Viscoelastic adaptations of Achilles and patellar tendons in elite athletes: a cross-sport myotonometry study

Adaptaciones viscoelásticas de los tendones de Aquiles y patelar en atletas de élite: un estudio de miotonometría entre deportes

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Abstract

Objective: To analyze and compare the viscoelastic properties of the Achilles and patellar tendons in elite athletes from different sports and determine whether there are significant differences attributable to sport-specific mechanical loading.
Methods: This is a cross-sectional study in which a total of 105 elite athletes (33 females; 72 males) from 11 distinct sport disciplines (road cycling, roller hockey, karate, athletics, volleyball, taekwondo, speed skating, judo, archery, handball, and boxing) were evaluated at a national high-performance sports center. The viscoelastic properties (stiffness, relaxation, decrement, among others) of both tendons were measured bilaterally using a portable myotonometry device (Myoton Pro®, Myoton, Tallinn, Estonia). The primary outcome was tendon stiffness.
Results: Significant differences were found in all measured variables for both tendons ($p < 0.001$) across sports, except for the decrement parameter in the patellar tendon ($p = 0.45$). The Achilles tendon demonstrated greater sport-specific adaptation, with stiffness showing the highest number of inter-sport differences (29 significant pairwise comparisons). Relaxation was the most variable parameter in the patellar tendon (9 significant comparisons).
Conclusions: The findings demonstrate that the viscoelastic properties of the Achilles and patellar tendons differ significantly based on the sport practiced by elite athletes. This suggests that long-term, sport-specific mechanical loading plays a crucial role in tendon adaptation, leading to functional specialization. While the cross-sectional design precludes causal inference, these results provide valuable reference data for training prescription and injury prevention strategies tailored to specific athletic disciplines.

Keywords

Biomechanics; sports performance; elite athletes; Myoton; stiffness; achilles tendon; patellar ligament.

Resumen

Objetivo: Analizar y comparar las propiedades viscoelásticas de los tendones de Aquiles y rotuliano en atletas de élite de diferentes deportes, determinando si existen diferencias significativas atribuibles a la carga mecánica específica de cada disciplina.
Métodos: En este estudio transversal, se evaluó a un total de 105 atletas de élite (33 mujeres; 72 hombres) de once disciplinas deportivas distintas (ciclismo de ruta, hockey sobre patines, karate, atletismo, voleibol, taekwondo, patinaje de velocidad, judo, tiro con arco, balonmano y boxeo) en un centro nacional de deportes de alto rendimiento. Las propiedades viscoelásticas (rigidez, relajación, decremento, entre otras) de ambos tendones se midieron bilateralmente utilizando un dispositivo portátil de miotonometría (Myoton Pro®, Myoton, Tallin, Estonia). El resultado principal fue la rigidez del tendón.
Resultados: Se encontraron diferencias significativas en todas las variables medidas para ambos tendones ($p < 0{,}001$) entre los deportes, excepto para el parámetro de decremento en el tendón rotuliano ($p = 0{,}45$). El tendón de Aquiles demostró una mayor adaptación específica al deporte, siendo la rigidez la que presentó el mayor número de diferencias entre disciplinas (29 comparaciones por pares significativas). La relajación fue el parámetro más variable en el tendón rotuliano (9 comparaciones significativas).
Conclusiones: Los hallazgos demuestran que las propiedades viscoelásticas de los tendones de Aquiles y rotuliano difieren significativamente según el deporte practicado por atletas de élite. Esto sugiere que la carga mecánica específica a largo plazo juega un papel crucial en la adaptación tendinosa, conduciendo a una especialización funcional. Aunque el diseño transversal impide inferencias causales, estos resultados proporcionan datos de referencia valiosos para la prescripción de entrenamiento y estrategias de prevención de lesiones adaptadas a la disciplina deportiva.

Palabras clave

Atletas de élite; biomecánica; rendimiento atlético; Myoton; rigidez; tendón calcáneo; ligamento rotuliano.

Introduction

Tendons are highly specialized tissues primarily composed of collagen and whose primary function is to transmit muscular force to bone (Szajkowski, Pasek, Dwornik, & Cieślar, 2024). These structures play a critical role in storing and releasing elastic energy, enhancing mechanical efficiency during movement and contributing to the biomechanics of the musculoskeletal system (Cristi-Sánchez et al., 2019). Furthermore, tendons exhibit remarkable adaptability, dynamically adjusting their properties in response to mechanical loading (Cristi-Sánchez et al., 2019; Szajkowski et al., 2024). This adaptation occurs through collagen synthesis and turnover, increased proteoglycan content in the extracellular matrix, and expansion of collagen fibril diameter. Together, these processes modify tendon composition and function under varying mechanical stimuli (Young, Cristi-Sánchez, Danes-Daetz, Monckeberg, & Aguirre, 2018). The extracellular matrix is central to this adaptive process, playing a crucial role in force transmission and tissue adaptation by responding to mechanical loading through regulating growth factors and matrix metalloproteinases (KjÆR, 2004). The patellar and Achilles tendons notably suffer high biomechanical demands, particularly during explosive sports movements such as running and jumping (Park & Chou, 2006). Therefore, tendon stiffness is a key determinant of athletic performance, especially for sports that demand rapid stretch-shortening cycles or high-velocity movements (Brughelli & Cronin, 2008).

