Exploring the biomechanical factors contributing to Achille Tendon ruptures

Exploración de los factores biomecánicos que contribuyen a las rupturas del tendón de Aquiles

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Abstract

Background: Achilles tendon ruptures represent a significant musculoskeletal problem, particularly among athletes and physically active individuals. Their occurrence is influenced by multiple biomechanical factors that reduce tendon resilience and increase susceptibility to failure.
Aim of the Study: This study aims to examine the main intrinsic and extrinsic biomechanical factors contributing to Achilles tendon rupture and to clarify how their interaction leads to injury.
Methodology: A structured systematic review of the scientific literature was conducted using predefined search, selection, and synthesis criteria to identify studies addressing biomechanical determinants of Achilles tendon rupture.
Results: The evidence indicates several intrinsic risk factors, including age-related structural changes, sex differences, variations in foot arch morphology, muscular imbalance, and pre-existing tendon pathology. Extrinsic contributors such as inappropriate training load, unsuitable footwear, surface characteristics, and sport-specific mechanical demands also play an important role. Rupture most often occurs during excessive eccentric loading or rapid forceful movements that exceed the tendon's biomechanical capacity.
Discussion: The findings suggest that rupture is best understood as the result of interaction between intrinsic tendon vulnerability and external mechanical stress. Injury becomes more likely when imposed loads surpass the tendon's structural and functional tolerance, emphasizing the importance of considering both individual susceptibility and activity-related loading conditions.
Conclusion: Understanding these interacting biomechanical factors may improve risk identification, guide preventive strategies, and inform rehabilitation programs aimed at enabling a safe return to physical activity.

Keywords

Achilles Tendon injuries; biomechanical phenomena; eccentric contraction; muscle strength; rehabilitation; tendon injuries.

Resumen

Antecedentes: Las roturas del tendón de Aquiles constituyen un problema musculoesquelético relevante, especialmente entre atletas y personas físicamente activas. Su aparición está influida por diversos factores biomecánicos que reducen la resistencia del tendón y aumentan su susceptibilidad a la lesión.
Objetivo del estudio: Este estudio tiene como objetivo analizar los principales factores biomecánicos intrínsecos y extrínsecos que contribuyen a la rotura del tendón de Aquiles y aclarar cómo su interacción conduce a la lesión.
Metodología: Se realizó una revisión sistemática estructurada de la literatura científica utilizando criterios predefinidos de búsqueda, selección y síntesis para identificar estudios sobre los determinantes biomecánicos de la rotura del tendón de Aquiles.
Resultados: La evidencia identifica factores intrínsecos como cambios estructurales asociados a la edad, diferencias por sexo, variaciones del arco plantar, desequilibrios musculares y patología tendinosa previa. Entre los factores extrínsecos destacan cargas de entrenamiento inadecuadas, calzado inapropiado, características de la superficie y exigencias mecánicas del deporte. La rotura suele producirse durante cargas excéntricas elevadas o movimientos rápidos que superan la capacidad del tendón.
Discusión: Los hallazgos indican que la rotura resulta de la interacción entre vulnerabilidad intrínseca y estrés mecánico externo. El riesgo aumenta cuando las cargas superan la tolerancia estructural del tendón, lo que subraya la importancia de considerar tanto la susceptibilidad individual como las condiciones de carga.
Conclusión: Comprender estos factores biomecánicos interrelacionados puede mejorar la identificación del riesgo, orientar estrategias preventivas y optimizar la rehabilitación para favorecer un retorno seguro a la actividad física.

Palabras clave

Contracción excéntrica; fenómenos biomecánicos; fuerza muscular; lesiones de los tendones; lesiones del Tendón de Aquiles; rehabilitación.

Introduction

The Achilles tendon, positioned along the back of the lower limb, is recognized as the largest and most durable tendon in human anatomy. It anchors the distal ends of the gastrocnemius and soleus muscles, which together form the triceps surae. This tendon is indispensable for enabling plantarflexion of the foot, a core motion that allows effective walking, sprinting, and leaping. Biomechanical studies indicate that it can tolerate forces reaching nearly ten times an individual's body weight during dynamic activities, highlighting its significance in human mobility (Wong et al., 2023). Its structural makeup is dominated by Type I collagen, supplemented by elastin, with fibers arranged in a helical pattern that facilitates efficient stress distribution and elastic recoil during loading (Wilharm et al., 2022; Maas et al., 2021; Thorpe et al., 2016). Surrounding the tendon is the paratenon, a compliant connective tissue layer that enables low-friction gliding and contributes to tendon vascularity and healing responses (Benjamin et al., 2008; Müller et al., 2018). The unique hierarchical architecture and high load-bearing capacity of the Achilles tendon are essential for locomotion, athletic performance, and energy storage during gait, yet these same features may predispose the tendon to failure when mechanical demand exceeds tissue tolerance (Freedman et al., 2014; Jung et al., 2009). Achilles tendon rupture is therefore considered a severe musculoskeletal injury with substantial functional consequences for both athletes and physically active individuals (Mansfield, et al., 2022; Grassi et al., 2022; Ochen et al., 2019).

