 males, 59 females; mean age 49 years, SD 15) with a healthy ankle joint were included in the study. Inclusion criteria was a preoperative weightbearing lateral radiograph of the foot (recorded between January 2012 and December 2016), exclusion criteria was any hardware present in the foot.

The calcaneal inclination (CI) angle was determined on lateral weightbearing radiographs. According to this, the foot was classified as a pes planus, pes cavus or normal-arched foot (see Table 1, Fig. 1) [17]. Three groups with equal sample sizes ($n = 33$) were formed. Additionally, the foot length (FL) and the length of the first metatarsal bone (ML) were measured.

2.2. Measurements on radiographs

In order to take the load dependence of the Achilles tendon moment arm into account, the Achilles tendon moment arm was determined on lateral weightbearing radiographs using the COR method (Fig. 1): The center of rotation of the ankle (COR) was defined with a circle fitting the curvature of the talar body. A line (L) connecting the calcaneal insertion point of the Achilles tendon (ATI) with the COR, was drawn. The ATI was defined accordingly: if a pointy calcaneal spur was visible at the calcaneal tuberosity, this point was set as the ATI. Otherwise, the caudal part of the second semicircle of the posterior surface of the calcaneal tuberosity was determined as ATI. Furthermore, the angle alpha between L and the horizontal line (L') – the moment arm of the Achilles tendon – was calculated.

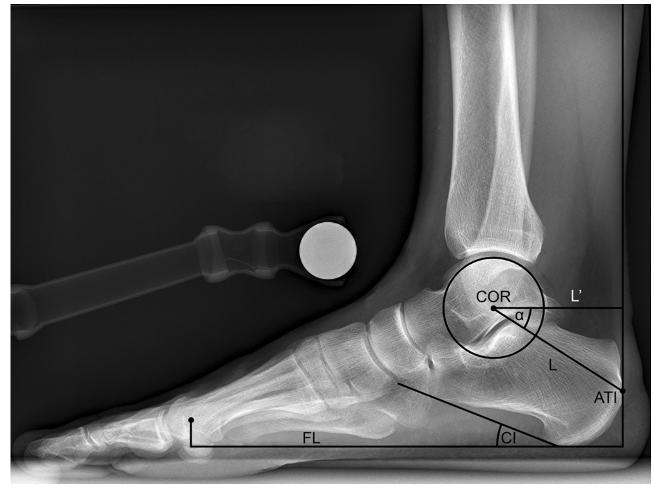

Fig. 1. The measurement of the lateral weightbearing radiograph were the center of the insertion of the Achilles tendon (ATI), the center of rotation of the ankle (COR), the line connecting the insertion point and the center of rotation (L), the angle alpha between L and a horizontal line (L', which is the moment arm of the Achilles tendon), the length of the foot (FL) and the calcaneal inclination (CI) angle.

All measurements were performed using a digital image processing software (IMS, Imagic, Glattbrugg, Switzerland). All described radiographic parameters were measured by a research associate not involved in patient care.

Table 1
Classification of pes planus, pes cavus and normal-arched food on the basis of the calcaneal inclination angle [17].

	Calcaneal inclination angle	
	Female	Male
Pes planus	<17.2°	<17.9°
Normal-arched foot	17.2°–23.3°	17.9°–25.4°
Pes cavus	>23.3°	>25.4°

2.3. Reliability

To test whether measurements on weight bearing radiographs are reliable and comparable to measurements on MRI, the angle alpha was measured and compared in 33 feet of which both a radiograph and MRI were available. Three blinded observers carried out these measurements in a random order. The interobserver reliability of the angle alpha on radiographs as well as on MRIs was calculated using intraclass correlation coefficients (ICC, single measurement, absolute agreement (2, 1)). To determine whether measuring the angle alpha on radiographs was comparable to measuring the angle alpha on MRIs, the intraobserver reliability was calculated between measurements performed on radiographs to measurements performed on MRIs. Intraobserver reliability was determined by comparing three measurements of alpha (measured on radiographs) performed by one observer with two weeks interval.

An ICC value greater than 0.9 stands for an excellent agreement, an ICC value between 0.75 and 0.9 for a good agreement and an ICC value between 0.5 and 0.75 indicates a moderate agreement [18].

2.4. Calculation of the moment arm of the Achilles tendon

The foot and the tibia were considered to be two rigid segments, with the center of the talus representing the center of rotation. Additionally, the influence of all other muscles was neglected. The resulting moment arm of the Achilles tendon ($L'_{calculated(i)}$) was calculated as follows:

$$L'_{calculated(i)} = \cos(alpha - plantarflexion(i)) \times L$$

$$i \in \{-30, -20, -10, 0, 10, 20, 30, 40, 50\}$$

2.5. Statistical data analysis

The statistical data analysis was performed with IBM SPSS Statistics, version 23 (Armonk, NY) and R Studio, version 3.1.3 (Boston, MA). The normal distribution of the data was tested with Shapiro–Wilk tests. Homogeneity of variance was assessed using Levene's test. By normally distributed data, one-way analyses of variance were performed (Bonferroni as post-hoc comparison) otherwise Kruskal–Wallis tests (Dunn-Bonferroni as post-hoc comparison) were carried out. A P value less than 0.05 was set as statistical significance level.