Enhanced tendon stiffness has been closely linked to improved running efficiency and overall athletic output, underscoring its significance in performance (Chang, Li, Wang, & Zhang, 2020). A systematic review and meta-analysis by Lazarczuk et al. (2022) confirmed that both resistance training and jump-based training lead to increased tendon stiffness and modulus, with the adaptations being specific to the type of load applied. Systematic evaluation and monitoring of tendon viscoelastic properties in athletes are essential for optimizing training loads and designing evidence-based programs (Pożarowszczyk et al., 2017). Biomechanical research employs various diagnostic tools, including ultrasonography and myotonometry (Dafun JR & Suniga, 2025; Jaén-Carrillo, Lawley, Rubio-Peirotén, & Cartón-Llorente, 2025; Williams & Gyer, 2025). Myotonometry has gained prominence in recent years due to its non-invasive nature, portability, ease of use, and applicability in both clinical and athletic settings, enabling precise and accessible analysis of tendon behavior (Römer et al., 2023; Trybulski et al., 2024).

Current evidence regarding tendon adaptation to mechanical loading indicates high sensitivity to strain magnitude, with effective adaptations typically requiring strains of 4.5% to 6.5% achieved under high mechanical loads (Lazarczuk et al., 2022; Stańczak, Kacprzak, & Gawda, 2024; Tsai et al., 2024). The load magnitude and the training program duration are key factors which influence the degree of tendon adaptation (Lazarczuk et al., 2022). Recent research suggests that the temporal coordination of loading sessions and the total loading volume within a certain range (e.g., 180-300s of weekly loading time) may be secondary factors, as the major adaptive changes in stiffness are mediated by material properties and occur within the first 8 weeks (Tsai et al., 2024).

In contrast to tendons, skeletal muscle is highly sensitive to metabolic stress and can hypertrophy effectively even under lower mechanical loads if contractions are performed to failure, leading to significant metabolic by-product accumulation (Roberts et al., 2023). This fundamental difference in adaptive drivers, high mechanical strain for tendon versus metabolic stress and activation for muscle, suggests potential for non-uniform adaptation within the muscle-tendon unit (Lambrianides, Epro, Arampatzis, & Karamanidis, 2024). The adaptive response of the tendon is also slower compared to skeletal muscle (KjÆR, 2004).

This divergence in adaptation mechanisms may explain the inconsistent findings in the literature regarding sport-specific tendon adaptation. Recent cross-sectional and longitudinal studies have demonstrated that tendon properties, such as thickness, stiffness, and cross-sectional area, can vary significantly across sport disciplines and are influenced by both the loading type and intensity. For example, elite athletes in sports with high repetitive loading, such as ski jumping and running, exhibit greater patellar and Achilles tendon cross-sectional areas and stiffness compared to athletes in water sports or sedentary controls, suggesting that tendon size and mechanical properties adjust to sport-specific demands (Götschi et al., 2022). However, some studies in adolescent athletes report that while patellar tendon thickness increases in response to certain sport-specific loads, Achilles tendon thickness may remain unchanged, indicating that adaptation is both tendon- and sport-dependent, and may also be influenced by sex and maturation (Chalatzoglidis, Arabatzi, & Christou, 2021). Furthermore, recent evidence highlights that individualized training interventions targeting optimal tendon strain can promote balanced muscle-tendon adaptation and potentially reduce injury risk, but a comprehensive, multi-sport comparison of viscoelastic tendon properties using standardized, non-invasive methodologies has not yet been conducted (Domroes, Weidlich, Bohm, Mersmann, & Arampatzis, 2024, 2025). These contradictory findings underscore the need for further research employing advanced assessment techniques to clarify the mechanisms and extent of sport-specific tendon adaptation.

Therefore, this study aimed to analyze the viscoelastic components of the patellar and Achilles tendons across a wide range of sports via myotonometry to determine whether mechanical properties vary according to sport-specific mechanical demand. The results provide critical insights into the effects of sport-specific training on tendon tissue and can establish reference values for developing tailored training programs and injury prevention protocols for elite athletes.

We hypothesized that the viscoelastic properties (stiffness, relaxation, and decrement) of both the Achilles and patellar tendons would exhibit significant differences among elite athletes from sports with distinct mechanical loading patterns.

