Systematic Review

Sex differences in biomechanical properties of the Achilles tendon may predispose men to higher risk of injury: A systematic review

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ABSTRACT

Importance: Men have a higher risk of Achilles tendon (AT) injury, and the impact of morphological and mechanical sex differences may play a role.

Aim: The aim of this study is to systematically review the literature to determine whether there are sex-specific differences in AT morphological and mechanical properties and analyze how these differences may impact AT injury in both men and women.

Evidence review: A systematic literature search of articles published between 2001 and 2021, in the MEDLINE, EMBASE, and Cochrane databases was performed during May 2022 according to PRISMA. The primary outcome measures included sex-related differences in the mechanical and morphological properties of the Achilles tendon. Secondary outcomes included impact of sex on Achilles tendon properties and adaptation.

Findings: Nineteen studies with a total of 1,143 participants (613 men and 530 women) were included in this systematic review. Men had increased measurements when compared with women in the following: AT length, thickness, cross-sectional area (CSA), stiffness, peak force, loading rate, and voluntary muscle contraction. Women had an increase in CSA deformation, strain, and compliance.

Conclusions and relevance: Our study demonstrates that men have an increased AT length, thickness, and CSA, indicating that men may be subjected biomechanically to higher loads in their day-to-day activities. In addition, men have lower deformation and compliance properties, along with increased AT stiffness, reducing their capacity to adapt during loading, potentially increasing their risk of injury.

Level of evidence: IV.

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What is already known:

- The Achilles tendon is the strongest tendon in the body, with its morphological properties correlating with athletic performance capacities.
- Men have a higher risk of Achilles tendon injury than women, yet it is unknown why men have this propensity to injury and how biomechanical properties contribute.

What are the new findings:

- Men have an increased Achilles tendon length, thickness, and cross-sectional area.
- Men are subjected to higher biomechanical loads in daily activities.
- Men have lower deformation and compliance Achilles tendon properties compared to women, which reduces the capacity to adapt to load and increases injury propensity.

Introduction

The Achilles tendon (AT) is the thickest and strongest tendon in the human body with the ability to store and release elastic energy during walking, running, and jumping [1,2]. AT length, thickness, and cross-sectional area (CSA) have all been shown to be positively correlated with physical activities affecting velocity, force, and power, including sprint and push-off performance [3]. In addition, the literature has demonstrated that variations in properties including AT length, thickness, cross-sectional area (CSA), and stiffness can result in changes in force and torque which can affect the rate of tendon degeneration and pathology [2,4–7]. Understanding how these factors play a role in tendon injury is important to manage and prevent Achilles tendon injury and rupture.

Although previous studies have demonstrated that men are two to eight times more likely to rupture their Achilles tendon than women, the role that sex differences in connective tissue morphology play in the rates of AT muscle and tendon injury in the male and female populations has yet to be established [8–10]. To our knowledge, there is no consensus regarding the influence of gender on AT biomechanical properties as there has yet to be a systematic review conducted on this subject. Understanding these sex-related biomechanical differences is important when managing and treating AT injury. The aim of this study is to systematically review the literature to determine whether there are sex-specific differences in AT morphological and mechanical properties have been reported and analyze how these differences may impact AT injury in both men and women.

Methods

Search strategy

A systematic literature search of articles published between 2001 and 2021, in the MEDLINE, EMBASE, and Cochrane databases was performed during May 2022 according to PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) [11]. The combination of search terms included: Achilles AND Gender OR Sex [Appendix 1]. All synonyms were combined with the Boolean command AND and linked by Boolean command OR.

Eligibility criteria

Studies were included if they met the following criteria: evaluated biomechanical properties of the Achilles tendon, were written in the English language, were peer-reviewed published, included male and female study participants, and were human subjects, with adult populations. Exclusion criteria included animal studies, review articles, or did not evaluate for sex-related differences.

