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ANATOMIC VARIATIONS

Differences in the strain applied to Achilles tendon fibers when the subtalar joint is overpronated: a simulation study

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Abstract

Purpose The purpose of this study was to investigate the strain applied to each of the tendon fiber bundles of the medial head of the gastrocnemius (MG), the lateral head of the gastrocnemius (LG), and the soleus muscle (Sol) that compose the Achilles tendon (AT) when the subtalar joint is pronated and supinated.

Methods Three AT twist types (least, moderate, extreme) were investigated. Using the MicroScribe system, the AT and the talocrural and subtalar joints were digitized to reconstruct three-dimensional models. Using this system, subtalar joint rotations in the pronation (20°) and supination (20°) directions were simulated, and the degrees of strain (%) on each tendon were calculated.

Results For all twist types, when the subtalar joint was pronated, MG, LG, and Sol stretched, and when supinated, MG, LG, and Sol shortened. In particular, the least and severe twist types had large degrees of strain of Sol when the subtalar joint was pronated, and furthermore, each tendon fiber composing Sol had different degrees of strain.

Conclusions The study results suggest that the degree of strain applied within the AT with subtalar joint pronation is not constant, and that, especially in least and extreme twist types, the risk of developing AT disorders may increase.

Keywords Achilles tendon · Twisted structure · Three-dimensional model · Achilles tendon disorder

Introduction

Although Achilles tendon (AT) disorders do not typically become severe, they occur frequently and are considered difficult to manage. Recently, several effective treatment methods were reported, but there are currently no effective methods to prevent them [1, 10]. The reason for this could be that the mechanisms of the disorders themselves are not completely understood.

With respect to the mechanism of onset, Clement et al. postulated that the development of a "whipping action" at the AT due to excessive pronation of the foot may be the mechanism for the onset of AT disorders or AT rupture [2].

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Recently, through previous studies, non-uniform strain in the AT has become a focus as a mechanistic factor in the development of AT disorders, and a study in fresh cadavers focused on the twisted structure of the AT as a factor for non-uniform strain in the AT [7]. In addition, a simulation study's results suggested that the degree of strain applied within the AT with calcaneus pronation is not constant, and that, especially in severe twists, the risk of developing AT disorders may increase [5]. However, the limitation of these reports is that they did not account for the moments of the actual ankle axis, specifically of the talocrural and subtalar joints.

The purpose of this study was to investigate the strain applied to each of the tendon fiber bundles of the medial head of the gastrocnemius (MG), the lateral head of the gastrocnemius (LG), and the soleus muscle (Sol) that compose the AT when the subtalar joint is pronated and supinated.

Materials and methods

Cadavers

Three legs from three Japanese male cadavers (mean age at death: 75 ± 14 years, left sides) that had been switched to alcohol after placement in 10% formalin were evaluated. This study was approved by the Ethics Committee of our university.

Methods

One author (first author) dissected the AT alone. First, the lower limbs were cut 10 cm above the knee to produce isolated specimens. From the facies posterior cruris, skin, subcutaneous tissue, and crural fascia were removed. Next, the connective tissue surrounding the AT was carefully removed, and the AT fiber bundles attached to the muscle bellies of MG, LG, and Sol were separated. Although these AT fiber bundles are strongly fused, by following the path of a relatively thick tendon fiber that represents each of these tendon fiber bundles, the border between them could be identified for separation. Furthermore, each fiber bundle was finely separated into 3–4-mm tendon fibers. In general, MG was separated into 5–6 tendon fibers, LG was separated into 4–6 fibers, and Sol was separated into 6–12 fibers. Subsequently, each leg was defined as Type I (least), Type II (moderate), or Type III (extreme), one leg for each twist type, based on a classification determined in a previous study [3, 5]. In the next step, the lower limb specimens were firmly fixed to the table such that they did not move, and a 3D Digitizer MicroScribe system (G2X-SYS, Revware, NC, USA) (Fig. 1) was used to create a three-dimensional reconstruction by digitizing the furthest distal ends of the muscle–tendon junctions of MG, LG, and Sol and the calcaneal tuberosity insertion site. The talocrural joint (the line connecting the inferior borders of the medial and lateral malleoli) and the subtalar joint (the line connecting the lateral border of the calcaneal tuberosity and the midpoint of the talar head) were designated as the joint axes [9]. Rhinoceros 3D software (McNeel, Seattle, WA) was used for three-dimensional construction (Fig. 2). The simulations were then used to calculate the strain applied to each of the tendon fiber bundles of MG, LG, and Sol that compose the AT as strain (%) during inversion (20°) and eversion (20°) on the subtalar joint axis on the talocrural joint axis (0°). Using the following formula, AT strain was expressed as the percentage of change of fiber bundle length from the initial limb position (LTS), when both flexion/extension and inversion/eversion were 0°, to the final position after motion [6].