3. Results

Between the three foot types, L ($p = 0.199$) and ML ($p = 0.200$) was on average statistically not significant. Furthermore, the average age between pes planus (51.1 years, SD 14.9), pes cavus (49.0 years, SD 15.4) and normal-arched feet (46.8 years, SD 14.1, $p = 0.347$) was also not significant.

The angle alpha was on average significantly different between all three foot types (pes cavus = 35.5°, SD 6.0; normal-arched foot = 31.4°, SD 5.6 and pes planus = 23.8°, SD 6.4; biggest p-value = 0.021). This resulted in a significant difference in L' between pes cavus (51 mm, SD 5) and pes planus (58 mm, SD 5; $p < 0.0001$) as well as normal-arched feet (56 mm, SD 6) and pes cavus (51 mm, SD 5; $p = 0.006$) in midstance. There is high evidence, that pes planus showed on average a bigger FL (191 mm, SD 15) compared to pes cavus (179 mm, SD 17; $p = 0.001$). For more results see Table 2.

The maximum of the calculated Achilles tendon moment arm length was found at different amounts of plantarflexion (for pes planus 62.5 mm, SD 4.8 at 20°; for normal-arched feet 65.2 mm, SD 5.7 at 30° and for pes cavus 63.2 mm, SD 6.9 at 40°) according to the model of the stance phases (Fig. 2).

The interrater reliability of alpha was higher on radiographs (ICC = 0.84, 95% confidence interval (CI): 0.73–0.91) than on MRIs (ICC = 0.61, 95% CI: 0.27–0.81). The ICC comparing alpha measured on MRIs and radiographs was 0.63 (95% CI: 0.50–0.74). The test-retest reliability of alpha on radiographs was 0.96, (95% CI: 0.93–0.98).

4. Discussion

The data from the present study suggests that the foot configuration determines the moment arm of the Achilles tendon dependent on the angle of plantarflexion. The maximum Achilles tendon moment arm is reached at different angles of plantarflexion for the various foot postures (cavus, planus, normal). This has to be taken into consideration when planning surgeries that change alpha or L, as they may also result in changes of plantarflexion power. Furthermore, a redistribution of joint moment arms and a reduced capacity to control forward velocity at heel strike have been suggested to be associated with adverse plantar pressure patterns [19].

Several methods have been applied to determine the Achilles tendon moment arm, such as tendon excursion [5,20] and sequential imaging [11,21,22] in changing foot positions. Due to the greater availability of radiographs compared to MRIs in daily clinical practice and taking into consideration the influence of load on the moment arm, measurements on weightbearing radiographs were performed in the present study. Furthermore, the high reliability of the angle alpha on radiographs observed in this study encourages the further use of radiographs compared to MRIs.

Kim et al. (2011) described a proximal migration of the ATI with age [23]. To examine a possible influence of age on the current study data, statistical difference in the age of the three groups was tested and not found.

In the literature, the increase in the length of the moment arm of the Achilles tendon amounted to 25% at rest when going from 15° dorsiflexion (4.4 cm) to 30° plantarflexion (5.5 cm), and 30% during maximum voluntary contraction (5.4 cm–7 cm) [21]. Compared with the results of our computation, the reported maximum average values of the calculated Achilles tendon moment arms in the literature are shorter.

To further interpret the effect of the shorter Achilles tendon moment arm on the maximum force used for propulsion is difficult. However, according to the principle of the moment formula, by consistent ground reaction force, the generated force has to be bigger with a shorter moment arm.

When going from dorsi- to plantarflexion, the proportional changes of the calculated moment arm are higher compared with the reported

Table 2
Results of statistical analysis.

