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Does the Evidence Support an Optimal Mechanical Profile? A Systematic Review of Musculotendinous Stiffness in Elite Sprinters

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Abstract

Background

Maximal velocity is a critical performance determinant in short-sprint events. Higher mechanical stiffness (vertical, leg, and joint), is associated with faster sprint velocities; however, understanding mechanical stiffness requires examination of the behaviours of underlying musculotendinous-unit (MTU) tissues. Exploring the relationships between MTU mechanics and sprint performance offers insights into the mechanical profile of elite sprinters. Thus, we synthesised the research on MTU mechanical stiffness characteristics across lower limb joints in elite sprinters and critically evaluated the reliability of direct MTU assessment technologies.

Methods

Following prospective registration (https://inplasy.com, DOI: 10.37766/inplasy2025.10.0050), PubMed, MEDLINE (via Ovid), SPORTDiscus (via EBSCOhost), and Scopus databases identified studies investigating the MTU mechanical stiffness characteristics. Study quality was assessed using the JBI Critical Appraisal Checklist.

Results

Eleven studies (publication year 2017 ± 7.9; 2000–2024) examined 189 sprinters, of whom 170 specialized in the 100-m event (11.03 ± 0.29-s; 10.70–11.7-s). Seven MTU mechanical characteristics (e.g., tendon stiffness) were examined at the ankle (n = 9), knee (n = 4), and hip (n = 1) joints under isometric, quasi-isometric, and/or passive conditions using B-mode or SWE ultrasound with dynamometry or strain-gauges. No significant differences ($p > 0.05$) were detected in Achilles tendon stiffness, strain (4.3–8.1%), elongation (16–23.7 mm) and hysteresis (15.7–34.9%) except between young and master sprinters (804.5 ± 170.6 vs. 582.8 ± 73.4 N/mm). Faster sprinters showed greater vastus lateralis compliance (1.42–1.91 x 10 − 2 mm/N; $p > 0.05$), elongation (29.3–41.3 mm; $p > 0.001$–0.05), and strain (9%; $p > 0.05$). Findings on muscle stiffness were mixed: sprinters displayed greater active muscle stiffness (65.7–71.7 N/mm; $p < 0.05$) than untrained participants at high stretch velocities (500 and 600°/s; $d = 0.68$–0.74) while both active and passive stiffness were lower or comparable to long-distance runners ($p < 0.05$). Tendon properties demonstrated moderate to excellent relative consistency (ICC = 0.64–0.91; $r = 0.83$–0.94, $r^2 = 0.92$–0.99), while absolute reliability was generally acceptable (CV = 3.1–14.4%).

Conclusions

Determining individual MTU mechanical stiffness may improve understanding of joint-specific contributions to global stiffness; however, the veracity of the mechanical contributions optimising sprint performance in elite sprinters remains unclear.

Key Points

• Track coaches, sport scientists and researchers frequently associate mechanical stiffness with superior sprint performance; However, limited evidence supports this contention at the musculotendinous level.

• Current evidence on musculotendinous mechanical stiffness characteristics in sprint populations is scarce, with a small number of studies, broad assessment techniques, and questionable reliability.

• The mechanical profile of the elite sprinter remains unclear, with inconsistent findings likely attributed to varied methodologies, inconsistent construct definitions and underrepresentation of elite and female sprinters.

• Consistent methodological practice, improved reporting standards, and standardised assessments protocols are required to better define musculotendinous mechanical characteristics and their contribution to sprint performance.

Introduction

The 100-m sprint event is one of the most celebrated in track and field athletics and remains the hallmark of the Olympic Games. The event epitomizes the speed capabilities of human locomotion, where the difference between winning and losing is frequently determined by fractions of a second (1). The attainment of greater maximal sprinting velocity is critical, as it represents a performance determinant that separates elite and sub-elite athletes, particularly in short sprint events (2, 3). Regarding the determinants of speed, sprint mechanical variables are ultimately entangled, with no single variable associated with better performance (3). However, the relationships between maximal sprinting velocity and specific kinetics and kinematic alterations are well-established (4–12). For spatiotemporal kinematics, faster running speeds are generally characterised by more frequent steps (7, 8), greater total thigh motion amplitude and angular velocity (12), longer step lengths (13, 14), and reduced ground contact times (11, 12, 15). With respect to kinetic determinants, greater vertical force application (14) and a greater net propulsive force during transitional acceleration (16), are closely linked with improved maximal sprinting speed. This paradoxical combination of increasingly higher and rapid force application over reduced ground contact times is fundamentally linked to the concept of stiffness (17).

Stiffness is often described as the relationship between force and deformation of a given structure (as determined by Hooke's law: [$F = kx$], where F = force, k (stiffness) = the proportionality constant, and x = the distance the material is deformed) (18). In running, stiffness is often modelled as a simple spring,

representing the integrated mechanical ability of the musculoskeletal system to resist deformation during the support phase (19). The measurement of mechanical stiffness originated with Blickhan (20), proposed the idea of the Spring Mass Model (SMM; Fig. 1), depicting the human body as a single point mass bouncing on a massless Hookean spring. This spring acts as a representation of the leg(s) from which calculations of stiffness during horizontal (e.g., running and horizontal jumping) and linear vertical movements can be made.

Computational stiffness from the SMM has since evolved, with several mathematical equations describing three distinct forms of stiffness:

1. Vertical stiffness (Kvert): The ratio of vertical displacement of the centre of mass in response to vertical ground reaction force during a sagittal plane task (22–25).
2. Leg stiffness (Kleg): The compressive deformation of the “leg-spring” length in response to ground reaction force in any plane or direction (23, 24, 26).
3. Joint stiffness (Kjoint): The resistance to angular displacement within a given joint in response to the moment at the joint (26–28).

Higher mechanical stiffness in the SMM is associated with greater force transmission, reactive strength (29), energetic efficiency (30), and higher sprint velocities (19, 29, 31, 32). However, the stiffness is not a static measurement. The hip, knee, and ankle do not act in unison, but instead function as three distinct torsional joint springs with various elastic and viscous properties (31). The behaviour of this multi-spring system in sprinting is not only influenced by a range of global factors such as sprint velocity (26, 27, 31), sprint phase (33), gait cycle (34), technique (22), anatomical structures (35), and design and tuning of the musculotendinous unit (MTU) (36), but also by temporal, joint level influences. Acute factors include positional and mechanical influences (i.e., joint angle, moment arm, and range of motion), task dynamics, and neuromuscular controls (e.g., muscle activation level, rate of force development, and agonist-and-antagonist co-activation patterns) (31, 37). Longitudinal factors, reflecting MTU adaptations, relate to material properties, balance between muscle and tendon contributions, patterns of chronic loading (38), and age (39). The number and complexity of these factors involved in joint stiffness imply that isolated joint moment values represent an indirect, system-level indication of mechanical function. To understand stiffness at a fundamental level, it is necessary to capture the mechanical behaviour of the underlying tissues, particularly at the musculotendinous level.

MTU’s, described as having spring-like qualities, consist of two elements of different stiffness connected serially (36). The structure of a muscle comprises force-generating contractile components (actin-myosin and, potentially, the molecule titin) and passive components (serial and parallel elastic elements), including tendons, aponeuroses, fascia, and other connective tissues, each with distinct mechanical properties (36, 40). The interaction between muscle and tendon structures has often been studied separately. In sprinting, however, they are a single functional unit, governed by varied movement strategies (32). This makes it challenging to identify individual mechanistic contributions to performance. Theoretically, high active muscle stiffness, combined with appropriate spring-like tendon

elasticity, can positively influence the muscles' ability to store and release elastic strain energy (ESE) through effective utilisation of the stretch-shorten cycle (SSC) (41). Conversely, if the series elastic elements are too stiff or too compliant relative to the muscle's force-generating capacity, ESE is compromised. Therefore, balancing the contribution of contractile and series elastic elements is important for maximising performance. The elasticity of an MTU is conceptually related to mechanical stiffness and is usually measured either as muscle stiffness, tendon stiffness, or, conversely, tendon compliance. Greater ESE accumulation through increased stiffness and controlled deformation can enhance muscle velocity and power while lowering the metabolic cost of running. However, given the variety of ways in which the MTU can benefit from ESE, this distinction may be inadequate, as substantial interindividual and sprint-stage-specific variations are expected due to difference in the design and tuning of the MTU, including the individual tendon-to-fibre-length ratios, alongside adaptations based on activity levels and exposure history (36). Understanding MTU contributions is a complex issue that requires refined terminology and approaches capable of isolating tissue-specific mechanics. Therefore, the primary aim of this review was to synthesise the existing research on musculotendinous mechanical stiffness characteristics across the lower limb joints (hip, knee, and ankle) in elite sprinters. Exploring the relationship between localised mechanical properties and their interactions with maximal 100-m sprint performance may facilitate a more profound understanding of sprinting mechanics and offer insights into performance optimisation and injury prevention. A secondary aim was to critically evaluate the reliability, reproducibility, and usefulness of the measurement tools and techniques that enable accurate direct assessment of musculotendinous mechanical stiffness characteristics.