Fig. 1 The MicroScribe system

$$\text{Strain}(\%) = \left[\left(\frac{L^T - L_S^T}{L_S^T}\right) \times 100\right].$$

The MicroScribe system is a high-precision instrument (manufacturer's specifications, measurement precision of 0.23 mm), but measurements must be performed manually. In addition, although the study cadavers were thoroughly fixed to the examination table such that they did not move, it was necessary to test whether they had moved, since the measurements entailed dissection of the ligament tissue. A previous study by the authors found the intraclass correlation coefficient (1, 1) to be 0.97–0.99, which indicates a high level of reliability and reproducibility [3, 5].

Results

The degree of strain applied to each of the tendon fiber bundles is shown by twist type in Table 1. In all twist types, different degrees of strain were applied to MG, LG, and Sol. In addition, in all twist types, MG, LG, and Sol stretched when pronated on the subtalar joint, and MG, LG, and Sol shortened when supinated on the subtalar joint. In particular, the least and severe twist types had large degrees of strain of Sol when the subtalar joint was pronated, and furthermore, each tendon fiber composing Sol had different degrees of strain.

Discussion

This study showed the degrees of strain of each of the tendon fiber bundles of MG, LG, and Sol that compose the AT by twist type when the subtalar joint was pronated or supinated. To the best of our knowledge, there have been no other reports that focused on the twist type in assessing the