Study selection

The title and abstract were reviewed, and eligible studies received a full-text review. The reference lists were also screened. Two independent reviewers screened all texts, and any inconsistencies throughout the study selection were resolved by a senior author.

Data extraction, analysis, interpretation

The primary outcome measures included AT length, thickness, cross-sectional area (CSA), stiffness, peak force, loading rate, and voluntary muscle contraction. Secondary outcomes included impact of sex on Achilles tendon properties and adaptation. Outcome effect measures were reported based on percentages of studies that evaluated and assessed each outcome. The outcomes were tabulated, and studies were included in the analysis if they had evaluated for differences between the sexes. A study was not included in a specific outcome analysis if they did not assess said outcome. Tables were created for thorough organization, assessment, and evaluation of the outcomes. Two reviewers assessed each study and worked independently. The data was collected by two authors independently. Any inconsistencies throughout the study selection were resolved by a senior author. Meta-analysis was deemed inappropriate due to the heterogeneity of studies included in our review. Per SWIM guidelines, we identified a set of standardized metrics for use in synthesizing [12].

Quality assessment and best evidence synthesis

Quality assessment was performed by two authors independently using a modified Modified Minors Score [13]. Inclusion criteria were: published in a peer-reviewed journal (PRJ), stated aim (SA), had comparative groups (CG), used masked assessment (MA), compared and controlled for sex/gender (SG), defined inclusion/exclusion criteria (IE), performed adequate statistical analysis (ASA), specified outcomes which were performed (SOP), and had baseline equivalence of groups (BE). If consensus was not reached, a third author independently reviewed and a decision was made. All studies were included in the analysis given the nature of the included study pool. Low, moderate, and high quality were defined as scores <3, 3–6, and 7–9, respectively. Due to the heterogeneity of outcomes, a modified version of a best evidence synthesis was used to combine the results to classify the evidence [14].

This study did not warrant registration and a protocol was not prepared. There were no amendments or financial support and no competing interests of review authors. All data used is publicly available data which has been published in a PRJ.

Results

Search and literature selection

The initial literature search resulted in 536 total studies. Once duplicates were removed and the articles were screened for inclusion and exclusion criteria, 37 studies were included, and full texts were assessed for eligibility. After initial screening, there were 18 additional articles excluded because they either did not evaluate the resident population or were systematic reviews or review articles [Fig. 1].
Study characteristics

Nineteen studies were included in this systematic review. In total, there were 1,143 participants, of which 613 were men and 530 were women [Table 1] [5,7,15–31].

Quality assessment

Amongst the quality assessment results, all included studies scored in high-quality range (7–9) [Fig. 2]. There were 5 studies with a score of 7, 12 studies with a score of 8, and 2 studies with a score of 9. It is important to note that only two studies performed blinded assessment. Quality of evidence was comparable between the different included studies.

Tendon length

Four studies evaluated measurements of length [Table 2] [5,16,19,30]. All studies that assessed AT length and pennation angle of the AT reported larger values in men when compared with women [16,19,30]. There were no significant differences reported in variation of tendon properties between medial and lateral aspects of the AT or in medial gastrocnemius fascicle length [5,16].

Tendon thickness/CSA

Six studies evaluated measurements of AT thickness/CSA [Table 3] [16–19,24,30]. Four of the five studies that evaluated CSA and AT thickness reported higher values for men when compared with women [16–19,30].

Tendon stiffness

Seven studies evaluated measurements of tendon stiffness [Table 4] [5,7,16,17,22,23,30]. Four of the five studies that reported AT stiffness demonstrated increased AT stiffness in men when compared with women [7,16,22,30]. Three of three studies reported increased gastrocnemius stiffness in men when compared with women [7,16,23]. Fourné et al. reported an overall increased globular angular joint stiffness in men when compared with women [17]. In addition, Fourné et al. reported an increase in the elastic component of plantar flexors with passive motion and active motion in men and women, respectively [17].