Within the context of athletic performance, especially in sports that demand rapid and forceful movements such as football (soccer), Achilles tendon ruptures are frequently regarded as potentially career-ending injuries, typically necessitating extensive rehabilitation periods (Della Villa et al., 2022). Research demonstrates that the consequences of such injuries extend beyond temporary absence from competition, as many athletes struggle to regain their prior performance levels, and evidence further indicates that a significant number fail to return fully to their pre-injury standard, underscoring the risk of lasting functional limitations (Mansfield et al., 2022). Outside the sphere of sports, ruptures of the Achilles tendon result in considerable pain and functional impairment, greatly limiting an individual's ability to carry out routine daily tasks (Shamrock et al., 2023). Achilles tendon ruptures not only compromise quality of life by restricting fundamental movements but also carry significant economic costs for individuals reliant on physical activity. Treatment expenses and productivity loss emphasize the need for effective prevention strategies, particularly as incidence rates have risen notably in recent decades across diverse populations (Powell et al., 2017). This upward trend indicates that the factors leading to Achilles tendon injuries are increasingly common, necessitating further investigation. These injuries typically occur in a wide age range but are more frequently reported in men aged 30 to 50 (Shamrock et al., 2023). Notably, men are more likely than women to sustain Achilles tendon ruptures at a comparatively younger age (Raikin, 2014). A strong correlation has been identified between Achilles tendon ruptures and involvement in recreational sporting activities, frequently attributed to the so-called "weekend warrior" pattern, in which individuals with minimal habitual exercise engage in episodes of strenuous physical effort (Shamrock et al., 2023). Achilles tendon ruptures have shown a growing incidence not only in the general population but also among professional athletes, with factors such as intensive training demands and playing surfaces thought to contribute to this elevated risk (Serrat et al., 2023; Hewett et al., 2024).

To comprehend the mechanisms underlying Achilles tendon ruptures, it is essential to consider fundamental biomechanical principles governing tendon injury. Load represents the external forces applied to the tendon, whereas stress refers to the internal force normalized to the tendon's cross-sectional area, and strain describes the relative deformation compared with its resting length (Gracey et al., 2020; Kharazi et al., 2021; Svensson et al., 2012). Tendons demonstrate pronounced viscoelastic behavior, combining elastic energy storage with time-dependent deformation, which enables efficient force transmission and recoil during movement (Roberts & Konow, 2013; Thorpe & Screen, 2016). However, this viscoelastic nature also makes tendon mechanical response sensitive to loading rate, as rapid loading increases stiffness and peak stress, potentially elevating the risk of structural failure (Wang et al., 2012; Bohm et al., 2015).

The mechanical behavior of the Achilles tendon is fundamentally influenced by its force–length and stress–strain relationships (Rosso & Valderrabano, 2010). A tendon's ability to store and release energy during movement is governed by these relationships, and exceeding the tendon's elastic limit can lead to structural failure. Mechanical hysteresis and the conditioning effect are key biomechanical properties of the Achilles tendon, reflecting energy loss and improved stress resistance under repeated loading (Rosso & Valderrabano, 2010). These principles underscore the importance of consistent and progressive training to enhance the tendon's capacity to withstand mechanical demands (Sepúlveda-González et al., 2025). Research indicates that Achilles tendon ruptures arise from a multifactorial interaction of intrinsic (patient-related) and extrinsic (activity-related) factors, rather than a single isolated cause (Wertz et al., 2013). A useful technique in sports medicine research is video analysis, which enables a thorough analysis of playing conditions, injury processes, and gross biomechanics, such as joint angles and range of motion at the moment of injury (Della Villa et al., 2022). Alterations in joint angles and angular velocity during high-demand movements have been shown to significantly influence lower-limb biomechanics, underscoring the importance of precise technique in modulating tendon loading patterns (Alkhawaldeh, 2024). Imaging techniques, particularly Magnetic Resonance Imaging (MRI), are essential for diagnosing Achilles tendon ruptures and evaluating tendon pathology. The Kuwada classification system, established in 1990, is a prevalent method for classifying the severity and retraction of Achilles tendon tears (Leppilahti et al., 1996). This classification aids in guiding treatment strategies based on the extent of the rupture. Table 1 presents the Kuwada classification system, which categorizes Achilles tendon ruptures according to the extent of structural damage and the size of the tendinous gap. This system serves as a practical framework for selecting appropriate management strategies, ranging from conservative treatment in partial tears to surgical repair or grafting in cases of large or neglected defects.

Table 1. Kuwada classification of Achilles tendon ruptures and corresponding treatment approaches.

Type	Description	Typical Treatment Approach
Type I	Partial rupture ≤50%	Conservative management (casting/immobilization)
Type II	Complete rupture with tendinous gap ≤3 cm	Primary Achilles repair (end-end anastomosis)
Type III	Complete rupture with tendinous gap 3 to 6 cm	A tendon/synthetic graft is often required
Type IV	Complete rupture with a defect of >6 cm (neglected)	Tendon/synthetic graft and gastrocnemius recession are often required

Note: Bendo & Ahmataj (2026).