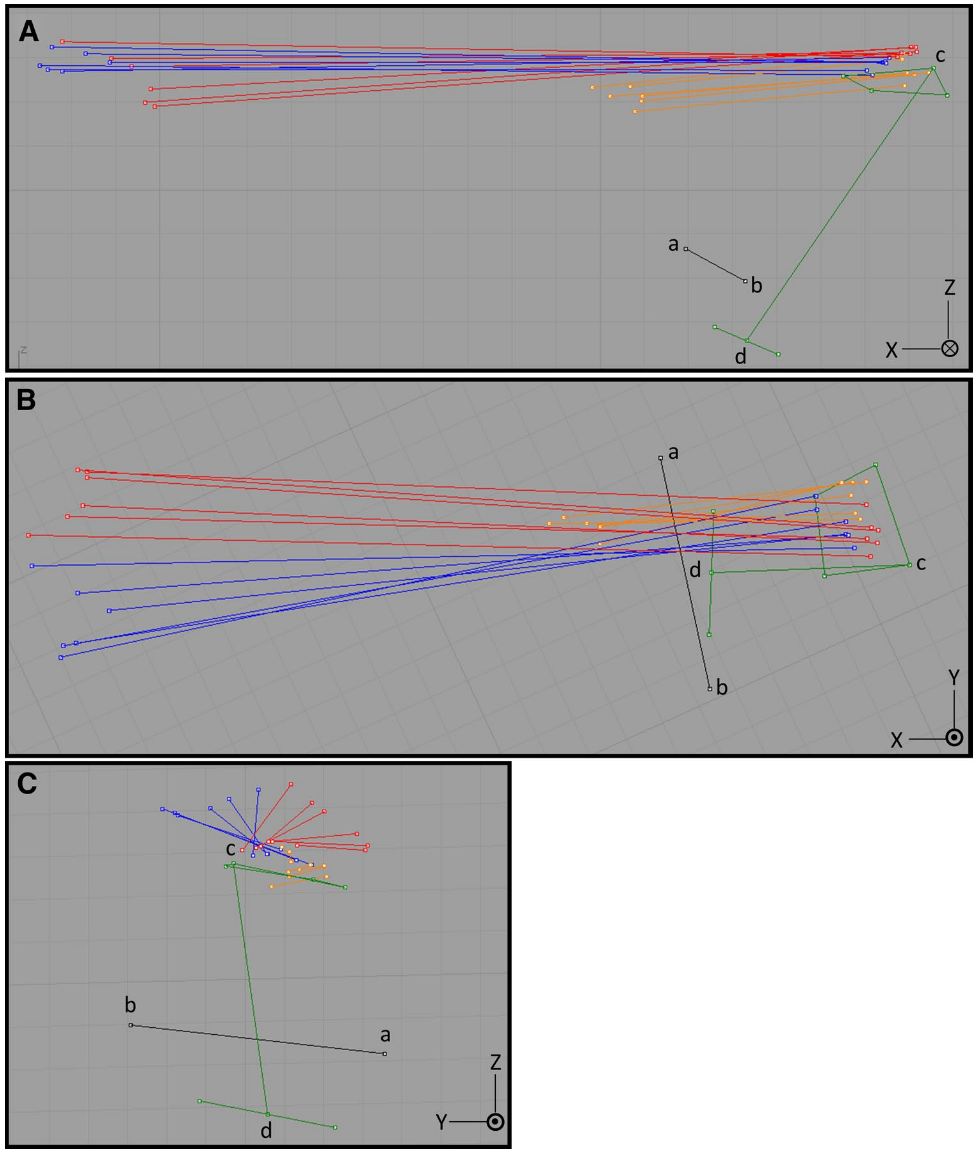

Fig. 2 Three-dimensional construction diagrams of the left Achilles tendon. **a** Lateral view. **b** Vertical view. **c** Proximal view. Red line: The fiber bundles from the medial head of the gastrocnemius. Blue line: The fiber bundles from the lateral head of the gastrocnemius. Yellow line: The fiber bundles from the soleus muscle. a–b line: The talocrural joint (the line connecting the inferior borders of the medial and lateral malleoli). c–d line: The subtalar joint (the line connecting the lateral border of the calcaneal tuberosity and the midpoint of the talar head). (Color figure online)

degree of strain of each of the tendon fiber bundles when the subtalar joint is pronated or supinated.

In the present study, the degree of Sol strain was − 7.5% ± 2.0–7.8% ± 1.6% when the subtalar joint was pronated (20°) and supinated (20°). A previous study reported that cadaveric calcaneal pronation (15°) and supination (15°) resulted in a maximum strain of − 9.4–15.3% [7]. This confirmed that the degrees of strain calculated in the simulation in this study were all within the range of biological movements.

As a mechanism of development of AT disorders, the non-uniform strain in the AT with calcaneal pronation has been reported as a cause [5, 7]. Moreover, it has been reported that AT disorders typically present 2–6 cm proximal to the calcaneal tuberosity [8] and occur more commonly on the medial side than on the lateral side [10], which is where Sol is located [4]. Based on these reports, it is presumed that the primary injured tissue is Sol. In the present study, the least and severe twist types had a large degree of strain of Sol when the subtalar joint was pronated, and furthermore, each tendon fiber composing Sol had different degrees of strain. Therefore, in the least and severe twist types, the risk of developing AT disorders may increase.

There are several limitations to this study. First, the results of this study using tendons in alcohol after placement in 10% formalin were likely to change the property comparatively to fresh tissue. Second, this study did not use detailed 3D data from CT or X-ray examinations. Therefore, the mobility of talocrural joint and subtalar joint were not considered. Third, this study involved simulations with cadavers. Therefore, gravity, weight-bearing, muscle activity, the posture of the foot, AT elasticity and function were not considered. In the future, we believe that it will be necessary to perform biomechanical research using our basic data with in vivo samples.

Table 1 The degree of strain applied to each of the tendon fiber bundles

	Pronation							Supination					
	20°			10°			0°	10°			20°		
	MG	LG	Sol	MG	LG	Sol		MG	LG	Sol	MG	LG	Sol
Type I	1.5 (0.9)	1.9 (1.2)	7.8 (1.6)	0.7 (0.5)	0.9 (0.6)	3.9 (0.8)	0	− 0.7 (0.5)	− 0.9 (0.6)	− 3.8 (0.9)	− 1.4 (1.0)	− 1.7 (1.2)	− 7.5 (2.0)
Type II	1.0 (0.7)	1.1 (0.7)	6.4 (0.9)	0.5 (0.3)	0.5 (0.3)	3.3 (0.5)	0	− 0.5 (0.3)	− 0.5 (0.3)	− 3.4 (0.5)	− 1.0 (0.7)	− 1.1 (0.7)	− 6.8 (1.0)
Type III	1.2 (0.6)	2.1 (0.9)	7.5 (2.1)	0.5 (0.3)	1.0 (0.5)	3.7 (1.1)	0	− 0.4 (0.3)	− 0.8 (0.4)	− 3.3 (1.2)	− 0.7 (0.5)	− 1.4 (0.9)	− 6.2 (2.3)

Values represent means (±SD) (%)

Talocrural joint axis: 0°

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Author contributions ME and TT contributed to study design and data collection, and drafted the manuscript; TI and TK contributed to data analysis and made critical revisions to the manuscript; WI, EN, RH, MI, and FK made critical revisions to the manuscript; IK supervised the study, contributed to analysis and interpretation of data, and made critical revisions to the manuscript. All authors read and approved the final manuscript prior to submission.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval The methods were carried out in accordance with the 1964 Declaration of Helsinki, and the cadavers were legally donated for the research by the Nippon Dental University of Life Dentistry at Niigata in Japan.

Informed consent Informed consent was obtained from the families of all subjects.

Availability of data and material The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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