Method

Experimental approach

This cross-sectional study was conducted in accordance with the STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) guidelines for observational research. The study investigated the biomechanical properties of the Achilles and patellar tendons in elite athletes from various sport disciplines. The assessments were performed between July 2024 and December 2024 at the Sports Biomechanics Laboratory of the High-Performance Center in Santiago, Chile, using the non-invasive MyotonPRO® device (Myoton, Tallinn, Estonia) to measure tendon viscoelastic components with high reproducibility. These evaluations were part of the athletes' routine monitoring program, and all participants were formally invited and authorized the use of their data for research purposes by signing the Informed Consent Form. Ethical approval was granted by the Institutional Research Ethics Committee (CAAE: 82274124.6.0000.5112, protocol: 7.272.986).

Participants

A priori sample size estimation was performed using G*Power software (version 3.1.9.7). We anticipated a large effect size ($f = 0.40$) for the primary outcome variable (Achilles tendon stiffness) among sport disciplines based on a pilot study and previous literature investigating tendon properties in athletes. For a one-way ANOVA with four groups (the planned comparison), an alpha level (α) of 0.05, and a desired statistical power ($1 - \beta$) of 0.80, the minimum required total sample size was calculated to be 36 participants ($n = 9$ per group). We aimed to recruit a minimum of 40 elite athletes to account for potential attrition and ensure robust power for post-hoc analyses.

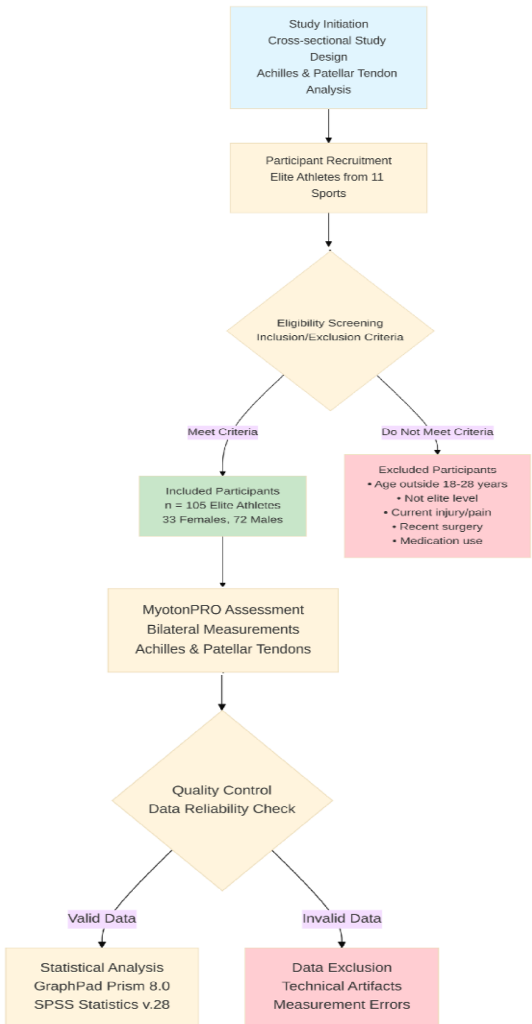
Participants were recruited through a combination of convenience and purposive sampling from elite athletes undergoing daily training at the High-Performance Center. All evaluations conducted in this study were integrated into the routine assessment protocols that these athletes regularly undergo as part of their continuous performance monitoring. The participants had to meet all of the following criteria to be eligible for the study: (a) be a currently competing elite athlete, defined as competing at a national or international level within the previous 12 months; (b) be aged between 18 and 38 years; (c) be actively involved in a structured, sport-specific competitive training program for a minimum of 12 hours per week; (d) have no current musculoskeletal pain or injury requiring treatment or modifying training; (e) have no history of major lower limb surgery (e.g., Achilles tendon repair, ligament reconstruction); (f) have not applied cryotherapy (ice) or used topical analgesics on the lower limbs within the last 72 hours prior to assessment; (g) have not engaged in exhaustive or unaccustomed exercise in the 24 hours prior to testing.

Participants were excluded from the final analysis based on the following criteria: (a) failure to complete all required phases of the testing protocol; (b) voluntary withdrawal from the study at any stage; (c) experiencing any discomfort or adverse event during testing that precluded completion; (d) identification of a technical artifact or measurement error that rendered the data unreliable. All participants provided written informed consent after receiving a detailed explanation of the study procedures. All measurements were performed under standardized environmental conditions (temperature: 22 ± 1°C; humidity: 50 ± 5%) to minimize variability and ensure data reliability.