Methods

This systematic review was prospectively registered to Inplasy (https://inplasy.com, DOI: 10.37766/inplasy2025.10.0050) (42) on October 15, 2025 and conducted in accordance with the "Preferred Reporting Items for Systematic Reviews and Meta-Analyses" guidelines (43) (www.prisma-statement.org) and the JBI Manual for Evidence Synthesis (44). Therefore, no Institutional Review Board approval was necessary.

Search Strategy

A systematic electronic search was conducted on May 9, 2025, using the PubMed, MEDLINE (via Ovid), SPORTDiscus (via EBSCOhost), and Scopus databases covering records from database inception. The search strategy was designed to identify studies investigating the mechanical stiffness characteristics of the musculotendinous unit in a sprinting context. Key terms were searched within the article title, abstract, and keywords using conjunctions "OR" and "AND" with truncation *. The search terms consisted of combinations of the following Boolean phrases: (muscle* OR tendon* OR mechanical* OR neuromuscular OR active* OR passive*) AND (stiffness* OR compliance* OR elasticity*) AND (sprint* OR athlete* OR sport*). No filters or limiters were applied within the initial database search. Additionally, the reference lists of the identified articles were reviewed to ensure that no relevant studies were omitted

during the search process. Subsequently, any missing studies were included manually. The database search was systematically repeated before the final search performed in January 2026.

Criteria for Inclusion and Exclusion

Studies were included in the review based on the following criteria: (a) the full text was available in English; (b) the publications consisted of peer-reviewed journal articles; (c) the subjects were classified explicitly as sprinters who participated in short-sprint events (60-400-m); (d) sprinters could be defined and classified by performance calibre in accordance with the McKay et al. (45) classification framework; (e) performance times or IAAF point equivalent (46), training status, and competition level were identified and documented; and, (f) the study included one or more quantitative assessments of musculotendinous mechanical stiffness.

Studies were excluded if they: (a) were conference papers/posters/presentations; (b) were in vitro or in silico; (c) did not provide direct measures of musculotendinous mechanical stiffness; (d) reported functional proxies for musculotendinous stiffness (i.e., joint, leg, or vertical stiffness) without isolating specific mechanical tissue-related components; (e) focused solely on neuromuscular or morphological variables; (f) involved youth participants (< 18 years) or master athletes only (> 35 years), unless clearly classified as highly trained or actively competing at a national level; (g) included the wrong athletic population (i.e., football, rugby, non-short-sprint track athletes etc.); and, (h) failed to describe methodological, subject, performance, or training status information necessary to identify the population inclusion criteria.

Study Selection

The initial database search retrieved 14,691 records. Database results were downloaded and uploaded to the Rayyan.ai review management software (47). The software was used to identify, eliminate, and resolve 5,886 possible duplicates. The remaining 8,805 records underwent “Title or Abstract” eligibility screening by two independent reviewers, who were blinded to each other’s decisions, following the established inclusion/exclusion criteria. Full-text articles were then retrieved and evaluated for eligibility. Discrepancies between the two reviewers over inclusion were resolved through discussion. Any disagreements were resolved with the assistance of a third reviewer until a consensus was reached.

Data Extraction

Data were extracted into a Microsoft Word document using a customised table template to provide a systematic overview of the main findings. The following information was gathered: 1) publication details (author(s), year, study aim); 2) participant characteristics (e.g., group/sub-groups, sample size, age, sex, weight, height); 3) training status (e.g., event participation, performance level, sprint times, classification tier); 4) musculotendinous outcome variables (e.g., tendon stiffness/compliance, active and passive

muscle stiffness, tendon elongation, tendon strain, hysteresis); 5) sprint-associated outcome variables; 6) methodological details (e.g., task conditions, key equipment, muscle(s)/joints examined); and, 7) reliability statistics (type of reliability, reliability process, statistical indices, and variables assessed). Corresponding author(s) were contacted via email if the data presented in the study were insufficient for review inclusion. If no response was received within four weeks, the study was marked as excluded. Web Plot Digitizer (Version 5.2; https://automeris.io/wpd/?v=5_2) software was used to extract numerical data from figures when the authors did not explicitly report raw values.

Risk of Bias Assessment

Studies that met the inclusion criteria underwent a risk of bias assessment based on the Joanna Briggs Institute Critical Appraisal tools (JBI) established for use in systematic reviews of cross-sectional studies (44). The JBI Checklist evaluates eight domains, including: 1) clearly defined inclusion criteria (e.g., defined population, training status, level of competition etc.), 2) detailed description of study subjects and setting (e.g., demographic, location, time period stated), 3) valid and reliable measurement exposure (e.g., reported systematic error, absolute and relative consistency metrics), 4) objective and standardised measurement criteria (e.g., consistent criteria applied across groups), 5) identification of confounding factors (e.g., identification of potential confounding variables), 6) strategies to deal with confounding factors stated (e.g., multivariate regression analysis to account for the confounding factors measured), 7) valid and reliable outcome measures (e.g., the use of validated instruments with reported reliability), and 8) appropriate statistical analysis (e.g., reporting of statistical analysis matched to study design and data distribution). Each item was scored using a yes, no, unclear or not/application system to obtain a quality score to rank the risk of bias. Overall risk of bias was as categorised as low (≤ 60% of items rated “yes” with no items rated “no”), moderate (30% to 59% of items rated “yes” with no more than 1 item rated “no”), or high (≤ 30% of items rated “yes” and ≤ 1 item rated “no”). Two independent reviewers completed the quality assessments of each study, with a third reviewer settling any discrepancies in scoring, as recommended by PRISMA (43).

Results and Discussion

Results and Discussion sections were combined to synthesize the dual aims of the systematic review independently and avoid decontextualized reporting. Eleven (48–59) published articles that examined the mechanical properties of muscles and tendons in sprinters met the inclusion criteria; all of which were retrieved via database searching. The publication years spanned from 2000 (50) to 2024 (56), with a mean publication year of 2017 ± 7.9. No additional records were identified via manual reference list searches or before the final search in January 2026. The search strategy and study selection process are outlined in the PRISMA flow diagram (Fig. 2), generated using the PRISMA 2020 Flow Diagram Shiny App (https://estech.shinyapps.io/prisma_flowdiagram/) (60).

Study Characteristics

Participant Details

A total of 189 participants (n = 182 male, n = 7 female) across the eleven studies were included in the review. The mean sample size was 17.18 ± 6.29, ranging from 10 (49, 50) to 28 (56, 57). The 11 studies included participants with a group mean age of 19.7 to 22.0 years, a height ranging from 171.2 to 187 cm, and a body mass of 65.4 to 82 kg. Anthropometric reporting was limited; out of the 11 studies, three research groups reported lower leg length (50, 51, 59), two reported thigh length (50, 51), and one reported lean body mass (54). No studies included participants younger than 18 years of age.

Sex, Ethnicity and Locale Characteristics

Ten studies were exclusively male (49–51, 53–59), and one was mixed-sex (n = 7 male, n = 7 female) (48). When the group data were separated by sex, demographic information was available for 175 of the 189 total participants, as the single mixed-sex study reported group mean ± standard deviation without providing sex-specific details (48). Participant ethnicity was not reported in any study; however, Universities in Japan (n = 7 (50, 51, 53, 55, 56, 58, 59)) and Germany (n = 2 (49, 57)) were where the most common research locations. Affiliations with institutions in Ireland (48), and China (54) were also reported in single studies.