In light of the growing incidence of Achilles tendon ruptures and the multifactorial nature of their development, a systematic synthesis of current evidence is necessary to clarify the biomechanical mechanisms associated with tendon failure. Variations in squat technique and external loading have been shown to significantly modify joint compressive forces and torque distribution in the lower limb, highlighting the importance of individualized load management to mitigate excessive tendon stress (Jadue Arriaza et al., 2025). The present systematic review aims to identify, evaluate, and integrate existing research on the mechanical, structural, and loading-related factors that may increase rupture risk. Specifically, this study seeks to determine how variations in tendon properties, external loading conditions, and movement mechanics interact to influence injury occurrence. By consolidating contemporary findings, this review intends to provide a clearer conceptual framework for understanding rupture mechanisms and to highlight gaps that may guide future experimental and clinical investigations.

Method

Review Design and Reporting Framework

This study was designed as a systematic review aimed at identifying and synthesizing evidence on biomechanical factors associated with Achilles tendon rupture. The review methodology followed established systematic review principles and reporting standards to ensure transparency, reproducibility, and methodological rigor.

Search Strategy

A structured literature search was conducted across major electronic databases, including PubMed, Scopus, Web of Science, and SPORTDiscus. The search strategy combined keywords and controlled vocabulary related to Achilles tendon rupture and biomechanics, such as “Achilles tendon,” “rupture,” “biomechanics,” “tendon loading,” “stress,” “strain,” “mechanical properties,” and “injury mechanisms.”

Boolean operators (AND/OR) were used to refine the search. Only studies published in peer-reviewed journals in the last sixteen years were considered, with particular emphasis placed on recent evidence. Reference lists of relevant articles were also screened to identify additional eligible studies.

Inclusion Criteria

Studies were considered eligible if they investigated biomechanical, structural, or mechanical factors associated with Achilles tendon rupture or tendon failure risk. Both experimental and observational studies were included, encompassing research involving human participants, cadaveric specimens, and validated biomechanical models or simulations. Eligible studies were required to report measurable biomechanical variables, such as tendon loading characteristics, stress–strain behavior, mechanical properties, or movement-related risk factors. Only peer-reviewed articles published in English were included to ensure scientific quality and accessibility of full methodological details.

Exclusion Criteria

Studies were excluded if their primary focus was unrelated to biomechanical mechanisms of injury. This included article dealing exclusively with surgical techniques, postoperative rehabilitation, imaging diagnostics without mechanical analysis, or purely clinical outcome comparisons. Case reports, conference abstracts, editorials, opinion papers, and non-peer-reviewed publications were also excluded. Additionally, studies lacking sufficient methodological transparency or those not providing data relevant to tendon loading, mechanical response, or rupture mechanisms were not considered in the synthesis.

Study Selection Process

All identified records were screened in two stages. First, titles and abstracts were reviewed to remove clearly irrelevant studies. Second, full texts of potentially eligible articles were assessed against the inclusion criteria. Disagreements in study eligibility were resolved through discussion and re-evaluation of study relevance.

Data Extraction and Synthesis

For each included study, relevant information was systematically extracted, including study design, characteristics of the sample or experimental model, biomechanical variables investigated, measurement techniques, and key outcomes. Owing to substantial variability in methodologies, experimental conditions, and reported outcome measures, a quantitative synthesis was not considered appropriate; therefore, a qualitative thematic approach was applied. The extracted findings were organized into major conceptual domains reflecting the primary biomechanical dimensions of interest, namely tendon structural characteristics, loading mechanics and movement-related factors, viscoelastic and strain-related responses, and both intrinsic and extrinsic determinants of rupture risk. This structured synthesis allowed recurring biomechanical patterns and relationships to be identified across studies, thereby supporting an integrated interpretation of factors contributing to Achilles tendon rupture.

Risk of Bias and Quality Considerations

Methodological quality and potential sources of bias were evaluated by examining study design, sample size, measurement validity, and clarity of biomechanical assessment procedures. Particular attention was given to experimental control, reproducibility of measurements, and the applicability of findings to real-world injury mechanisms. These considerations informed the interpretation of results and the strength of conclusions drawn from the evidence.

Results

The results were synthesized by grouping findings according to the frequency and consistency with which specific biomechanical factors were reported across the included studies. Rather than presenting individual findings in isolation, intrinsic and extrinsic contributors to Achilles tendon rupture were categorized based on the number of studies supporting each factor and the strength of the reported associations. This approach allowed commonly reported determinants such as age, sex, tendon degeneration, loading patterns, training errors, and sport-specific mechanical demands to be distinguished from less consistently documented factors. By organizing the evidence thematically and comparatively, the analysis provides a clearer indication of which biomechanical variables are most strongly supported in the literature as contributors to tendon rupture risk.