Procedure

Measurements were conducted by high-performance specialists using a standardized protocol to ensure accuracy and reliability (Mencel, Marusiak, Jaskólska, Jaskólski, & Kisiel-Sajewicz, 2021). Participants were instructed to maintain complete muscle relaxation during testing in a controlled environment, free from external interference such as noise, vibrations, or extreme temperatures. Each participant was positioned on an examination table with postures optimized for full relaxation. The target tendon was supported by custom-designed support to eliminate extraneous tension. The device probe was applied perpendicularly to the tissue surface with a constant preload of 1.18 N, followed by a 15 ms mechanical impulse (0.3–0.4 N force). Measurements with a coefficient of variation (CV) exceeding 3% were discarded and repeated according to established recommendations (Jiménez-Sánchez et al., 2018). For Achilles tendon assessments, participants lay prone with feet extending beyond the table, and the measurement point was marked 6 cm from the plantar heel border. Participants adopted a supine position for patellar tendon evaluations with their knees semi-flexed at 30°, and the measurement site was identified 3 cm distal to the inferior patellar pole (Mencel et al., 2021). Figure 1 shows the flowchart of experimental procedures.

Figure 1. Study design flowchart. The diagram details the process from participant recruitment and screening.



Instrument

The Myoton Pro® (Myoton, Tallinn, Estonia) was employed to assess the mechanical properties of the patellar and Achilles tendons. The device was calibrated according to the manufacturer's specifications prior to starting the data collection period. All evaluations were performed by two experienced high-performance specialists who had undergone standardized training in the use of the MyotonPRO® device and had a minimum of two years of practical experience with the technique to ensure protocol adherence and measurement consistency.

This tool utilizes a free oscillation technique to evaluate tissue mechanical response, demonstrating high reliability in tendon assessments, particularly for the Achilles tendon, where both intra- and inter-observer reliability have been well-documented (Römer et al., 2023). The device operates by delivering a brief mechanical impulse that induces damp tissue oscillations, enabling precise quantification of viscoelastic properties and load-response characteristics. The following variables were measured in the right and left limbs for each tendon: frequency (Hz), stiffness (N/m), decrement (dimensionless), relaxation time (ms), and creep (viscoelastic deformation, Deborah number) (Morgan, Martin, Williams, Pearce, & Morris, 2018; Szajkowski et al., 2024). A detailed description of these parameters is provided in Table 1. Uniform testing protocols were maintained across all evaluations, including a 15 ms pulse duration, 0.8 s measurement interval, and a 3 mm probe diameter (Jiménez-Sánchez et al., 2018). All measurements were performed under standardized environmental conditions (temperature: 22 ± 1°C; humidity: 50 ± 5%) to minimize the influence of external factors on tissue properties. The device was calibrated daily before the start of each collection session to ensure data accuracy and reliability, strictly following the manufacturer's guidelines. The calibration procedure involved the use of a test block with known mechanical properties, ensuring that stiffness and frequency measurements were within the pre-established error limits set by the manufacturer. Only the device's probe made direct contact with the skin overlying the target tissue during testing, ensuring perpendicular and stable application to minimize measurement variability. Furthermore, participants were instructed to refrain from physical activity for at least 24 hours before testing to avoid acute effects of exercise on tendon mechanical properties. The evaluators were blinded to the sport discipline of the participants during measurements to prevent assessment bias.

Table 1. Variables, definition, calculation and units.

Variable	Definition	Formula	Unit of Measurement
Frequency	The natural oscillation frequency of the tissue after a mechanical perturbation. Indicates the dynamic stiffness of the tissue.	$f = (1 / 2\pi) \sqrt{(k / m)}$	Hertz (Hz)
Stiffness	Resistance of the tissue to deformation when an external force is applied. Related to structural elasticity.	$S = F / \Delta x$	Newton/meter (N/m)
Decrement	The rate at which the amplitude of the tissue's vibration decreases after a perturbation. Reflects the viscoelastic properties of the tissue.	$D = (A_1 - A_2) / A_1$	Dimensionless
Relaxation	Reduction in the internal tension of the tissue over time when a constant deformation is maintained. Reflects the viscoelastic ability to relax.	$\varepsilon(t) = \varepsilon_0 e\hat{}(-\lambda t)$	Milliseconds (ms)
Creep	Slow and progressive increase in the deformation of the tissue under a constant load maintained over time.	$\varepsilon(t) = \varepsilon_0 + \Delta\varepsilon (1 - e\hat{}(-\beta t))$	Millimeters (Deborah N°)

Data analysis

Data were analyzed using GraphPad Prism® 8.0 and SPSS v.28. The normality of all variables was confirmed by the Kolmogorov-Smirnov test ($p > 0.05$), and homogeneity of variances was assessed with Levene's test ($p > 0.05$). Descriptive data are presented as mean ± standard deviation (95% confidence intervals), stratified by sport. The independent effect of sport discipline on tendon properties was first assessed using unadjusted one-way ANOVA. An ANCOVA was subsequently performed with age, body mass index (BMI), and years of training experience as covariates. All ANCOVA assumptions were tested and met. Inter-sport differences were analyzed using these models, with post hoc comparisons conducted via Tukey's HSD test. Effect sizes were calculated using eta-squared (η^2) for ANOVA and partial eta-squared (ηp^2) for ANCOVA. Cohen's d was computed for significant pairwise comparisons. A Bonferroni correction was applied to control Type I error, with a significance level of $\alpha \leq 0.05$.