Force, torque, moment

Six studies evaluated measurements related to force, torque, or moment [Table 4] [15,17,21,22,30,31]. Four studies reported increased plantar flexion torque and moment in men compared with women [15,21,30,31]. Two studies reported increased peak AT tendon force in men compared with women [22,30]. Peak AT stress, AT load, AT loading rates, and maximum voluntary contraction were all found to be higher in men when compared with women [23,30]. Intziegiani et al. evaluated AT CSA during rest and contraction and found that men high a higher CSA at both time points when compared with women [21]. Intziegiani et al. also found that CSA deformation, strain, and compliance were
### Table 1

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Study type</th>
<th>N (Male)</th>
<th>N (Female)</th>
<th>Age</th>
<th>Outcomes evaluated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deng et al. [16]</td>
<td>2021</td>
<td>Biomechanical Study, Correlational</td>
<td>18</td>
<td>18</td>
<td></td>
<td>Gender variation in the mechanical and architectural properties of the gastrocnemius muscle and AT</td>
</tr>
<tr>
<td>Foure et al. [17]</td>
<td>2012</td>
<td>Biomechanical Study, Cross-Sectional Study</td>
<td>49/43(CSA)</td>
<td>31/16 (CSA)</td>
<td></td>
<td>Sex Differences in muscle-tendon stiffness can affect the active and passive components of the plantar flexor's Series Elastic Component, intrinsic mechanical properties, and moment arm length</td>
</tr>
<tr>
<td>Fu et al. [18]</td>
<td>2016</td>
<td>Biomechanical Study, Cross-Sectional Study</td>
<td>165</td>
<td>161</td>
<td></td>
<td>Evaluate the elastic properties of the AT by shear wave elastography in different age and sex groups</td>
</tr>
<tr>
<td>Gonzalez et al. [19]</td>
<td>2020</td>
<td>Clinical Study; Prospective Study</td>
<td>35</td>
<td>30</td>
<td></td>
<td>Analyze physical AT properties (length, CSA, dimensions, etc.) in relation to the healthy athlete</td>
</tr>
<tr>
<td>Ho et al. [20]</td>
<td>2019</td>
<td>Biomechanical Study; Cross-Sectional Study</td>
<td>53</td>
<td>38</td>
<td>37.9 ± 11.6</td>
<td>Examine the influence of variables (age, sex, ROM, etc.) on AT intra-tendinous morphological changes in runners</td>
</tr>
<tr>
<td>Intziegianni et al. [21]</td>
<td>2017</td>
<td>Biomechanical Study</td>
<td>15</td>
<td>15</td>
<td>Male: 30 ± 4; Female: 28 ± 3</td>
<td>Examine the AT-CSA deformation unique to gender from rest to the maximum voluntary isometric contraction</td>
</tr>
<tr>
<td>Lepley et al. [22]</td>
<td>2018</td>
<td>Biomechanical Study, Cross-Sectional Study</td>
<td>18</td>
<td>17</td>
<td>Men: 23.9 ± 2.4; Women: 24.0 ± 3.9</td>
<td>Gender-specific mechanical properties of AT before and after 60 min of repetitive loading exercise</td>
</tr>
<tr>