Intrinsic Biomechanical Factors

The intrinsic biomechanical factors presented in this section are derived from studies retained after the structured identification, screening, and eligibility assessment process described in the Method section. Only studies providing direct biomechanical or structural evidence relevant to Achilles tendon rupture were included in this synthesis. The results were organized by grouping the findings according to the consistency with which specific intrinsic determinants were reported across the selected literature. Current research trends indicate that the most frequently examined intrinsic contributors include demographic characteristics (particularly age and sex), tendon material properties and degeneration, foot morphology, and neuromuscular factors influencing load distribution across the ankle joint. Several studies consistently highlight age-related alterations in collagen organization, reductions in tendon elasticity, and prior tendinopathy as major determinants of structural vulnerability. In parallel, increasing attention has been given to anatomical features such as arch morphology and to functional factors including calf muscle strength, flexibility, and ankle range of motion, all of which influence internal tendon stress during movement. Functional capacity and biomechanical variables have been identified as strong predictors of pain in athletes, emphasizing the relevance of dynamic joint stability and structural parameters in load-related musculoskeletal disorders (Fariño Cortez et al., 2025).The synthesis of these findings is summarized in Table 2, which compiles the principal intrinsic risk factors identified across the included studies and reflects the prevailing directions of current biomechanical research on Achilles tendon rupture.

Age and sex were identified as intrinsic determinants of Achilles tendon rupture based on consistent findings across multiple recent epidemiological, cohort, and review studies included in this synthesis. Several large population analyses report that the incidence of rupture is markedly higher in men and most frequently occurs in adults between the third and fifth decades of life, indicating a reproducible demographic pattern across datasets (Svedman et al., 2024; Shamrock et al., 2023). Contemporary reviews and biomechanical analyses likewise classify age and sex among the primary non-modifiable risk factors, linking them to differences in tendon structure, activity exposure, and neuromuscular coordination (Sankova et al., 2024; Xergia et al., 2023). Additional large cohort and registry-based investigations further confirm that male sex and age-related tissue changes are repeatedly associated with increased rupture or re-rupture risk, supporting their classification as intrinsic contributors rather than isolated observations (Choi et al., 2024). Taken together, the convergence of epidemiological, clinical, and mechanistic evidence across several independent studies justifies the inclusion of age and sex as core intrinsic variables influencing Achilles tendon rupture susceptibility.

Achilles tendon ruptures are prevalent among individuals aged three to five, with a higher incidence in men compared to women (Shamrock et al., 2023), and men typically experiencing these injuries at a younger age than women (Raikin, 2014). Collagen fiber disarray and a lack of suppleness are signs of age-related tendon deterioration (Rosso & Valderrabano, 2010), as well as any hormonal factors, could be a factor in this demographic trend. Women may have a smaller tendon cross-sectional area and possibly different tendon stress and physical activity patterns, which could explain their lower rupture rate (Egger & Berkowitz, 2017). The lower limb's biomechanics and the stress that the Achilles tendon experience are also significantly influenced by the shape of the foot arch. The risk of rupture can be increased by both high arches and flat feet. Because of the changed biomechanics and asynchronous movement between the foot and ankle, flat feet can cause excessive inward rolling of the foot during the gait cycle, which increases the strain on the Achilles tendon (Medina Pabón & Naqvi, 2023). Conversely, high arches, characterized by a reduced contact area with the ground, might impair the foot's capacity to absorb shock, increasing the impact forces that reach the Achilles tendon and increasing the tendon's stress (Shamrock et al., 2023). Another important intrinsic risk factor is an imbalance in the strength and flexibility of the muscles surrounding the ankle joint. Insufficient flexibility and strength of the gastroc-soleus muscle complex can increase strain on the Achilles tendon during physical activity, as limited calf flexibility and restricted ankle dorsiflexion elevate mechanical stress on the tendon, heightening the risk of injury (Shamrock et al., 2023) Adequate strength and flexibility of the calf muscles, along with a sufficient range of motion in the ankle joint, are therefore crucial for maintaining proper biomechanics and minimizing stress on the Achilles tendon. The intrinsic health and material properties of the Achilles tendon are critical determinants of its susceptibility to rupture. Pre-existing Achilles tendinopathy leads to degenerative tendon tissue changes, weakening the tendon and heightening rupture risk. These changes include alterations in collagen structure and decreased tensile strength, compounded by poor blood supply in certain impairs healing, contributing to degeneration. A prior history of Achilles tendinopathy or injury further elevates the risk of tendon rupture (Shamrock et al., 2023) Furthermore, a history of tendinopathy or fracture in other parts of the lower limb has also been identified as a potential risk factor (van der Vlist et al., 2019). These findings suggest that prior injury may indicate underlying weaknesses or biomechanical abnormalities that continue to predispose the tendon to further damage. Table 2 presents the intrinsic risk factors identified through the structured synthesis of the included studies. To strengthen interpretability, the factors were retained only when supported by evidence from multiple independent sources rather than single reports. Demographic determinants such as age and sex are consistently documented across large epidemiological datasets and systematic reviews as primary non-modifiable contributors to rupture incidence. Structural characteristics, including foot morphology and tendon dimensions, have been linked in several biomechanical investigations to altered load transmission and stress concentration. Functional variables such as calf muscle strength, flexibility, and ankle range of motion are likewise repeatedly examined as modulators of tendon strain during dynamic tasks. Finally, tendon-specific features particularly degeneration, collagen disorganization, and prior tendinopathy are among the most consistently reported predictors of mechanical vulnerability. To enhance transparency, the table now indicates the approximate level of evidential support for each factor based on the number of studies in which it was reported.