Results

The mean weight of male athletes (79.1 ± 12.9 kg; 95% CI: 76.2-82.0) was significantly higher than that of female athletes (66.8 ± 9.7 kg; 95% CI: 63.5-70.1), with a mean difference of 12.3 kg (p < 0.001; Cohen's d = 1.05, 95% CI: 0.67-1.42). Similarly, the mean height of male participants (178.3 ± 9.8 cm; 95% CI: 176.1-180.5) was consistently greater than that of female participants (164.6 ± 5.6 cm; 95% CI: 162.7-166.5), representing a mean difference of 13.7 cm (p < 0.001; Cohen's d = 1.74, 95% CI: 1.32-2.15). In contrast, mean age was homogeneous between groups, with complete overlap of confidence intervals (24.9 ± 4.5 years for males vs. 24.2 ± 4.6 years for females; mean difference: 0.7 years; p = 0.42; Cohen's d = 0.15, 95% CI: -0.21-0.52), indicating no statistically significant difference in this variable. The results presented in Table 2 display the values of biomechanical properties for the Achilles and patellar tendons.

Table 2. Myotonometry variables across sports for Achilles and Patellar tendons. Data presented as mean ± standard deviation (95% confidence interval).

Sport	Tendon	Frequency (Hz)	Stiffness (N/m)	Decrement	Relaxation (ms)	Creep
Cycling	Achilles	27.7 ± 2.3 (26.3–29.1)*	663.0 ± 74.3 (612–714)§	1.0 ± 0.1 (0.9–1.1)*	7.7 ± 1.0 (6.5–8.9)‡	0.5 ± 0.5 (0.2–0.8)†
	Patellar	21.9 ± 1.7 (20.8–23.0)§	579.6 ± 72.5 (521–638)§	0.9 ± 0.7 (0.7–1.1)	9.1 ± 1.2 (8.3–9.9)§	0.5 ± 0.6 (0.3–0.7)§
Roller hockey	Achilles	30.2 ± 1.4 (29.4–31.0)*	803.0 ± 57.0 (765–841)§	0.8 ± 0.1 (0.7–0.9)†	6.3 ± 3.9 (5.1–7.5)‡	0.4 ± 0.8 (0.2–0.6)‡
	Patellar	21.8 ± 2.6 (20.7–22.9)§	580.0 ± 94.1 (525–635)§	0.9 ± 0.1 (0.8–1.0)	9.2 ± 1.5 (8.5–9.9)§	0.5 ± 0.8 (0.3–0.7)§
Karate	Achilles	30.4 ± 2.6 (29.1–31.7)*	785.9 ± 92.1 (726–846)§	0.8 ± 0.1 (0.7–0.9)†	6.5 ± 9.1 (5.3–7.7)‡	0.4 ± 0.5 (0.2–0.6)‡
	Patellar	21.9 ± 2.6 (20.8–23.0)§	594.5 ± 107.8 (537–652)§	0.9 ± 0.8 (0.7–1.1)	9.2 ± 1.9 (8.5–9.9)§	0.5 ± 0.1 (0.4–0.6)§
Athletics	Achilles	31.1 ± 1.9 (30.0–32.2)*	824.4 ± 100.9 (769–880)§	0.8 ± 0.2 (0.7–0.9)†	6.2 ± 0.8 (5.8–6.6)‡	0.4 ± 0.4 (0.2–0.6)‡
	Patellar	22.7 ± 2.8 (21.5–23.9)§	612.8 ± 102.2 (556–670)§	0.9 ± 0.1 (0.8–1.0)	8.8 ± 1.7 (8.1–9.5)§	0.6 ± 0.9 (0.4–0.8)§
Indoor volleyball	Achilles	32.5 ± 3.1 (31.0–34.0)*	866.5 ± 76.6 (822–911)§	0.7 ± 0.1 (0.6–0.8)†	5.9 ± 4.7 (4.7–7.1)‡	0.4 ± 0.4 (0.2–0.6)‡
	Patellar	22.5 ± 1.7 (21.6–23.4)§	600.2 ± 63.4 (572–628)§	0.9 ± 0.1 (0.8–1.0)	8.9 ± 0.9 (8.5–9.3)§	0.5 ± 0.4 (0.3–0.7)§
Taekwondo	Achilles	24.9 ± 4.0 (23.2–26.6)†	584.6 ± 116.1 (525–644)#	1.0 ± 0.5 (0.8–1.2)§	9.2 ± 2.1 (8.3–10.1)#	0.5 ± 0.1 (0.4–0.6)#
	Patellar	20.6 ± 2.4 (19.6–21.6)	595.6 ± 111.4 (538–653)	0.9 ± 0.5 (0.7–1.1)	9.8 ± 2.0 (9.0–10.6)§	0.6 ± 0.1 (0.5–0.7)
Inline speed skating	Achilles	26.2 ± 4.7 (24.3–28.1)	635.9 ± 122.9 (571–701)#	1.1 ± 0.2 (1.0–1.2)	8.5 ± 3.0 (7.5–9.5)#	0.5 ± 0.1 (0.4–0.6)
	Patellar	23.7 ± 4.5 (22.0–25.4)	630.1 ± 131.1 (559–701)	0.9 ± 0.5 (0.7–1.1)	9.8 ± 2.0 (9.0–10.6)	0.6 ± 0.1 (0.5–0.7)