<td>Morrison et al. [5]</td>
<td>2015</td>
<td>Biomechanical Study, Cross-Sectional Study</td>
<td>10</td>
<td>10</td>
<td>30.6 ± 7.3</td>
<td>Sex-specific resting length and stiffness of AT for competitive cyclists; lateral vs. medial AT properties</td>
</tr>
<tr>
<td>Muraoka et al. [23]</td>
<td>2005</td>
<td>Biomechanical Study, Cross-Sectional Study</td>
<td>24</td>
<td>12</td>
<td>Men: 27 ± 4; Women: 25 ± 5</td>
<td>Analyze the relationship between the mechanical features of the AT and triceps muscle strength, as well as any gender-related variances</td>
</tr>
<tr>
<td>Simpson et al. [26]</td>
<td>2017</td>
<td>Biomechanical Study, Cross-Sectional Study</td>
<td>10</td>
<td>11</td>
<td>Male: 24.0 ± 3; Female: 22.0 ± 3</td>
<td>Association between the velocity of the gastrocnemius muscle fascicle shortening and the stretch of the AT during isometric plantar flexion contractions, assuming variations in velocity and stretch between sexes</td>
</tr>
<tr>
<td>Sprague et al. [27]</td>
<td>2020</td>
<td>Biomechanical Study, Retrospective Analysis Study</td>
<td>70</td>
<td>48</td>
<td>Male: 39.1 ± 14.6; Female: 35.6 ± 14.8</td>
<td>Correlation of viscoelastic characteristics of the AT, sex, and age – in an uninjured AT</td>
</tr>
<tr>
<td>Tas et al. [7]</td>
<td>2019</td>
<td>Biomechanical Study, Experimental Study</td>
<td>24</td>
<td>30</td>
<td>Male: 21.5 ± 1.6; Female: 21.3 ± 1.6</td>
<td>Gender-specific variations in the AT and gastrocnemius at rest and tensioned state</td>
</tr>
<tr>
<td>Westh et al. [28]</td>
<td>2007</td>
<td>Biomechanical Study, Cross-Sectional Study</td>
<td>10</td>
<td>10 (runners); 10 (non-runners)</td>
<td>Male: 30.6 ± 4.9; Female: 25.6 ± 0.8</td>
<td>Explore the differences in structural and mechanical AT and PT properties in male runners, female runners, and female non-runners; impact of habitual training on these properties</td>
</tr>
<tr>
<td>Wezenbeek et al. [29]</td>
<td>2018</td>
<td>Controlled Laboratory Study; Clinical Study</td>
<td>31</td>
<td>32</td>
<td>Mean 34.4; 33 subjects b/w 18–25; 30 subjects b/w 40-55</td>
<td>Impact of age, sex, and type of exercise on the rise in AT blood flow</td>
</tr>
<tr>
<td>Zhang et al. [30]</td>
<td>2021</td>
<td>Biomechanical Study, Randomized Control Trial</td>
<td>15</td>
<td>15</td>
<td>Male: 24.7 ± 2.6; Female: 24.1 ± 2.7</td>
<td>In an inactive participant, explore sex differences of AT morphological and mechanical properties (force, stiffness, viscoelasticity)</td>
</tr>
<tr>
<td>Zhou et al. [31]</td>
<td>2017</td>
<td>Biomechanical Study, Cross-Sectional Study</td>
<td>7</td>
<td>7</td>
<td>Men: mean 34.7; Women: mean 29.0</td>
<td>During the standing calf raise, evaluate the sex-related architectural changes of the gastrocnemius muscle and AT</td>
</tr>
</tbody>
</table>