Table 2. Intrinsic risk factors contributing to Achilles tendon rupture.

Intrinsic Risk Factor	Description	Evidence Support*
Age	Increased risk with advancing age, particularly in the 30–50-year range.	Strong (reported in multiple epidemiological studies and reviews)
Sex	Higher incidence in males compared to females.	Strong (supported by population studies and systematic reviews)
Foot Arch Morphology	Pes planus or pes cavus may alter loading and increase tendon stress.	Moderate (reported in biomechanical and clinical studies)
Muscle Strength & Flexibility	Reduced calf flexibility, strength imbalance, and limited dorsiflexion increase tendon strain.	Moderate–Strong (reported in biomechanical and clinical investigations)
Tendon Structural Properties	Degeneration, collagen disorganization, reduced vascularity, and stiffness changes weaken the tendon.	Strong (consistently reported in tendinopathy and rupture literature)
Previous Injury / Tendinopathy	Prior Achilles pathology or lower-limb injury increases rupture susceptibility.	Strong (reported in cohort and clinical studies)

*Evidence categories reflect convergence across the included studies (strong = consistently reported across multiple independent studies; moderate = reported in several but not all sources).
Note: Bendo & Ahmataj (2026).

Extrinsic Biomechanical Factors

The extrinsic biomechanical factors summarized in this section are derived from studies retained through the structured screening process and selected for their relevance to external loading conditions, environmental influences, and activity-related determinants of Achilles tendon rupture. To improve interpretability, the evidence was synthesized by grouping findings according to how consistently specific external factors were reported across the included studies rather than presenting them as isolated observations. Across the contemporary literature, the most frequently documented extrinsic contributors include training-related load errors, footwear characteristics, surface interactions, and the mechanical demands of specific sports. Multiple studies converge in identifying abrupt increases in training volume or intensity, inadequate recovery, and sport-specific high-load movements as dominant external contributors to tendon overload. Low-load resistance training combined with blood flow restriction has been shown to induce structural and functional improvements in lower limb tendons comparable to high-load protocols, suggesting a viable rehabilitation alternative when heavy loading is contraindicated (Osorio-Torres et al., 2025). Footwear design, particularly heel height, cushioning, and support, has likewise been examined in several biomechanical investigations as a modifier of tendon strain. Environmental conditions such as hard or unstable playing surfaces are also repeatedly discussed as amplifiers of impact forces transmitted through the lower limb. The synthesis of these findings is summarized in Table 3, which now reflects the consistency with which each extrinsic factor is reported across the included studies and clarifies the relative strength of support for each category.

Moreover, training on challenging terrains, like hills, raises the likelihood of Achilles tendon injuries due to increased stress on the tendon (Shamrock et al., 2023). Footwear characteristics constitute a crucial factor in modulating the mechanical load imposed on the Achilles tendon. Athletic shoes that provide insufficient flexibility or inadequate heel support may elevate tendon strain, thereby increasing injury risk. Moreover, the prolonged use of high-heeled footwear can progressively shorten the Achilles tendon, predisposing individuals to injury when activities demand complete ankle dorsiflexion and full range of motion (Wertz et al., 2013). The heel height and cushioning of footwear influence the loading on the Achilles tendon (Marrone et al., 2024). Notably, it has been demonstrated that minimalist shoes, which are designed to simulate barefoot running, may increase the strain on the Achilles tendon (Sinclair & Sant, 2016), while high-top shoes may provide some relief from the peak strain on the Achilles tendon (Rowson et al., 2010). The likelihood of Achilles tendon rupture can also be influenced by the surface used for physical activity; hard or slippery surfaces amplify impact forces transmitted through the lower extremity, thereby increasing stress on the tendon (Wukich, 2025). Specific examples highlight the influence of landing surfaces in gymnastics on joint torques and the varying effects of running on different terrains, such as asphalt and sand (Wertz et al., 2013). Finally, the inherent biomechanical demands of specific sports contribute significantly to the incidence of Achilles tendon ruptures. Sports like basketball, tennis, and soccer that require a lot of running, jumping, and abrupt starts and pauses are more likely to cause these ailments (Della Villa et al., 2022). The nature of basketball puts a lot of mechanical strain on the Achilles tendon (Petway et al., 2022). It has been determined that certain soccer movements, such as vertical jumping, cross-over cutting, and forward acceleration from standing, frequently result in rupture (Della Villa et al., 2022). Basketball players have been shown to exhibit a "false step" mechanism prior to Achilles tendon rupture, which entails a backward stride followed by quick ankle dorsiflexion (Petway et al., 2022).

Extrinsic factors related to activity exposure and training environment were identified as important contributors to Achilles tendon rupture based on converging findings from recent clinical, epidemiological, and biomechanical studies included in this review. Several contemporary investigations indicate that rapid increases in training intensity or volume can exceed the adaptive capacity of the tendon, leading to cumulative mechanical overload and elevated injury risk (Bohm et al., 2015). In addition, inadequate preparation and recovery strategies such as insufficient warm-up routines, limited post-exercise recovery, and short rest intervals between sessions have been associated with impaired tendon remodeling and reduced load tolerance in both experimental and clinical research (Magnusson & Kjaer, 2019; Grassi et al., 2022). Collectively, the consistency of these findings across independent studies supports the interpretation that training load management represents a key external determinant of Achilles tendon injury susceptibility rather than an isolated observation.