Variable	Description	Foot type 1: mean (SD) Foot type 2: mean (SD)	p-Value
L'	The length of the moment arm of the Achilles tendon [mm]	Pes planus: 58 (5) Normal-arched foot: 56 (6)	0.452
		Pes planus: 58 (5) Pes cavus: 51 (5)	< 0.0001
		Normal-arched foot: 56 (6) Pes cavus: 51 (5)	0.006
L	The distance between the Achilles tendon insertion and the center of the ankle joint [mm]	Pes planus: 63 (5) Normal-arched foot: 66 (6) Pes cavus: 64 (7)	0.199
alpha	The angle between the moment arm of the Achilles tendon and the Achilles tendon insertion [degrees]	Pes planus: 23.8 (6.4) Normal-arched foot: 31.4 (5.6)	< 0.0001
		Pes planus: 23.8 (6.4) Pes cavus: 35.5 (6.0)	< 0.0001
		Normal-arched foot: 31.4 (5.6) Pes cavus: 35.5 (6.0)	0.021
FL	The length of the foot [mm]	Pes planus: 191 (15) Normal-arched foot: 187 (16)	0.954
		Pes planus: 191 (15) Pes cavus: 179 (17)	0.001
		Normal-arched foot: 187 (16) Pes cavus: 179 (17)	0.026
ML	The length of the first metatarsal bone [mm]	Pes planus: 70 (6) Normal-arched foot: 69 (6) Pes cavus: 68 (5)	0.200

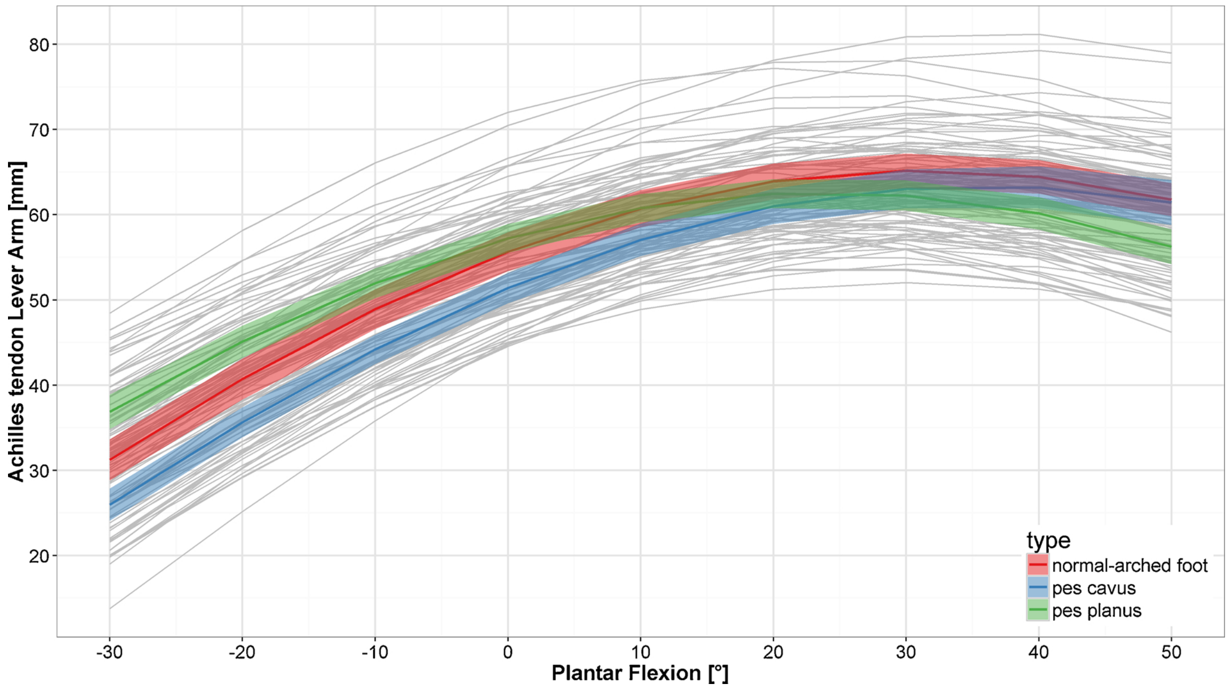

Fig. 2. The Achilles tendon moment arm for different degrees of plantarflexion for normal-arched foot, pes cavus and pes planus (mean and 95% confidence interval).

values in the literature [7,21]. A possible reason for this could be that the above mentioned authors used nonweightbearing MRI images to measure the Achilles tendon moment arms. Thus the tendon was not loaded and the methods used to measure were different.

This study has several limitations which need to be considered. For one, the ATI is an area, but for the sake of simplicity it was considered it to be a point. A second limitation was that the direction of the Achilles tendon pull was defined as being vertical, since the direction of the calf muscle pull could not be determined. Furthermore, the influences of the muscles were neglected, making it difficult to draw conclusions on the kinematics and kinetics of the foot using a static model.

In conclusion, the data suggests that it is feasible to use radiographs to measure the Achilles tendon moment arm. Furthermore, the maximum Achilles tendon moment arm is reached at different angles of plantarflexion for the various foot postures (cavus, planus, normal). The data of this study based on a radiographic model will provide important knowledge to the surgeon when planning surgery and calculating the amount of correction needed. Obtained data will also help to explain symptoms and to understand functional incompetence of a patient.

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Declarations of interest

None.

Ethical approval

2017-00348.

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