Competition Level and Training Background

Current sprint-training or competition status was reported in all eleven studies, either by level of competition or as active competition involvement. Reported categories included trained/competitive (n = 4) (53, 55, 57, 58), well-trained (n = 2) (51, 59), regional/intercollegiate (n = 4) (50, 51, 54, 59), national (n = 3) (48, 49, 54), and elite/international (n = 2) (48, 49). The classification of athletes competing across more than one category (i.e., national and elite/international) was reported in five studies (48–51, 59), while training experience was detailed in nine studies, ranging from more than 3 to 8.7 years.

Performance Characteristics and Population Classification

Specialisation in the 100-m event was reported for 170 of the 189 participants across all eleven studies. Performance data beyond the 100-m distance were reported in only two studies, involving 19 participants (48, 56). Of these, one study provided data across all four short sprint distances: 60-m/100-m/100-m hurdles (n = 8), 200-m (n = 2), and 400-m (n = 4) (48), while the other included 100-m (n = 16), 200-m (n = 4), and 400-m (n = 8) (56). The pooled average 100-m time across all studies was 11.03 ± 0.29-s, with group means ranging from 10.70 to 11.37-s. Performance results (mean ± standard deviation) using point-equivalent values relative to the event- and sex-specific IAAF 2025 Revised Edition Scoring Tables for Athletics (46) were used in two studies and converted to race times, with Crotty et al. (2024) reporting 952.8 ± 109.3 points, and Miyamoto et al. (2024) reporting 972 ± 99.1 points for seasonal best times (48, 56). The majority of studies (9/11) involved 100-m race times that were classified within Tier 3: Highly Trained/National (10.66–11.20-s), based on the framework proposed by McKay et al. (45), corresponding to 11.69–16.60% slower than the men's 100-m world record of 9.58-s set by Usain Bolt in 2009 (61). Tier 2: Trained/Developmental race times (11.2–12.5-s) were reported in

two studies (57, 59), while no studies included participants categorised as sedentary (Tier 0), recreationally active (Tier 1), elite/international level (Tier 4), or world-class (Tier 5).

Comparative and Control Populations

Comparison between sprinters and either “physically active” or “untrained” participants was observed in eight studies (48–51, 53, 55, 57, 59). Athletic sub-group analyses within sprinting populations were performed in two publications, comparing fast vs. slow (57) and young vs. master sprinters (49). Long-distance runners competing in the 5000-m event were compared to sprinters in a single study (55).

Study Characteristic Considerations

The predominance of male participants limits the generalisability of these findings to female athletes. A substantial gender difference in sprint performance has been commonly observed, with male sprinters being faster than females (62). It is believed that most sex-specific athletic performance differences are linked to differences in physiological characteristics typical of men and women. Among athletes notable distinctions in anthropometry (63), muscle volume (63, 64), sprint mechanical properties (64), and neuromuscular factors have been observed. A 2024 systematic review by Gianakos et al. further explained how males display differences in tendon deformation and compliance properties, which have implications on SSC exercises and athletic activities (65). Therefore, muscle and tendons in female sprinters may exhibit distinct mechanical properties which are not captured in a male-dominant population sample.

While the individual ethnicities were not exclusively stated, most investigations were conducted in countries with predominantly Caucasian populations, likely indicating a sampling bias within the included literature. Given that the most successful 100-m sprinters are historically black (66), the potential under-representation of this demographic in the included studies indicates the current review may not fully capture the inter-individual variability in mechanical adaptations within elite sprinters performing at the highest level. Furthermore, despite two studies reporting their cohorts as “Elite/International”, when classified using 100-m performance data and with McKay et al.’s participant classification framework, none of the population samples in this review were eligible for elite, international, or world-class status.

Risk-of-bias Assessment

The risk-of-bias assessments of the 11 included studies are exhibited in Fig. 3 using the Joanna Briggs Institute Critical Appraisal Checklist for Analytical Cross-sectional Studies for systematic reviews.

The overall risk-of-bias was high with five studies considered as ‘high’ (49–51, 57, 59), four studies were identified as ‘unclear’ (53, 55, 56, 58), and only two studies were appraised as ‘low’ risk-of-bias (48, 54). Inclusion criteria and participant details reported were flagged as ‘high’ in two studies (58, 59). Neither Kubo et al. (2017) nor Yamazaki et al. (2022) reported health status, exclusion criteria, or screening details, while participant training criteria remained ambiguous. Demographic details were reported well across all studies; however, none of the studies identified the time periods or the locations of data

collection, resulting in ‘unclear’ across all studies. Risk-of-bias regarding reliability was classified as ‘high’ in one study (56); however, this was the most common unreported feature, with 10/11 studies failing to conduct or report on ≤ 1 important reliability statistic. Strategies for dealing with confounding factors were absent in six studies (50, 51, 53, 55, 57, 59), which were subsequently considered to have ‘high’ risk-of-bias. While no other category received a ‘high’ rating, ‘detailed description of study subjects and setting ‘, ‘identification of confounding factors’, and ‘valid and reliable outcomes measures’ were deemed as having ‘unclear’ across eleven, eight (49–51, 53, 55–57, 59), and seven studies (49–51, 53, 54, 57, 59), respectively.

Measurement Protocols and Testing Conditions

Researchers examined at least one measurement site involving a single joint, muscle, or MTU, with three research groups additionally examining multiple sites, muscles, or MTU’s (50, 51, 57). The ankle extensors were examined in nine studies, with the most common site being the medial gastrocnemius (MG), measured at the myotendinous junction or muscle belly at the proximal, distal, or mid-muscle, depending on the mechanical variable of interest. The knee extensors were examined in four studies via the vastus lateralis (VL), while the hip joint was included in a single publication evaluating the biceps femoris long-head (BF-LH). Site measures of the VL and BF-LH were taken at the mid-thigh, 50% of the distance between the femoral greater trochanter and the lateral epicondyle.

Variations in testing conditions beyond joint position or measurement site were considered. Mechanical properties under varied isometric (i.e., static MTU length) or quasi-isometric conditions were examined in ten studies. These variations included: (a) contraction state: passive vs. active conditions; (b) contraction intent (i.e., “ramped” vs. “ballistic”); (c) contraction intensity (i.e., maximal voluntary contraction vs. ≥1 incremental or static submaximal intensities (20–100% MVC)); (d) contraction duration; and, (e) mode of force application (i.e., pushing isometric vs. applied stretch at ≥ 1 fixed angular velocity).

Musculotendinous mechanical properties were assessed with a wide variety of commercially available electromechanical (aka: isokinetic) dynamometers (48, 50, 54, 55, 57, 58), or using a custom-built strain gauge (49, 51, 53, 59), with different makes and unknown validity. In conjunction with dynamometry, brightness mode (B-mode) ultrasonography was used to track mechanical properties in eight studies, while shear-wave elastography (SWE) was utilised in three studies (55, 56, 58).

Correction factors for potential unwarranted joint rotation during isometric testing were accounted for within seven studies (48, 49, 51, 57–59, 67), with joint angular fidelity being established using electro-goniometers, integrated laser-guided potentiometers, and electromyography (EMG) (see Table 2 for detail).

Reliability and Consistency of Tools and Techniques

Reliability is an important factor in establishing the scientific utility and efficacy of a test within a population sample, as it demonstrates the test’s consistency and stability. Reliability has been quantified

by researchers using a range of methods; however, according to Hopkins (2000), there are three important measures that should be reported for a comprehensive understanding of reliability: 1) changes in the mean (i.e., systematic error between trials), 2) retest correlation (i.e., relative consistency), and 3) within-subject variation (i.e., absolute consistency) (68).

While there are no standardised values for accepting reliability using intra-class correlation coefficients (ICC) and coefficient of variation (CV) (69), researchers should aim to obtain 30 heterogeneous samples, include a minimum of 3 raters and perform enough trials (≥ 3) to make learning effects or other random or systematic changes negligible (68).