Table 3 summarizes the principal extrinsic risk factors identified in the included literature. The factors presented were retained only when supported by converging evidence across multiple independent studies rather than single observations. Training-related variables, including rapid increases in exercise intensity, insufficient recovery, and inappropriate workload progression, are among the most consistently reported external contributors to tendon overload in recent clinical and biomechanical research. Footwear characteristics, such as heel height, cushioning, and structural support, have likewise been examined across several investigations as modifiers of Achilles tendon strain and loading patterns. Environmental conditions such as hard or unstable playing surfaces are also repeatedly discussed as amplifiers of impact forces transmitted through the lower limb. In youth elite football players, injury incidence appears to vary according to competitive category, while contextual factors may influence the anatomical location of injuries rather than the affected tissue or side (Gamonales et al., 2024).

Finally, the biomechanical demands of sports involving repetitive running, jumping, and rapid directional changes are consistently highlighted as contexts in which rupture risk is elevated. Strength-based semi-squat training has been shown to enhance jump performance and peak muscular power with lower perceived exertion and muscle soreness compared to plyometric protocols, suggesting differential mechanical loading patterns that may influence tendon stress and injury risk (Fonseca et al., 2022). Lower-limb and trunk muscle strength have been shown to significantly influence jump-based performance, indicating that muscular capacity plays a critical role in modulating force transmission through the kinetic chain and potentially affecting Achilles tendon loading (Suhadi et al., 2023). The table therefore reflects the convergence of findings across contemporary studies and serves as a structured synthesis of the external determinants most frequently discussed in the literature.

Table 3. Extrinsic risk factors associated with Achilles tendon rupture.

Extrinsic Risk Factors	Description
Training Errors	Sudden increases in intensity or volume, inadequate warm-up/cool-down, insufficient rest, training on hills or uneven surfaces.
Footwear Characteristics	Inadequate support, high heels, influence of heel height and cushioning, and potential increased loading with minimalist footwear.
Playing Surface Interactions	Hard or slippery surfaces can increase impact forces.
Biomechanical Demands of Specific Sports	High-impact sports with running, jumping, and sudden changes in direction; specific movements in sports like soccer and basketball.

Evidence categories reflect the consistency with which each factor was reported across the included studies.
Note: Bendo & Ahmataj (2026).

Mechanisms of Injury

Achilles tendon rupture does not typically result from a single isolated event but rather from the interaction between intrinsic tissue vulnerability and extrinsic mechanical loading conditions. The literature consistently indicates that rupture occurs when external forces exceed the tendon's current structural tolerance, which is itself influenced by individual characteristics such as age-related degeneration, prior tendinopathy, tendon stiffness, and neuromuscular function. In this context, intrinsic factors determine the mechanical threshold of the tendon, whereas extrinsic factors define the magnitude, rate, and direction of applied loads.

Several studies describe rupture events occurring during high-demand movements such as landing, acceleration, or sudden directional change, where eccentric loading of the gastrocnemius–soleus complex produces rapid tendon elongation under tension. An 8-week conservative rehabilitation program combining eccentric loading and extracorporeal shockwave therapy has been shown to improve tendon structure, reduce pain, and enhance lower-limb strength and power, underscoring the role of controlled mechanical loading in tendon remodeling (Sánchez-Gómez et al., 2023).

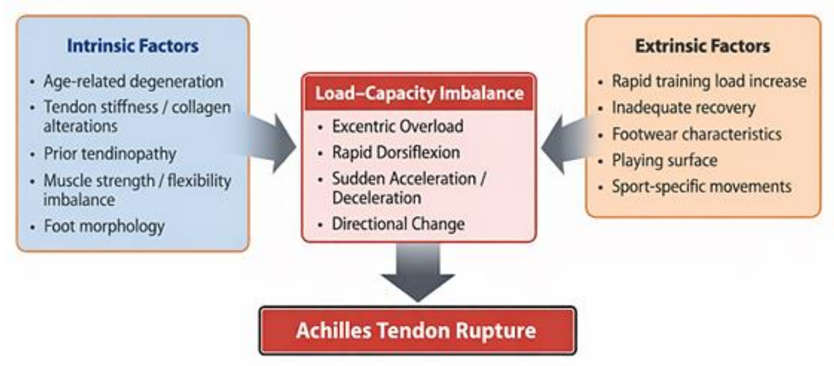
However, the risk associated with these movements increases substantially when they occur in the presence of predisposing intrinsic conditions, such as reduced tendon elasticity, limited ankle dorsiflexion, or impaired muscle coordination. Similarly, external contributors including rapid increases in training load, inappropriate footwear, or high-impact playing surfaces may amplify the mechanical stress experienced by the tendon, thereby interacting with internal tissue properties to precipitate failure.

Taken together, current evidence suggests that Achilles tendon rupture is best understood as the outcome of a load-capacity imbalance: intrinsic factors influence tendon resilience, while extrinsic conditions modulate the mechanical demands placed upon it. The injury therefore emerges when external loading surpasses the adaptive capacity of a structurally or functionally compromised tendon.