Judo	Achilles	26.7 ± 2.8 (25.5–27.9)	641.9 ± 67.4 (605–679)#	1.1 ± 0.2 (1.0–1.2)	7.9 ± 1.0 (7.4–8.4)#	0.5 ± 0.6 (0.3–0.7)#
	Patellar	23.3 ± 2.7 (22.2–24.4)§	643.1 ± 118.7 (582–704)§	1.0 ± 0.9 (0.8–1.2)	8.8 ± 1.7 (8.1–9.5)§	0.5 ± 0.9 (0.3–0.7)§
Archery	Achilles	22.6 ± 1.4 (21.9–23.3)†	542.6 ± 48.3 (514–571)#	1.2 ± 0.1 (1.1–1.3)†	9.6 ± 1.1 (9.1–10.1)#	0.6 ± 0.6 (0.4–0.8)#
	Patellar	18.1 ± 3.3 (16.9–19.3)	416.7 ± 151.6 (359–474)†	0.9 ± 0.1 (0.8–1.0)	13.2 ± 3.6 (11.8–14.6)†	0.7 ± 0.1 (0.6–0.8)†
Handball	Achilles	30.3 ± 2.1 (29.3–31.3)	756.8 ± 110.3 (699–815)#	0.8 ± 0.7 (0.6–1.0)	6.7 ± 1.9 (6.1–7.3)#	0.4 ± 0.1 (0.3–0.5)#
	Patellar	20.9 ± 1.8 (20.1–21.7)	571.1 ± 86.8 (528–614)	0.9 ± 0.1 (0.8–1.0)	9.6 ± 1.4 (9.0–10.2)	0.6 ± 0.6 (0.4–0.8)
Boxing	Achilles	29.2 ± 1.9 (28.3–30.1)	730.7 ± 67.5 (694–768)	0.9 ± 0.1 (0.8–1.0)	6.9 ± 6.1 (5.7–8.1)	0.4 ± 0.3 (0.2–0.6)
	Patellar	22.1 ± 1.9 (21.2–23.0)	602.8 ± 102.0 (549–657)	0.9 ± 0.1 (0.8–1.0)	9.0 ± 1.5 (8.4–9.6)	0.5 ± 0.8 (0.3–0.7)

Note. Data presented as mean ± standard deviation (95% confidence interval). p<0.01 vs Indoor volleyball and Archery. † p<0.009 vs Taekwondo and Archery. ‡ p<0.001 vs Taekwondo, Inline speed skating, Judo, and Archery. § p<0.002 vs Handball and/or Archery (depending on variable).

A one-way analysis of variance (ANOVA) revealed statistically significant differences in all biomechanical variables for both tendons among athlete groups (p ≤ 0.001 for all comparisons), with the exception of decrement in the patellar tendon (p = 0.45), which showed no significant effect. The analyses were associated with large effect sizes for the significant main effects, as indicated by eta-squared (η^2) values ranging from 0.18 to 0.34, confirming that the sport discipline accounted for a substantial proportion of the variance in tendon properties.

Post hoc analyses using Tukey's HSD test were conducted to identify specific group differences. Stiffness exhibited the highest number of inter-sport differences for the Achilles tendon. Volleyball players demonstrated the most pronounced disparities compared to other sports (e.g., vs. swimmers: Cohen's d = 1.95, 95% CI [1.40, 2.50], p = 0.04), indicating an extremely large effect. The greatest variability for the patellar tendon was observed in the relaxation variable, with archery yielding the most distinct values (e.g., vs. runners: Cohen's d = -1.40, 95% CI [-2.10, -0.70], p = 0.002), representing a large negative effect. As anticipated from the ANOVA result, all pairwise comparisons for patellar tendon decrement showed negligible effect sizes (all |d| < 0.20), consistent with the non-significant finding. Analysis of covariance (ANCOVA) adjusting for age, body mass index, and training experience confirmed that these significant inter-sport differences persisted (all p ≤ 0.01 for the main effect of sport discipline). The adjusted model estimates are presented in Table 3.