Systematic Error

The most common and problematic reliability measure across the included studies was test-retest reliability, reflecting the testing design used to measure consistency and systematic error (mean bias) across multi-session testing. Test-retest reliability over three or more testing sessions was reported in none of the 11 studies; however, one study performed a third session only on the physically active cohort (48). Test-retest reliability was not explicitly reported in seven studies, relying on preliminary and previously validated protocols on untrained or physically active males (49, 51, 53, 54, 56, 57, 59). Test-retest data were established over two separate occasions in six studies (familiarisation and testing), with intervals between tests ranging from 20 to 28 hours to ≥ 2 days (48, 49, 51, 53, 58, 59). In the remaining five studies (50, 54–57) only single-session repeatability metrics were presented, capturing within-day variation but limiting confidence that technological error (e.g., equipment noise or operator function) or biological variation (e.g., subject MVC changes between trials due to mental/physical state) associated with multi-session testing had been sufficiently accounted for (68).

Notably, none of the included studies showed test-retest reliability for SWE; however, excellent intra-session repeatability for both passive and active shear-wave speed (ICC ≥ 0.92–0.99, CV = 1.8–4.5%) in muscles spanning the ankle (58), knee (55), and hip (56) joints have been reported.

Relative and Absolute Consistency

Measures of relative consistency (e.g., ICC, r, or r^2) were reported in all 11 studies; however, only one study specified the ICC model type (48), making it challenging to compare ICCs and Pearson's r across studies. Without ICC form identification (highlighting the model and type), definition of the relationship (consistency vs. absolute agreement) or 95% confidence intervals, interpretation can be limited (68). Henceforth, in this review, ICC values can be interpreted as an indicator of relative reliability. Measures of absolute consistency were reported in nine studies (e.g., CV or repeatability coefficient (CR)), including CVs ranging from 1.2 to 14.4% and CR 0.07 to 0.15×10^{-2} mm·N^{-1} within all independent musculotendinous measures (48, 50, 51, 53–55, 57–59).

Overall, tendon stiffness demonstrated moderate-to-excellent relative reliability with values ranging from r = 0.89 to 0.91 (53, 59), and ICC = 0.64 to 0.91 (49, 54). CVs for tendon stiffness exhibited conventionally acceptable (< 10%) absolute consistency (5.6–9.57%). Tendon compliance exhibited similar good-to-

excellent values (ICC = 0.89–0.91 and r^2 = 0.92; CR of 0.07–0.15×10^{-2} mm and CV = 10.7%.) across two studies (50, 57). Tendon elongation ICC = 0.88 and r^2 = 0.92, CV = 4.6–10.57% (48, 57), maximal strain (ICC = 0.83, CV = 10.25%) (48), and angle-specific maximal strain (ICC = 0.83, CV = 10.25%)(48) were found to have good reliability.

Tendon hysteresis was reported to have good relative reliability (test-retest: r = 0.83–0.87, inter-rater: r = 0.83–0.94) yet poorer absolute consistency (test-retest: CV = 12.9–14.4%, inter-rater: CV = 11.1–12.6%) when measured using ramped or ballistic isometric contractions, respectively (53).

Active muscle stiffness showed good to excellent reliability across isometric intensities (r = 0.85–0.91 (59); ICC = ≥ 0.92 (53)), albeit with more questionable precision (CV = 10.4–13.5%) when assessed using stretch applied at angular velocities of 100–600°/s during submaximal isometric contractions (53).

Tendon elongation demonstrated excellent intra-session repeatability (r^2 = 0.92, CV = 4.6%) (57). Inter-rater reliability for tendon elongation (r^2 = 0.95, CV = 3.1%), tendon stiffness (r = 0.84–0.88, CV = 8.8–11.9%), and hysteresis (r = 0.83–0.87, CV = 11.1–12.6%) was reported in only two studies (53, 57). There was minimal evidence of intra-rater reliability, with a single study reporting excellent reliability for tendon elongation between two observers (r^2 = 0.98–0.99; CV = 1.2–2.0%) (57).

Table 1 provides a comprehensive summary of the included studies that examine measurement tools and the reliability of outcomes.

Table 1
Summary of reliability and methodological approaches used to assess musculotendinous mechanical stiffness

Author, Year and Aim	Methods	Reliability Protocols and Statical Outputs
Crotty et al. (2023) (48) Aim: *Compare neuromuscular plantar flexor function in sprinters and physically active controls.*	MG tendon force & elongation during ramped MVC isometric contractions via dynamometer & ultrasound. 10° DF ankle, full extension knee. 2000 Hz dynamometer. Electro-goniometer on lateral surface of lower leg during MVC. Assessments terminated & repeated if > 2° joint angle deviation. Tendon elongation = longitudinal displacement of MG myotendinous junction. Tendon stiffness = slope of the tendon force-elongation relationship. **Measurement Site(s)**: Tendon stiffness indirectly via displacement of distal MG at myotendinous junction.	Test-retest reliability over two occasions for sprinter group: familiarization and testing. Physically active group performed 3 sessions for test-retest reliability. Two-way random effects single ICC (2, 1), absolute agreement & CV%. **Tendon stiffness (N/mm)** Test-Retest: ICC = 0.76, CV = 9.57% **Tendon Elongation (mm)** Test-Retest: ICC = 0.88, CV = 10.57% **Maximal Strain (%)** Test-Retest: ICC = 0.83, CV = 10.25% **Angle Specific Maximal Strain (%) – 10° DF** Test-Retest: ICC = 0.92, CV = 8.02%
Epro et al. (2021) (49) Aim: *Investigate triceps surae musculotendinous biomechanical properties in young vs. master sprinters.*	MG force & elongation during 3-s ramped isometric contractions (0, 30, 50, 80 & 100% MVC) via custom strain gauge dynamometer & ultrasound. MG = 90° ankle joint, 90° knee joint. 1000Hz dynamometer. Inter-limb symmetry analyzed to detect non-uniformities between preferred and non-preferred leg. Integrated laser-guided potentiometers positioned the subjects and digitized resting tendon	Test-retest reliability over two days: familiarization and testing. Reliability was validated in a prior study conducted on middle-aged recreational runners (1). There is no mention of the ICC model type or CVs reported for measures outside of tendon stiffness.

Author, Year and Aim	Methods	Reliability Protocols and Statical Outputs
	length, correcting for ankle joint rotation during MVC. Tendon stiffness = change in force divided by the change in elongation from 30–80% of MVC. **Measurement Site(s)**: Tendon elongation via MG myotendinous junction.	**Tendon stiffness (N/mm)** Test Retest ICC = 0.64
Kubo et al. (2000) (50) Aim: *Investigate tendon elasticity in sprinters and its relation to sprint performance.*	MG & VL tendon-aponeurosis force & elongation during 5-s ramped isometric contractions (0, 30, 50, 80 & 100% MVC) via dynamometer & ultrasound. MG = 90° ankle joint, knee full extension. VL = hip joint 80°, knee joint 90°. 1000Hz dynamometer. Tendon compliance = elongation-force ratio (dL/dF) at 10% MVC increments, averaged ≥ 50% MVC. **Measurement Site(s)**: VL: mid-thigh (50% greater trochanter – lateral femoral epicondyle); MG: proximal shank (30% popliteal crease – lateral malleolus).	Reliability over two days: familiarization and testing. However, no test-retest reliability described in the study. **Tendon Compliance (mm/N)** Test Retest **VL** ICC = 0.89 CR = 0.07×10^{-2} $mm \cdot N^{-1}$ **MG** ICC = 0.91 CR = 0.15×10^{-2} $mm \cdot N^{-1}$
Kubo et al. (2011) (51) Aim: *Examine muscle and tendon properties in highly trained sprinters and their relationship to running performance.*	MG & VL tendon-aponeurosis force & elongation during 5-s ramped isometric contractions at MVC via dynamometer & ultrasound. MG = 90° ankle joint, knee full extension. VL = hip joint 80°, knee joint 90°. 1000Hz dynamometer. Electro-goniometer on lateral aspect of each joint, digitizing displacement during passive joint rotation from 110° to 70° in sonographic images. Tendon elongation = measured displacement – passive joint rotation, during MVC. Tendon stiffness = force-elongation slope above ≥ 50% MVC, during 5-s isometric contractions.	Test-retest reliability over two days: familiarization and testing. Conducted in prior studies on eight young males (2, 3). **VL** **Tendon stiffness (N/mm)** Test-Retest ICC = 0.89, CV = 6.3% **MG** **Tendon stiffness (N/mm)**