Achilles tendon ruptures commonly occur through specific biomechanical mechanisms. One of the main mechanisms of injury is excessive eccentric loading, which occurs during activities like landing from a jump or decelerating (Mansfield et al., 2022). This involves the rapid lengthening of the tendon while it is under tension, placing significant strain on its fibers. Eccentric contractions, where the muscle lengthens while contracting, generate high forces and can overload the tendon if the load exceeds its capacity. An Achilles tendon rupture can also result from abrupt and vigorous ankle plantarflexion or dorsiflexion (Shamrock et al., 2023). This frequently happens when a tendon is exposed to an abrupt and severe range of motion, such as at the start of a sprint or when jumping. The tendon may experience rupture as a result of strains exceeding its natural tensile strength caused by such quick and powerful movements. Another factor contributing to Achilles tendon ruptures is abrupt direction changes and fast acceleration or deceleration, which are typical in sports like basketball, soccer, and tennis (Della Villa et al., 2022). These dynamic movements require the tendon to rapidly adapt to changing forces and directions, increasing the possibility of injury if the tendon is not sufficiently conditioned to support such loads. The "false step" is a particular process that has been seen in some sports, like basketball. A quick ankle dorsiflexion after taking a backward step with the injured leg may cause tendon overload because of the abrupt stretch and shift in joint angle (Petway et al., 2022).

A conceptual model illustrating the interaction between intrinsic tendon vulnerability and external mechanical loading conditions is presented in Figure 1, highlighting how rupture is likely to occur when applied forces exceed the structural capacity of the tendon.

Figure 1. Conceptual interaction model of intrinsic and extrinsic biomechanical factors contributing to Achilles tendon rupture.



Note: Bendo & Ahmataj (2026).

The model illustrates how intrinsic factors influence tendon structural tolerance, whereas extrinsic factors determine the magnitude and rate of applied mechanical loads. Rupture is proposed to occur when external loading exceeds the adaptive capacity of the tendon, resulting in a load–capacity imbalance during high-demand movements such as eccentric loading, rapid dorsiflexion, or sudden directional changes.

Discussion

Achilles tendon rupture is now widely recognized as a multifactorial condition arising from the interaction between intrinsic tissue characteristics and externally imposed mechanical demands, rather than from a single isolated cause (Janssen et al., 2025; Xergia et al., 2023). Contemporary biomechanical and clinical literature consistently emphasizes that tendon failure occurs when external loading exceeds the structural and functional capacity of the tendon, which is shaped by both individual biological factors and activity-related exposures.

Intrinsic factors such as advanced age, foot arch abnormalities, and tendon degeneration increase susceptibility to tendon rupture, particularly when combined with extrinsic stressors like sudden training intensity increases or high-impact sports (Sankovaet al., 2024). This interplay amplifies mechanical loading on the tendon, thereby heightening vulnerability to injury during strenuous or high - intensity activity. Achilles tendon rupture typically arises from a combination of predisposing intrinsic factors and extrinsic triggers that exceed the tendon's strength. Various physical activities impose differing forces on the tendon, and repetitive strain without adequate recovery can decrease its rupture threshold (Shamrock et al., 2023). Sport-specific mechanical loading has been shown to induce significant differences in tendon viscoelastic properties, highlighting its capacity for functional adaptation to long-term training demands (Sepúlveda-González et al., 2025). These Achilles tendons loading patterns can also be considerably changed by the type of footwear worn (Marrone et al., 2024). Recent biomechanical investigations indicate that running in minimalist or reduced-support footwear may increase mechanical loading on the Achilles tendon, particularly by elevating tendon strain and plantarflexor demand during stance and push-off phases of gait (Malisoux et al., 2016).

Understanding these specific loading patterns and the tendon's tolerance limits is therefore crucial for developing effective strategies aimed at preventing Achilles tendon ruptures. The findings synthesized from the provided research align with the broader body of literature on Achilles tendon ruptures, which consistently highlights the multifactorial etiology of these injuries. The growing volume of research devoted to Achilles tendon injuries reflects an increasing awareness of their profound consequences, not only in terms of physical function but also in relation to long-term quality of life and overall well-being (Wang et al., 2023). Although the present review provides an integrated synthesis of the principal biomechanical contributors to Achilles tendon rupture, several areas remain insufficiently understood and warrant further investigation. Measures of maximal isokinetic strength, segmental muscle mass, asymmetries, strength deficits, and fatigue index have been proposed as relevant indicators for estimating injury risk, suggesting that prospective monitoring of neuromuscular parameters may clarify rupture susceptibility (Preciado Martinez et al., 2024). Recent literature emphasizes the need for longitudinal and prospective studies to clarify how tendinopathy progresses to rupture and to determine which combinations of intrinsic and extrinsic factors most strongly predict failure (Janssen et al., 2025; Xergia et al., 2023). Additional biomechanical analyses across a broader range of sports and movement contexts are also recommended, as sport-specific loading patterns and footwear characteristics continue to be identified as important modifiers of tendon stress (Bohm et al., 2015). Comprehensive biomechanical assessment of kinematic and kinetic variables has been shown to optimize technique and reduce injury risk in high-demand sports, emphasizing the importance of joint mechanics and load distribution (Monterrosa Quintero et al., 2025).