General characteristics of included studies. AT, Achilles tendon; N, number; ROM, Range of Motion; CSA, Cross-sectional area.

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found to be statistically and significantly higher in females compared to males [21].

**Discussion**

This study demonstrates variations between men and women in AT length, thickness, CSA, stiffness, force, and response to loading. These findings establish that men may have a biomechanical predisposition to sustaining an AT injury. Sex-specific differences in AT morphological and mechanical properties may play a role in the rate and risk of AT degeneration and injury. It is well known that men have a higher rate of AT injury when compared with women, although the reasons for this susceptibility have yet to be established [9,10]. Understanding how these factors may result in altered gait and biomechanics, particularly during...
activities involving running and jumping, is important in the prevention and management of AT injury in both men and women. The results of this study demonstrated increased AT length and pennation angle in men when compared with women. In addition, this study

**Table 2**

<table>
<thead>
<tr>
<th>Achilles Tendon Length Outcomes</th>
<th>Male vs. Female</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pennation angle</td>
<td>M&gt;F</td>
<td>[16]</td>
</tr>
<tr>
<td>Achilles tendon length</td>
<td>M&gt;F</td>
<td>[16,19,30]</td>
</tr>
<tr>
<td>Medial gastrocnemius fascicle</td>
<td>M = F</td>
<td>[16]</td>
</tr>
<tr>
<td>Variation of tendon properties</td>
<td>M = F</td>
<td>[5]</td>
</tr>
<tr>
<td>Achilles tendon</td>
<td>Cross-sectional area</td>
<td>M&gt;F</td>
</tr>
<tr>
<td></td>
<td>Thickness</td>
<td>M&gt;F</td>
</tr>
</tbody>
</table>

Larger Achilles tendon length was found in males, but no significant differences were reported in gastrocnemius or Achilles tendon medial and lateral aspect length. Higher thickness and cross-sectional area in males in 4 of 5 studies.

**Table 3**

<table>
<thead>
<tr>
<th>Tendon Stiffness Outcomes</th>
<th>Male versus Female</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Achilles tendon stiffness</td>
<td>M&gt;F</td>
<td>[7,16,22,30]</td>
</tr>
<tr>
<td>Gastrocnemius stiffness</td>
<td>M&gt;F</td>
<td>[7,16,23]</td>
</tr>
<tr>
<td>Globular angular joint stiffness</td>
<td>M&gt;F</td>
<td>[17]</td>
</tr>
<tr>
<td>Series elastic component of plantar flexors – Passive</td>
<td>M&gt;F</td>
<td>[17]</td>
</tr>
<tr>
<td>Series elastic component of plantar flexors – Active</td>
<td>F&gt;M</td>
<td>[17]</td>
</tr>
</tbody>
</table>

Greater Achilles tendon stiffness in males in 4 of 5 studies.

**Fig. 2.** Bias assessment.
found an increase in AT thickness and CSA in men when compared with women. These dimensions indicate an adaptation of increased force generation capacity and higher body mass in men when compared with women [21]. Previous studies have demonstrated that increased AT length and CSA were positively correlated with energy cost during submaximal running with an increased ability to store elastic energy from the ground reaction force [32]. These architectural properties can also be positively correlated with muscle strength, maximum force development, and power which was demonstrated in our results as men had higher AT force, maximum voluntary contractions, and plantar flexion torque [16]. These higher values also indicate tendon adaptation to mechanical loads in daily activities with increased stress, strain, and CSA which may signify that men may be subjected biomechanically to higher loads in their day-to-day activities, potentially increasing their risk of injury [30].

Our study also demonstrated an increase in AT stiffness in men when compared with women. Bell et al. reported that women may have lower vertical stiffness as a result of higher estrogen levels which has been shown to be linked to collagen synthesis [33]. Miller et al. also reported that estrogen may modulate the synthetic response of fibroblasts to mechanical loading [34]. Previous studies have demonstrated that a stiffer tendon is beneficial to sports performances, however, stiffness also decreases the ability to withstand repetitive stress [35,36]. Therefore, a stiffer tendon may be prone to a higher rate of injury and rupture with forceful, sudden contractions during activities, thereby increasing the risk of AT injury in the male population [30,36]. Intzigianni et al. reported that the AT deforms at its transverse level by reducing its CSA and that women demonstrate a significantly higher CSA deformation under maximum voluntary isometric contraction which indicates a more compliant tendon when compared with men [21]. These higher deformation and compliance properties combined with the smaller size of the tendon along with lower tendon stiffness may allow for better adaptation during loading. Kubo et al. demonstrated lower stiffness and hysteresis of the tendon structure in women as compared to their male counterparts [4]. These findings may provide an explanation for the gender differences observed in muscle and tendon function and stretch-shortening cycle exercises with athletic activities and underscores why men may be at a higher risk for AT injury [4].