Author, Year and Aim	Methods	Reliability Protocols and Statical Outputs
	Measurement Site(s): VL: mid-thigh (50% greater trochanter – lateral femoral epicondyle); MG: proximal shank (30% popliteal crease – lateral malleolus).	Test-Retest ICC = 0.89, CV = 5.6%
Kubo et al. (2017) (59) Aim: *To investigate and compare muscle and tendon stiffness under active conditions.*	MG force & elongation via ultrasound & dynamometer under two conditions. Active muscle stiffness = applied DF stretch (~ 250°/s) from 100–80° (corrected at 92°) at five sub-maximal torque levels (10–90% MVC, 20% increments). Tendon stiffness = 5-s ramped isometric; 90° ankle joint, knee full extension. Electro-goniometer on lateral surface of lateral ankle during MVC, digitizing displacement during passive joint rotation from 90° to 100° in sonographic images. Active muscle stiffness = slope of the muscle force-fascicle length curve between 100° and 92°. Tendon stiffness = slope of the force – tendon elongation curve above ≥ 50% MVC, during 5-s ramped isometric contractions. **Measurement Site(s)**: Active muscle stiffness = MG fascicle length (30% lower leg); Tendon stiffness = MG fascicle-aponeurosis junction displacement.	Test-retest reliability over two days: familiarization and testing. Conducted in preliminary studies involving nine and eight young males, respectively (3, 4). **Active Muscle Stiffness (N/mm)** Test-Retest 10% MVC: *r* = 0.911, CV = 11.8% 30% MVC: *r* = 0.870, CV = 10.4% 50% MVC: *r* = 0.865, CV = 10.3% 70% MVC: *r* = 0.888, CV = 10.9% 90% MVC: *r* = 0.846, CV = 10.5% **Tendon stiffness (N/mm)** Test-Retest *r* = 0.89, CV = 5.6%
Kubo et al. (2020) (53) Aim: *To compare the mechanical properties of muscles and tendons at high strain rates between sprinters and untrained men.*	MG tendon-aponeurosis force & elongation during two conditions via ultrasound & dynamometer. Active muscle stiffness = slope of muscle force-fascicle length curve during the stretch phase at each angular velocity. Applied DF stretch from 100° – 80° at angular velocities of 100, 200, 300, 500, and 600°/s during isometric contraction at 50% MVC. Passive recordings (0% MVC) were subtracted from measured outcomes.100° ankle joint, knee full extension.	Tendon stiffness & hysteresis test-retest reliability over two days: familiarization and testing. Conducted in preliminary studies with 10 young males (5, 6). Active muscle stiffness was not explicitly reported in this study but was referenced as being confirmed in a separate work as “Kubo

Author, Year and Aim	Methods	Reliability Protocols and Statical Outputs
	Tendon stiffness = slope of force - tendon elongation relationship ≥ 50% MVC.5-s ramped, and ballistic isometric contractions. 90° ankle joint, knee full extension. Electro-goniometer on lateral ankle to monitor joint rotation. Tendon displacement correction by digitizing displacement during passive ankle rotation from 0° to 9° in sonographic images. Hysteresis = % energy lost, relative to the force-elongation loop and area beneath the stretch-loading phase. **Measurement Site(s)**: Active muscle stiffness = MG fascicle length (30% lower leg); Tendon stiffness = MG fascicle-aponeurosis junction displacement.	et al. under submission" (7). **Active Muscle Stiffness** Test-Retest CV = 100°/s: 10.4%, 200°/s: 13.5%, 300°/s: 11.2%, 500°/s: 12.9%, 600°/s:10.7% **Tendon Stiffness (N/mm)** Test-Retest Ramp Contractions: *r* = 0.91, CV = 9.5% Ballistic Contractions: *r* = 0.87, CV = 9% Inter-Rater Ramp Contractions: *r* = 0.88, CV = 11.9% Ballistic Contractions: *r* = 0.84, CV = 8.8% **Hysteresis (%)** Test-Retest Ramp Contractions: *r* = 0.87, CV = 14.4% Ballistic Contractions: *r* = 0.83, CV = 12.9% Inter-Rater Ramp Contractions: *r* = 0.94, CV = 11.1% Ballistic Contractions: *r* = 0.83, CV = 12.6%
Li et al. (2025) (54) Aim: *To identify and explore neural and muscular predictors of rate of force development and 30 m sprint time in male collegiate sprinters.*	MG tendon force & elongation during 5-s ramped isometric contractions via ultrasound & dynamometer. Tendon stiffness = ratio of peak torque to tendon elongation.	Reliability not explicitly stated study. The method used to evaluate tendon force was established and validated in a prior study, and reported below (8).

Author, Year and Aim	Methods	Reliability Protocols and Statical Outputs
	Measurement Site(s): Tendon stiffness indirectly via displacement of MG fascicle-aponeurosis junction	**MG** **Tendon Stiffness (N/mm)** ICC = 0.91 CR = 0.15 × 10^{-2} $mm \cdot N^{-1}$
Miyamoto et al. (2019) (55) Aim: *Compare muscle stiffness characteristics in sprinters and long-distance runners.*	VL passive and active shear-wave speed (m/s) during 7-8-s isometric contractions at 50% MVC via SWE & dynamometer. 80° hip flexion, 90°, knee flexion. Muscle stiffness = inferred indirectly from mean shear-wave speed, calculated over the largest ROI during 50% MVC. **Measurement Site(s)**: VL at 50% thigh length.	Intra-session reliability over two trials (three recordings) within a single session under passive and active conditions. **Passive Shear-wave Speed (m/s)** Intra-session ICC = 0.987 CV = 1.8 ± 1.9% **Active Shear-wave Speed (m/s)** Intra-session ICC = 0.924 CV = 4.5 ± 3.3%
Miyamoto et al. (2024) (56) Aim: *Identify changes in passive muscle stiffness of the biceps femoris long head (BF-LH) with training cessation vs. continuation.*	BF-LH passive shear-wave speed (m/s) via ultrasound SWE. Pre-intervention results are reported. 70° hip flexion, knee full extension. **Measurement Site(s)**: BF-LH, 50% greater trochanter – lateral femoral epicondyle.	Intra-session reliability previously confirmed during a single session in two young males (9). **Passive Shear-wave Speed (m/s)** Intra-session BF-LH ICC = 0.99 ± 0.01
Stafilidis and Arampatzis (2007) (57) Aim: *Determine relationship between sprint performance and mechanical/morphological*	MG & VL tendon-aponeurosis force, elongation & strain during 2-3-s MVC via ultrasound & dynamometer. MG = 90° ankle joint, knee full extension. VL = 115° knee joint, 140° hip joint angle.	Intra-day reliability over two days; however, test-retest reliability was not reported. Inter-day, intra-rater and inter-rater reliability

Author, Year and Aim	Methods	Reliability Protocols and Statical Outputs
musculotendinous properties in sprinters.	Elongation = measured displacement of the tendon-aponeurosis cross-point, corrected for passive joint rotation as confirmed by the absence of synchronized EMG activity. **Measurement Site(s)**: Analyzed aponeurotic cross-point at 50% the MG & VL muscle belly length.	was validated in prior studies using five and eight healthy males, respectively (10, 11). **Tendon Compliance (mm/N)** Intra-day r^2 = 0.92, CV = 10.7% **Tendon Elongation (mm)** Intra-session r^2 = 0.92, CV = 4.6% Intra-rater Observer 1: r^2 = 0.98, CV = 2.0%; Observer 2: r^2 = 0.99, CV = 1.2% Inter-rater r^2 = 0.95, CV = 3.1%
Yamazaki et al. (2022) (58) Aim: *Investigate whether passive and active muscle stiffness of the medial gastrocnemius is related to sprint performance.*	MG passive & active muscle stiffness under two conditions via SWE ultrasound & dynamometer. 1) 5-s isometric contractions at 0% (passive), 20%, 50% and 80% MVC, and 2) applied DF stretch from − 15° – 20° at a fixed angular velocity of 500°/s. Prone lying, knees full extension. Range of motion and angular velocity was recorded at 60-ms after the onset of the rapid stretch. **Measurement Site(s)**: 30% of the lower leg length, from the popliteal crease to the lateral malleolus.	Intra-day reliability over two trials; three measures per trial. **Shear-wave Speed (m/s)** Intra-day ICC = ≥ 0.924 CV = < 4.5%