Table 3. Comparative analysis of tendon biomechanical properties across sport disciplines: Unadjusted (One-way ANOVA) and Adjusted (ANCOVA) models.

Tendon	Variable	Model	Volleyball	Swimming	Running	Archery	P- Value	Effect Size (η^2 or ηp^2)
Achilles	Stiffness (N/m)	ANOVA	310.5 ± 25.1	245.8 ± 22.4	280.3 ± 24.8	235.6 ± 26.9	<0.001	η^2 = 0.34
		ANCOVA	308.9 (300.1–317.7)	247.1 (238.3–255.9)	279.5 (270.7–288.3)	238.5 (229.7–247.3)	<0.001	ηp^2 = 0.31
	Relaxation (%)	ANOVA	14.8 ± 2.1	19.2 ± 1.8	16.5 ± 2.0	21.5 ± 2.3	<0.001	η^2 = 0.28
		ANCOVA	14.9 (14.1–15.7)	19.1 (18.3–19.9)	16.4 (15.6–17.2)	21.3 (20.5–22.1)	<0.001	ηp^2 = 0.26
Patellar	Stiffness (N/m)	ANOVA	285.7 ± 30.5	260.1 ± 28.9	295.8 ± 31.2	255.0 ± 29.5	<0.001	η^2 = 0.18
		ANCOVA	284.2 (273.1–295.3)	261.5 (250.4–272.6)	294.0 (282.9–305.1)	256.3 (245.2–267.4)	<0.001	ηp^2 = 0.17
	Relaxation (%)	ANOVA	16.5 ± 3.0	18.8 ± 2.8	15.2 ± 2.5	22.1 ± 3.2	<0.001	η^2 = 0.25
		ANCOVA	16.6 (15.3–17.9)	18.7 (17.4–20.0)	15.1 (13.8–16.4)	21.9 (20.6–23.2)	<0.001	ηp^2 = 0.23
	Decrement	ANOVA	1.55 ± 0.30	1.62 ± 0.35	1.58 ± 0.32	1.60 ± 0.34	0.45	η^2 = 0.02
		ANCOVA	1.56 (1.45–1.67)	1.61 (1.50–1.72)	1.57 (1.46–1.68)	1.59 (1.48–1.70)	0.48	ηp^2 = 0.02

Note: ANOVA (Unadjusted): Data are presented as Mean ± Standard Deviation. ANCOVA (Adjusted): Data are presented as Adjusted Mean (95% Confidence Interval). The model was adjusted for age, body mass and height. Effect Size: η^2 (Eta-squared) is reported for the ANOVA models. ηp^2 (Partial Eta-squared) is reported for the ANCOVA models. Bold p-values indicate statistical significance (α < 0.05).

Discussion

This study analyzed the viscoelastic properties of the patellar and Achilles tendons in athletes from different sport disciplines using myotonometry. Our findings confirm the initial hypothesis that sport-specific biomechanical demands are associated with distinct tendon adaptations. Athletes engaged in explosive and impact-based disciplines (e.g., volleyball, sprinting) exhibited increased Achilles tendon stiffness, which may optimize performance and mechanical efficiency. Conversely, endurance-oriented sports (e.g., distance running, cycling, swimming) showed lower stiffness, suggesting adaptations for improved load absorption during sustained exertion. These results reinforce the concept that tendon properties are modulated by the functional requirements and loading patterns of each discipline (Domroes et al., 2024; Seymore, Hanlon, Pohlig, Elliott, & Silbernagel, 2025; Wang et al., 2025).

Tendons act as key mechanical structures, transmitting forces from muscle to bone while storing and releasing elastic energy (Domroes et al., 2025). Their viscoelastic properties, particularly stiffness and elasticity, are critical for balancing performance efficiency and injury prevention (Seymore et al., 2025; Williams & Gyer, 2025). Increased stiffness can enhance rapid force transmission and mechanical efficiency in explosive tasks, but may also reduce shock absorption capacity (Volesky et al., 2025). Conversely, greater compliance facilitates energy dissipation and tolerance to repetitive cyclic loads, constituting a particularly advantageous adaptation in endurance sports (Lazarczuk et al., 2022; Sasajima & Kubo, 2024). These physiological mechanisms explain why the Achilles tendon, heavily loaded during vertical propulsion, exhibits more pronounced sport-specific adaptations compared to the patellar tendon.