The ability of male tendons to adapt to daily mechanical load, stress, and strain allows for the tendon to be subjected to a higher load and peak AT force than women [31]. However, if the stress exposed to the tendon is larger than the tendon can load, injury may occur – often the reason that men are more prone to Achilles injury. Given that men typically sustain AT ruptures in sporting activity, preventative measures can be taken to minimize degeneration of tendon mechanical properties. Incorporating frequent physical exercise rather than following a sedentary lifestyle will be of benefit, especially to those who enjoy occasional participation in recreational sporting activities [31]. Wezenbeek et al. demonstrated that running, skipping rope, and cycling exercises increase tendon blood flow and the metabolic rate of AT tissue [29]. Additionally, plyometric exercises can be utilized to target the AT as these have been shown to directly involve the tendon [24].

Animal studies evaluating sex differences between mechanical, structural, and histological properties of Achilles tendon and muscle have demonstrated superior tendon material properties in female tendons when compared with male tendons [37]. Pardes et al. found that female tendons had greater resistance to deformation under load with more efficient energy transfer as a result of decreased viscoelastic properties [37]. The authors attribute the greater susceptibility for AT damage observed clinically in men over women to these sex- and hormone-related differences resulting in inferior tendon and muscle properties [37].

Understanding the various differences in muscle and tendon biomechanical properties between men and women is an important consideration in order to better individualize the management and treatment following an AT injury. Rehabilitation protocols addressing sex differences in strength, stiffness, and deformation in response to load may be beneficial when rehabilitating a male or female patient to better expedite their return to daily or sport activities. In addition, knowledge of these differences may also aid in developing sex-specific preventative measures. Further research including a sex-specific rehabilitative comparative study is necessary to develop sex-specific exercises aimed at reducing the susceptibility of subsequent AT injury. It would be of value to pursue investigation of similar biomechanical metrics as the current study in the context of sex-specific rehabilitation, as well as to evaluate these protocols and their impact on return-to-sport and return-to-work. Similar study protocols have been conducted for anterior cruciate ligament rehabilitation which could be used as a framework for AT future research.

There are several limitations to this study. This study is a systematic review evaluating heterogeneous data thereby limiting statistical analysis, as well as cross-sectional comparison between studies. Our systematic review only included human data, which although focuses the results on the human population, does not evaluate biomechanical differences in the animal population that may be relevant.

**Conclusion**

This study demonstrates sex-specific biomechanical differences between men and women. Men have an increased AT length, thickness, and CSA, indicating that they may be subjected biomechanically to higher loads in their day-to-day activities. In addition, men have lower deformation and compliance properties, along with increased AT stiffness, reducing their capacity to adapt during loading, potentially increasing their risk of injury. Understanding the various differences in muscle and tendon biomechanical properties between men and women is important to better individualize the management and treatment following an AT injury.

**Ethical approval**

Ethical approval was not sought for the present study because this is a systematic review where we did not obtain access to any patient records.

**Declaration of competing interest**

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

- James Calder reports a relationship with Arthrex Inc that includes: consulting or advisory and speaking and lecture fees. James Calder reports a relationship with Bone Joint Journal that includes: board membership. James Calder reports a relationship with Innovate Orthopaedics Ltd that includes: equity or stocks. James Calder reports a relationship with Knee Surgery, Sports Traumatology, and Arthroscopy that includes: board membership. James Calder reports a relationship with Smith and Nephew Inc that includes: consulting or advisory. John Kennedy reports a relationship with Arthrex Inc that includes: consulting or advisory.

**Appendix 1. Search strategy**

<table>
<thead>
<tr>
<th>Search Terms</th>
<th>(Achilles Tendon) AND (Gender) OR (Sex)</th>
<th>(Achilles Tendon) AND (Gender) OR (Sex)</th>
<th>(Achilles Tendon) AND (Gender) OR (Sex)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filter by Year</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Filter by Language</td>
<td>English</td>
<td>English</td>
<td>English</td>
</tr>
</tbody>
</table>

**References**