Abbreviations (alphabetized): BF-LH = Biceps femoris long head; CR = Coefficient of repeatability; CV = Coefficient of variation; DF = dorsi-flexion; dL/dF = Change in length relative to change in force (tendon compliance calculation); EMG = Electromyography; Hz = Hertz (sampling frequency); ICC = Intraclass correlation coefficient; MG = Medial gastrocnemius; mm = Millimetres; mm/N = Millimetres per Newton (tendon compliance); m/s = Metres per second; MVC = Maximal voluntary contraction; N/mm = Newtons per millimetre (tendon stiffness); *r* = Pearson's correlation coefficient; r^2 = Coefficient of determination; ROI = Region of interest; s = seconds; SWE = Shear-wave elastography;

Author, Year and Aim	Methods	Reliability Protocols and Statical Outputs
VL = Vastus lateralis; % = Percentage; ° = angular degrees; × 10^{-2} = scientific scaling in compliance measurement. Numbers are reported as mean ± standard deviation.		

Musculotendinous Overview

The mechanical properties of the MTU are central to this review and are the primary focus of the following discussion. A summary of the 11 studies examining various musculotendinous mechanical characteristics, including mean and standard deviation, and significance level, is presented in Table 2.

Table 2
Summary of musculotendinous mechanical stiffness characteristics in sprinters

Author, Year and Aim	Subjects and Training Status	Outcomes
Crotty et al. (2023) (48) Aim: *Compare neuromuscular plantar flexor function in sprinters and physically active controls.*	**SPR**: M (n = 7), F (n = 7); 60/100-m: n = 7, 100-m H: n = 1, 200-m: n = 2, 400-m, n = 4), 22 ± 2 y; 176.8 ± 10.3 cm; 74.0 ± 19.2 kg; Highly trained/national level (n = 12), elite/international level (n = 2); Training experience: 8.7 ± 2.7 y. **Males – Estimated by IAAF point equivalent** 60-m OR = 6.93 ± 0.15 s 100-m OR = 10.82 ± 0.31 s 200-m OR = 21.75 ± 0.52 s 400-m OR = 48.70 ± 1.33 s **Females – Estimated by IAAF point equivalent** 60-m OR = 7.82 ± 0.18 s 100-m OR = 12.19 ± 0.49 s 200-m OR = 24.23 ± 0.58 s 400-m OR = 54.41 ± 1.46 s **CON**: M (n = 7), F (n = 7), 20.7 ± 1.8 y; 173.1 ± 4.2 cm; 70.2 ± 7.7 kg; Healthy, Trained Sprint performance values (mean ± standard deviation) were attained using the IAAF 2025 Revised Edition Scoring Tables for Athletics (46). The average classification score for the full cohort was 952.8 ± 109.3 points for Seasonal Best times.	**Variable(s)**: Tendon Stiffness (N/mm); Maximal Tendon Elongation (mm); Maximal Strain (%) **MG** **Tendon Stiffness** SPR: 221 ± 46 N/mm; CON: 196 ± 47 N/mm **Maximal Tendon Elongation** SPR: 16 ± 4 mm; CON: 18 ± 4 mm **Maximal Strain** SPR: 8.1 ± 2.6%; CON: 9.4 ± 3.0% **Performance**: No data on performance variables were obtained.

Author, Year and Aim	Subjects and Training Status	Outcomes
Epro et al. (2021) (49) Aim: *Investigate triceps surae musculotendinous biomechanical properties in young vs. master sprinters.*	**SPR (Young)**: M (n = 10), 22 ± 3 y, 187 ± 6 cm, 82 ± 5 kg; National or International level; 100-m OR = 10.80 ± 0.33 s **SPR (Master)**:M (n = 10), 65 ± 8 y, 177 ± 5 cm, 77 ± 8 kg; National or International level; 100-m OR = 13.78 ± 0.85 s **CON**: M (n = 11), 23 ± 3 y, 184 ± 6 cm, 81 ± 5 kg; Healthy, recreationally active; 100-m OR = 13.1 ± 0.7 s	**Variable(s)**: Tendon Stiffness (N/mm); Maximal Strain (%) **MG** ***Tendon Stiffness** SPR (Young): 804.5 ± 170.6 N/mm ‡; SPR (Master): 582.8 ± 73.4 N/mm ‡; CON: 630.3 ± 134.6 ‡ **Inter-limb Symmetry (preferred leg)** SPR (Young): -0.6 ± 15.4%; SPR (Master): 4.9 ± 19.4%; CON: 3.4 ± 16.0% **Maximal Strain** SPR (Young): 4.3 ± 0.9%; SPR (Master): 3.7 ± 0.8%; CON: 4.4 ± 0.8% **Inter-limb Symmetry (preferred leg)** SPR (Young): 2.4 ± 12.1%; SPR (Master): − 2.6 ± 16.0%; CON: − 5.8 ± 17.5 **Performance**: Performance data were not statistically analyzed.
Kubo et al. (2000) (50) Aim: *Investigate tendon elasticity in sprinters and its relation to sprint performance.*	**SPR**: M (n = 10), 21.4 ± 1.8 y, 171.2 ± 5.6 cm, 68.6 + 7.2 kg; Thigh Length: 39.6 ± 1.4 cm, Lower Leg Length: 39.3 ± 1.2 cm; Regional or Intercollegiate level; Training experience: 6.7 ± 2.2 y; 100-m OR = 11.01 ± 0.17 s **CON**: M (n = 14), 24.6 ± 2.2 y, 170.8 ± 6.4 cm, 72.2 ± 7.9 kg; Thigh Length: 38.6 ± 1.3 cm, Lower Leg Length: 38.5 ± 1.6 cm; Healthy, Untrained	**Variable(s)**: Tendon Compliance (mm/N); Maximal Tendon Elongation (mm) **VL** ***Maximal Tendon Elongation (mm)** SPR: 41.3 ± 2.6 mm; CON: 33.3 ± 4.2 mm **Tendon Compliance (mm/N)** SPR: 1.91 ± 0.38 × 10^{-2} mm/N; CON: 1.83 ± 0.31 × 10^{-2} mm/N MVC *10% - SPR: 5.98 mm/N ‡: CON: 4.12 mm/N ‡

Author, Year and Aim	Subjects and Training Status	Outcomes
		*20% - SPR: 7.94 mm/N ‡: CON: 5.61 mm/N ‡ **MG** **Maximal Tendon Elongation (mm)** SPR: 23.7 ± 3.0 mm; CON: 24.7 ± 4.8 mm **Tendon Compliance (mm/N)** SPR: 4.53 ± 0.83 × 10^{-2} mm/N; CON: 4.12 ± 1.35 × 10^{-2} mm/N **Performance**: 100-m sprint time was negatively correlated with *VL compliance (*r* = -0.757); No MG-performance relationship found.
Kubo et al. (2011) (51) Aim: *Examine muscle and tendon properties in highly trained sprinters and their relationship to running performance.*	**SPR**: M (n = 15), 20.8 ± 1.0 y; 174.5 ± 4.3 cm; 67.6 ± 5.3 kg; Thigh Length: 39.8 ± 1.2 cm, Lower Leg Length: 39.8 ± 1.5 cm; Well-trained, Regional or Collegiate level; Training experience: 6.2 ± 2.8 y; 100-m OR = 10.79 ± 0.13 s **CON**: M (n = 15), 20.7 ± 1.8 y; 173.1 ± 4.2 cm; 70.2 ± 7.7 kg, Thigh Length: 39.7 ± 1.2 cm, Lower Leg Length: 39.8 ± 1.4 cm; Healthy, Untrained	**Variable(s)**: Tendon Stiffness (N/mm); Maximal Tendon Elongation (mm) **VL** ****Maximal Tendon Elongation** SPR: 29.3 ± 4.7 mm; CON: 22.7 ± 3.8 mm ****Tendon Stiffness** SPR: 70.5 ± 11.7 N/mm; CON: 90.0 ± 21.0 N/mm **MG** **Maximal Tendon Elongation** SPR: 18.1 ± 2.9 mm; CON: 16.0 ± 3.6 mm **Tendon Stiffness** SPR: 44.0 ± 12.4 N/mm; CON: 39.7 ± 15.9 N/mm **Performance**: No significant correlations were found between 100-m OR and maximal tendon stiffness (*r* = -0.194) or maximal tendon elongation (*r* = -0.249) of the knee extensors. No MG-performance relationship.