Furthermore, ongoing research evaluating rehabilitation strategies and adjunctive treatments including load-based exercise protocols and biological therapies such as platelet-rich plasma suggests that optimizing tendon adaptation and recovery may play a key role in reducing injury risk (Scott et al., 2020). From a preventive perspective, current evidence consistently supports progressive load management and gradual increases in training intensity as essential strategies to minimize tendon overload and promote tissue resilience.

Additionally, proper warm-up and stretching routines that target the calf muscles and enhance ankle mobility are essential (Shamrock et al., 2023). The risk of injury can be further reduced by choosing footwear that is appropriate for the activity and the biomechanical profile of the wearer (Marrone et al., 2024). Another crucial component of prevention is considering the playing surface and how it could affect tendon loading (Wukich, 2025). Biomechanical evaluation holds promise in identifying individuals predisposed to Achilles tendon rupture, thereby enabling the application of targeted preventive measures. Moreover, a thorough understanding of the biomechanical mechanisms underlying the initial injury is crucial for optimizing rehabilitation strategies and ensuring a safe return to athletic activity. Early and controlled mobilization, along with weight-bearing, can enhance tendon healing and functional recovery. Functional rehabilitation strategies that emphasize progressive strengthening, particularly through eccentric loading, are essential for rebuilding strength and endurance in the injured Achilles tendon and associated calf musculature (Kongsgaard et al., 2005). PRP injections and dry needling are investigated as adjunct therapies in Achilles tendon rupture rehabilitation, but their effectiveness is unclear. Establishing clear criteria for a safe return to sport, based on objective measures of strength, range of motion, and functional performance, is essential to minimize the risk of re-rupture (Mansfield et al., 2022).

Taken together, the findings of this review reinforce the concept that Achilles tendon rupture should not be interpreted as the consequence of a single isolated factor but rather as the result of interacting biomechanical influences. Intrinsic characteristics such as tendon degeneration, structural properties, and neuromuscular control appear to determine the tissue’s capacity to withstand load, whereas extrinsic conditions including training demands, footwear, and environmental context govern the magnitude and rate of mechanical stress applied to the tendon. Rupture is therefore most likely to occur when these domains converge to create a load capacity imbalance, particularly during high-demand movements involving rapid force generation or eccentric loading. Viewing injury through this interaction-based framework may help future research move beyond isolated risk factors toward integrated biomechanical models capable of better predicting injury susceptibility and informing more individualized prevention strategies.

Conclusions

In summary, Achilles tendon ruptures are complex injuries influenced by a multitude of biomechanical factors. Intrinsic risk factors such as advancing age, gender predisposition, abnormalities in foot arch morphology, imbalances in muscle strength and flexibility, pre-existing tendon pathology, and a history of prior injuries all contribute to an individual's susceptibility. These factors can interact with extrinsic influences stemming from training errors, inappropriate footwear, the characteristics of the playing surface, and the specific biomechanical demands imposed by different sports. The primary mechanisms of injury involve excessive eccentric loading and rapid, forceful movements that exceed the tendon's tensile capacity. Future research should focus on gaining a more granular understanding of the intricate interactions between specific intrinsic and extrinsic risk factors and on elucidating the longitudinal progression from tendinopathy to rupture. Further investigation into the biomechanics of Achilles tendon loading across various sports and with different types of footwear is also warranted. Additionally, continued research into the effectiveness of diverse rehabilitation protocols and the role of adjunct therapies will be crucial for optimizing patient outcomes.

Ultimately, a comprehensive understanding of the biomechanical factors that contribute to Achilles tendon ruptures is of paramount clinical significance. By considering these factors in clinical assessments and injury prevention programs, healthcare professionals can develop more tailored interventions that address individual risk profiles and the specific demands of various activities, with the goal of reducing the incidence of these debilitating injuries and facilitating a safe and successful return to activity for those affected.

Impact of the study

By integrating intrinsic and extrinsic biomechanical risk factors, this work highlights the multifactorial nature of Achilles tendon ruptures. The findings underscore the importance of biomechanically informed prevention strategies and rehabilitation protocols, which may reduce the incidence of injuries and improve recovery outcomes for athletes and active individuals.

Limitations

This study is primarily based on a synthesis of existing literature, and as such, it may be limited by potential bias in reported findings and variability in study methodologies. Additionally, the absence of large-scale, longitudinal studies restricts the ability to draw definitive causal relationships between biomechanical factors and Achilles tendon rupture risk.

Future Research Directions

Further research should prioritize longitudinal and prospective studies to better establish causal pathways between risk factors and tendon rupture. Advanced imaging, biomechanical modeling, and motion analysis technologies may also provide deeper insights into tendon loading mechanisms. Moreover, studies exploring individualized prevention programs and sport-specific rehabilitation strategies are warranted.

Transparency

The authors affirm that the manuscript upholds principles of honesty, accuracy, and ethical integrity, ensuring that all essential aspects are fully reported and that any inconsistencies have been clearly addressed.

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Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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