**ABSTRACT INTRODUCTION:** Achilles tendon injuries are common, occurring about 250,000 per year in the US alone, yet the mechanisms of tendon injuries and degeneration remain unknown. One interesting feature in the structure of the Achilles tendon is that the fibres of the Achilles tendon do not descend straight down but experience a variable degree of spiral torsion. A number of authors have speculated that fibre torsion is nature’s way of increasing tendon strength that allows elongation and elastic recoil in the tendon while others suggested that fibre torsion results in less fibre buckling leading to less deformation of individual fibres under tension (1-3). However, quantitative analysis of the role of fibre torsion in the Achilles tendon has not been done. The aim of this study is to investigate the role of fibre torsion presents in the Achilles tendon using subject-specific FE model and tissue mechanical experiment. Our hypothesis is that fibre torsion allows even distribution of stress across the whole tendon thus improving tissue strength.

**METHODS:**

Mechanical experiment: Data from a previous study (4) was used where fresh-frozen human Achilles tendons from donors were imaged with ultrasound and then undergone cyclic testing with a MTS machine.

**Subject specific FE model generation:** We used Free Form Deformation as in our previous publication (5) to generate ten subject-specific finite element models of the Achilles tendon (eight female and two male, average age 68 yrs) using ultrasound images from the above mentioned study (4).

**Fibre torsion implementation:** Van Gils et al. (3) reported the existence of fibre torsion in the Achilles tendon and quantified the degree of torsion to be between 50 to 60 degrees in the average around 37 degrees. We used the mutually-orthogonal curvilinear material coordinate system in our FE models and aligned it according to the fibre torsion in the Achilles using a previously validated fibre fitting procedure (6). Five different torsion angles were implemented – 0, 15, 30, 45, 60 degrees.

**Material property optimization:** The values of material coefficients for transversely isotropic material properties (7) were estimated using the cyclic experimental data from a previous study (4) in a similar way as in our previous work. In order to characterize the influence of fibre torsion, material coefficients for different torsion angles were obtained separately. Therefore, for each tissue, we performed five material optimizations at the five different torsion angles investigated – 0, 15, 30, 45, 60 degrees.

**Tendon rupture prediction:** In our previous publication, we numerically predicted tendon rupture load for the case of no fibre torsion using the experimentally reported failure stress of the Achilles tendon (~100N). In this study, we investigated how fibre torsion changes the tissue internal stress by measuring the rupture loads at different torsion angles. Therefore, for each torsion angle (0, 15, 30, 45, 60 degrees) cases, we predicted the rupture load for the tissue. We used the force ratio of triceps components reported by Albracht et al. (8), which is 3:2:1 for soleus: medial gastrocnemius: lateral gastrocnemius. The tissue model was stretched until rupture and recorded the rupture load for the ten subject-specific models at five different torsion angles stated above.

**RESULTS SECTION:** Fibre torsion was successfully implemented as shown in Fig 1. Stress distribution patterns changed after implementation of fibre torsion in the model. When no fibre torsion is present, the stress is concentrated solely on the medial side of the tendon but introduction of fibre torsion redistributed this stress concentration to both medial and lateral sides, essentially relieving stress concentration. As seen in Fig 2, the degree of fibre torsion plays a role in how much stress is redistributed. When rupture loads were measured, it was found that fibre torsion angles of up to 30 degrees significantly improved tissue strength up to 33%. When considering the predicted rupture loads from all five cases, there appears to be a range of torsion angles that are optimal for tissue strength and when goes outside of this range, the tissue strength actually decreased.

**DISCUSSION:** Through subject specific finite element models (both in terms of geometry and material properties) we found out that the torsion in tendon fibres play a role of equalizing stresses on medial and lateral side. The motion of the foot from dorsiflexion eversion to plantar flexion inversion results in medial side of the tendon to experience higher stress and strains (9) (as shown in our no fibre torsion model in Figure 2). This will be detrimental to the tissue and will weaken the overall strength of the tissue. Fibre torsion, however, redistributes this stress concentration on the medial side to wider areas, subsequently relieving stress concentrations. This will improve the strength of the tissue especially under in-vivo loading cases. One of the limitations of this study is that the data is from a cadaveric study hence it was not possible to implement the actual in vivo loading conditions. Another limitation is that viscoelastic nature of tendon was not capture in our material model, which was transversely isotropic hyperelastic material. These limitations will be dealt with in our future works.

**SIGNIFICANCE:** (1-2 sentences): To the authors’ knowledge, this is the first study that elucidated the role of fibre torsion in the Achilles tendon in a quantitative manner. Our study also revealed that there exists an optimal torsion angle for tissue strength, which can be utilized in designing a training or rehabilitation protocol for people with tendon injuries or degenerations.


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![Fig 1. Fibre torsion implemented in FE models. It is a posterior view with medial on the right and lateral on the left](image1)

![Fig 2. Stress changes with respect to the fibre torsion angle changes. The presence of fibre torsion changes the stress concentration on the medial side to both medial and lateral sides](image2)

![Fig 3. Fibre torsion significantly improves tissue strength up to 30% when the angle is smaller than 30 degrees. There appears to be an optimal torsion angle for tissue strength.](image3)