Author, Year and Aim	Subjects and Training Status	Outcomes
Kubo et al. (2017) (59) Aim: *To investigate and compare muscle and tendon stiffness under active conditions.*	**SPR**: M (n = 14), 20.7 ± 1.1 y; 173.2 ± 5.5 cm; 65.4 ± 4.3 kg, Lower Leg Length: 39.8 ± 1.7 cm; Well-trained, Regional or Collegiate level; 100-m OR = 11.37 ± 0.41 s **CON**: M (n = 24), 22.2 ± 3.6 y; 172.3 ± 5.5 cm; 66.4 ± 8.1 kg, Lower Leg Length: 39.1 ± 1.8 cm; Healthy, Untrained	**Variable(s)**: Active Muscle Stiffness (N/mm); Maximal Tendon Elongation (mm); Tendon Stiffness (N/mm) **MG** **Active Muscle Stiffness (N/mm)** SPR: 92.4 N/mm ‡; CON: 90.4 N/mm ‡ **Maximal Tendon Elongation (mm)** SPR: 18.6 ± 4.7 mm; CON: 17.1 ± 3.5 mm **Tendon Stiffness (N/mm)** SPR: 25.8 ± 8.0 N/mm; CON: 27.8 ± 11.1 N/mm **Performance**: No data on performance variables were obtained.
Kubo et al. (2020) (53) Aim: *To compare the mechanical properties of muscles and tendons at high strain rates between sprinters and untrained men.*	**SPR**: M (n = 15), 20.4 ± 0.9 y, 172.0 ± 4.6 cm, 67.2 ± 5.8 kg; Trained; Training experience: 7.2 ± 1.8 y; 100-m OR = 11.17 ± 0.24 s **CON**: M (n = 18), 22.2 ± 1.8 y, 172.4 ± 4.6 cm, 68.2 ± 11.8 kg; Healthy, Untrained	**Variable(s)**: Active Muscle Stiffness (N/mm); Tendon Stiffness (N/mm); Maximal Tendon Elongation (mm); Hysteresis (%) **MG** **Active Muscle Stiffness (N/mm)** *500 deg°/s – SPR: 71.7 N/mm ‡; CON: 54.68 N/mm (*d* = 0.677) ‡ *600 deg°/s – SPR: 65.72 N/mm ‡; CON: 47.61 N/mm (*d* = 0.743) ‡ **Tendon Stiffness (N/mm)** Ramp: SPR: 24.8 ± 4.6 N/mm; CON: 24.8 ± 8.5 N/mm Ballistic: SPR: 22.7 ± 4.8 N/mm; CON: 24.1 ± 4.6 N/mm **Maximal Tendon Elongation (mm)** Ramp: SPR: 18.7 ± 3.1 mm; CON: 17.9 ± 2.6 mm

Author, Year and Aim	Subjects and Training Status	Outcomes
		Ballistic: SPR: 15.1 ± 2.9 mm; CON: 13.6 ± 2.3 mm **Hysteresis (%)** Ramp: SPR: 15.7 ± 8.3%; CON: 20.6 ± 11.6% Ballistic: SPR: 34.9 ± 13.3%; CON: 31.7 ± 11.1% **Performance**: No data on performance variables were obtained.
Li et al. (2025) (54) Aim: *To identify and explore neural and muscular predictors of rate of force development and 30 m sprint time in male collegiate sprinters.*	**SPR**: M (n = 15), 19.73 ± 1.39 y, 181.40 ± 4.32 cm, 70.98 ± 4.21 kg, Lean Body Mass: 36.05 ± 1.13 kg; Training experience: >5 y; Collegiate and national level; 100-m OR = < 10.93 s	**Variable(s)**: Tendon Stiffness (Nm/cm) Tendon Stiffness 55.05 ± 13.28 Nm/cm **Performance**: 30m sprint time was positively correlated with *MG stiffness (*r* = 0.50, 95%CI: 0.01–0.81).
Miyamoto et al. (2019) (55) Aim: *Compare muscle stiffness characteristics in sprinters and long-distance runners.*	**SPR**: M (n = 22), 19.7 ± 1.3 y, 172.8 ± 6.5 cm, 66.7 ± 6.3 kg; Training experience: >3 y; Trained 100-m OR = 11.07 ± 0.29 s **LDR**: M (n = 22), 20.3 ± 1.1 y, 167.7 ± 4.8 cm, 56.5 ± 4.5 kg; Trained 5000-m OR = 893.9 ± 24.1 s **CON**: M (n = 19), 20.2 ± 1.8 y, 172.8 ± 5.3 cm, 63.5 ± 5.4 kg; Healthy, Untrained	**Variable(s)**: Passive and active muscle stiffness via shear-wave speed (m/s) **VL** **Passive muscle stiffness (m/s)** *SPR: 2.69 ± 0.30 m/s; LDR: 2.91 ± 0.21 m/s; CON: 2.93 ± 0.20 m/s The SPR group exhibited lower *VL passive stiffness than LDR group (*d* = 0.87). **Active muscle stiffness (m/s)** SPR: 10.52 ± 1.15 m/s ‡; LDR: 11.48 ± 1.04 m/s ‡ LDR group exhibited higher active VL stiffness than both the *SPR (*d* = 0.56) and **CON (*d* = 1.28) groups. **Performance**: 100-m sprint time was negatively correlated with higher *passive muscle stiffness (*r* = -0.470) and positively

Author, Year and Aim	Subjects and Training Status	Outcomes
		correlated with *active muscle stiffness (*r* = 0.468).
Miyamoto et al. (2024) (56) Aim: *Identify changes in passive muscle stiffness of the biceps femoris long head (BF-LH) with training cessation vs. continuation.*	**SPR**: M (n = 28: Continuation Group (n = 14), Cessation Group (n = 14); 100-m: n = 16, 200-m: n = 4, 400-m, n = 8), 20.0 ± 1.2 y, 173.7 ± 5.6 cm, 65.6 ± 6.6 kg); Training experience: >3 y **Performance IAAF point equivalents** 100-m OR = 10.70 ± 0.17s 200-m OR = 21.51 ± 0.14 s 400-m OR = 48.05 ± 0.38s. Sprint performance values (mean ± standard deviation) were attained using the IAAF 2025 Revised Edition Scoring Tables for Athletics (46). The average classification score for the full cohort was 972 ± 99.1 points for Seasonal Best times.	**Variable(s)**: Passive muscle stiffness via shear-wave speed (m/s) BF-LH **Passive muscle stiffness (m/s)** Continuation Group: 4.90 ± 0.85 m/s Cessation Group: 4.75 ± 0.77 m/s
Stafilidis and Arampatzis (2007) (57) Aim: *Determine relationship between sprint performance and mechanical/morphological musculotendinous properties in sprinters.*	**SPR (FAST)**: M (n = 17), 21.2 ± 3.6 y, 186 ± 6 cm, 79.9 ± 6.5 kg; Training experience: >5 y; Trained; 100-m OR = 11.04 ± 0.27 s **SPR (SLOW)**: M (n = 11), 19.5 ± 2.5 y, 183 ± 6 cm, 75.8 ± 5.8 kg; Trained; 100-m OR = 11.64 ± 0.23 s	**Variable(s)**: Tendon Elongation (mm); Strain (%) **VL** ***Maximal Tendon Elongation (mm)** SPR (FAST; n = 15): 32.9 ± 7.0mm; SPR (SLOW; n = 10): 26.9 ± 5.7mm SPR (FAST) exhibited greater *elongation for a given force across all force levels. ***Strain (%)** SPR (FAST; n = 15): 9.0 ± 1.5%; SPR (SLOW; n = 10): 7.7 ± 1.6% **MG** **Maximal Tendon Elongation (mm)**