Our results are consistent with recent findings showing the Achilles tendon as the most sensitive structure to sport-specific loading (Römer, Czupajllo, Wolfarth, Sichting, & Legerlotz, 2024; Trybulski et al., 2024). For instance, swimmers present significantly lower stiffness compared to handball and volleyball athletes (Römer et al., 2024), following a pattern also observed in our cohort. This suggests that repetitive vertical loading, typical in court and track-and-field sports, promotes remodeling that enhances stiffness, whereas cyclic endurance training favors compliance. In contrast, patellar tendon decrement showed no sport-related differences, which is in line with recent reports (Hagen et al., 2023; Monte, Skypala, Vilimek, Juras, & Jandačka, 2023; Wang et al., 2024). Such divergence between tendons highlights their differential sensitivity to loading patterns and should be considered in sport-specific monitoring and training design. Interestingly, our results differ from studies that reported no between-sport differences in Achilles tendon stiffness among collegiate athletes (Althoff et al., 2024; Cushman et al., 2025). These discrepancies may be explained by differences in training intensity, competitive level, and cumulative load exposure. For example, elite basketball players display more pronounced structural adaptations than recreationally trained individuals (Schmidt, Verderber, Germano, & Nitzsche, 2025; Vicentini, Mercer, & Simeone, 2025).

From a practical perspective, our findings provide actionable insights for coaches and sports professionals. Monitoring tendon properties can support individualized training load management, optimize performance, and facilitate early detection of tendinopathy risk (Bravo-Sánchez, Abián, Jimenez, & Abián-Vicén, 2021; Bravo-Sánchez, Abián, Jiménez, & Abián-Vicén, 2019). Myotonometry offers reliable estimates of stiffness, elasticity, and damping by applying a brief mechanical impulse and analyzing the oscillatory response. Although it cannot fully capture the hierarchical tendon structure, it has clear advantages over imaging-based methods: it is portable, time-efficient, and requires minimal operator expertise (Trybulski et al., 2024; Volesky et al., 2025). These characteristics make myotonometry a valuable tool in applied settings for high-performance programs. Coaches and medical staff could integrate it into routine assessments to track sport-specific adaptations, detect early signs of overuse, and adjust training loads proactively. Recent studies confirm its reliability in athletic populations (Domroes et al., 2025; Trybulski et al., 2024), and our results further support its role in performance monitoring and injury prevention.

Some limitations of this study must be acknowledged. First, although myotonometry is reliable, portable, and user-friendly, it does not provide a comprehensive characterization of tendon structure compared to advanced imaging techniques such as elastography or high-resolution ultrasound. Future studies should consider integrating multimodal approaches to combine the practicality of myotonometry with the structural detail of imaging methods. Second, while the sample was balanced across different sports, subgroup sizes were relatively small in some disciplines, which may have reduced statistical power and increased the risk of type II error. Expanding the number of athletes per discipline or conducting multicenter studies would strengthen the robustness and generalizability of findings. Third, individual variability related to factors such as previous injury history, training background, sex, and external load exposure was not controlled. These variables can substantially influence tendon properties and should be systematically accounted for in future designs, either through stratified recruitment or advanced statistical modeling. Finally, the cross-sectional design precludes establishing causal relationships between training load and tendon adaptation. Longitudinal designs are needed to clarify whether the observed differences reflect chronic training-induced remodeling or pre-existing individual characteristics. Follow-up studies tracking athletes across training cycles or competitive seasons would provide more conclusive evidence of adaptation dynamics.

Conclusions

The findings of this study support the hypothesis that tendon viscoelastic properties vary significantly across sports, with the Achilles tendon demonstrating higher sensitivity to sport-specific mechanical demands compared to the patellar. Sports such as archery and taekwondo exhibited the lowest values in both tendons, consistent with their reduced reliance on elastic energy storage and release. In contrast, volleyball showed the highest values, suggesting that mechanical loading patterns drive differential adaptations in tendon stiffness and related properties. Stiffness emerged as a critical factor in tendon adaptability, with direct implications for athletic performance. Myotonometric tendon evaluation thus enables identifying adaptive patterns which inform precise adjustments to training loads in elite athletes.

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Author Contributions

Conceptualization, A.B.-G. and C.J.B.; methodology, A.B.-G., C.J.B. and E.A.-M.; formal analysis, M.A.-I. and L.M.D.; investigation, S.S.-G., J.T.-C. and C.P.T.; data curation, M.A.-I. and L.M.D.; writing—original draft preparation, S.S.-G., E.A.-M. and C.J.B.; writing—review and editing, all authors; supervision, A.B.-G. and E.A.-M. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

The study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board of the Estadual University of Minas Gerais (protocol code 7.272.986, date of approval: 12 June 2024). Informed consent was obtained from all subjects involved in the study.

Data Availability Statement

The data presented in this study are available upon request from the corresponding author. The data are not publicly available due to privacy and ethical restrictions.

Conflicts of Interest

The authors declare no conflicts of interest.

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