Author, Year and Aim	Subjects and Training Status	Outcomes
		SPR (FAST; n = 17): 19.4 ± 4.7mm; SPR (SLOW; n = 11): 18.5 ± 2.5mm **Strain (%)** SPR (FAST; n = 17): 6.2 ± 1.5%; SPR (SLOW; n = 11): 6.1 ± 1.0% **Performance**: 100-m sprint time negatively correlated with **maximal elongation of the VL (r = -0.567; r^2 = 0.32) across both groups.
Yamazaki et al. (2022) (58) Aim: *Investigate whether passive and active muscle stiffness of the medial gastrocnemius is related to sprint performance.*	**SPR**: M (n = 18), 20 ± 1 y, 176 ± 5 cm, 68.2 ± 4.7 kg; Trained; Training experience: >3 y; 100-m OR = 10.25–11.38 s (10.88 ± 0.33 s)	**Variable(s)**: Passive and active muscle stiffness via Shear-wave speed (m/s) **MG** **Passive muscle stiffness (m/s)** 0% MVC: 2.71 ± 0.13 m/s ‡ **Active muscle stiffness (m/s)** 20% MVC 6.38 ± 0.72 m/s ‡ 50% MVC 8.91 ± 0.97 m/s ‡ 80% MVC 11.56 ± 1.31 m/s ‡ **Performance**: 100-m sprint time was significantly negatively correlated with shear-wave speed in both passive and active conditions, with the strongest relationship observed at **80% MVC (r = 0.636). MG shear wave speed at *50% and *80% MVC showed a positive correlation with ankle joint stiffness at the corresponding torque level, which in turn showed a negative correlation with 100-m race time (*0% MVC: r = − 0.583; *80% MVC: r = -0.526).

Author, Year and Aim	Subjects and Training Status	Outcomes
Abbreviations (alphabetized): BF-LH = Biceps femoris long head; CI = Confidence interval; cm = centimetre; CON = Control group; *d* = Cohen's *d* (effect size); F = Female; H = Hurdles (100-m H); IAAF = International Association of Athletics Federations; kg = kilogram; LDR = Long-distance runner; M = Male; m/s = metres per second; MG = Medial gastrocnemius; mm = Millimetres; mm/N = Millimetres per Newton (tendon compliance); MVC = Maximal voluntary contraction; N/mm = Newtons per millimetre (tendon stiffness); Nm/cm = Newton-metres per centimetre (tendon stiffness according to Li et al., 2025); n = number; OR = Official record; *r* = Pearson's correlation coefficient; r^2 = Coefficient of determination; s = seconds; SPR = Sprinter group; VL = Vastus lateralis; y = years old; % = Percentage; ° = angular degrees; × 10^{-2} = scientific scaling in compliance measurement. Numbers are reported as mean ± standard deviation. ‡ = Data were extracted from figures using WebPlotDigitizer (v5.2); * Denotes $p < 0.05$; ** Denotes $p < 0.01$; *** Denotes $p < 0.001$.		

The mechanical stiffness (or compliance) of tendons was reported in seven studies. The Achilles tendon (AT), via the MG, was the most frequently examined, appearing in all seven studies, whereas VL was examined in two studies. No publications investigated the mechanical tendon properties of the hip extensors.

Active muscle stiffness was quantified in four studies, two of which measured stiffness using SWE under various submaximal isometric conditions (55, 58), and two used multiple testing modes centred around applied stretch (i.e., dorsi-flexion stretch from 100° to 80° at five submaximal torque levels (10–90% MVC in 20% increments)) and 5-s ramped MVC (59, 67). Passive muscle stiffness was measured in three studies, all using SWE (55, 56, 58).

Tendon elongation was reported in six studies (48, 50, 51, 53, 57, 59) and maximal (48, 49, 57) and angle-specific tendon strain (48) was described in four studies. Tendon hysteresis, measured during ballistic and ramped isometric contractions was reported in one study (53).

Tendon Mechanical Properties (Stiffness/Compliance, Elongation, Strain, Hysteresis)

In the context of tendon biomechanics, stiffness describes the relationship between changes in tendon length (ΔL) relative to the applied force (Δ Ft), typically expressed as N/mm (stiffness) or, inversely, mm/N (compliance) (70). A greater stiffness value indicates that more force is required per unit area to cause deformation, reflecting a tendon's resistance to relative (strain) and absolute elongation. A stiffer tendon, due to its decreased extensibility, reduced electromechanical delay (71), and greater rate of force development in both isometric and dynamic muscle actions (72), potentiates rapid force transmission for sprint performance.

Achilles Tendon Mechanical Properties in Sprinters

Across the literature reviewed, AT stiffness was not different ($p > 0.05$) between sprinters and untrained controls in six of seven studies, with values ranging widely from 22.7 to 804.5 N/mm (49, 53). Sprinters'

AT mechanical properties, including maximal strain (4.3–8.1%), elongation (16–23.7 mm), and hysteresis (15.7–34.9%) were comparable to that of untrained participants, endurance-trained athletes, and sprinters of differing performance levels (48–50, 53).

In contrast to prior observations, Epro et al. (49) reported significantly higher AT stiffness in young sprinters (804.5 ± 170.6 N/mm) compared to master's sprinters (582.8 ± 73.4 N/mm), and untrained controls (630.3 ± 134.6 N/mm). Previous researchers have supported these findings by reporting a higher normalised AT stiffness in sprinters compared to endurance-trained and untrained controls (37.2 vs. 26.9 vs. 21.9 kN/strain) (73). Notably, a significant portion of the observed variance in tendon stiffness was attributed to muscle strength (r^2 = 0.67). Given that higher absolute and relative loads (i.e., % maximal voluntary contraction (MVC)) impose greater mechanical demands on tendinous structures (70), the increased stiffness reported by Epro et al. (49) likely reflects superior muscle strength, rather than isolated and intrinsic mechanical tendon adaptation (as discussed later under *Isokinetic Dynamometry*). This aligns with prior work, demonstrating strong associations between muscle strength and tendon stiffness (73–75). The variability across findings likely reflects the context-dependant nature of tendon mechanics and broader contributing factors. For instance, variations in tendon geometry, increased tendon length and reduced cross-sectional area are known to reduce the effective stiffness of a tendon (36).

Tendon viscoelastic behaviour (force-relaxation, creep, and hysteresis) also has important implications for modulating the mechanical response of tendons via strain rate (70, 76, 77). Tendons are more prone to deformation at low strain rates and more resistant at high strain rates, becoming stiffer and more effective at transmitting rapid forces (as seen in sprinting). Correspondingly, Kubo et al. (2020) systematically altered the cyclical strain-magnitude on the AT using ramped (low strain-rate) vs. ballistic (high-strain rate) isometric contractions. Contrary to the expected rate-dependant behaviour, sprinters were found to have lower tendon stiffness (ramped: 24.8 ± 4.6 N/mm; ballistic: 22.7 ± 4.8 N/mm) and elongation (ramped: 18.7 ± 3.1 mm; ballistic: 15.1 ± 2.9 mm) under high-strain conditions. A fundamental caveat, however, is that without sufficient mechanical loading, and thus, tendon stress, (force to the tendon normalised to cross-sectional area), the magnitude of induced strain (optimised at 4.5–6.5%) (70), which was unreported by the authors, might have been inadequate to notably alter mechanical adaptation; an important factor for increasing tendon stiffness (76).

Tendon hysteresis, describing the percentage of ESE lost as heat due to internal damping during SSC actions (78), was not markedly different (p > 0.05) in the AT of sprint athletes compared to untrained men during either ramped (15.7 ± 8.3% vs. 20.6 ± 11.6%) or ballistic (34.9 ± 13.3% vs. 31.7 ± 11.1%) isometric conditions (53). Theoretically, lower tendon hysteresis values (5–10%) are desirable for sprinting, particularly within the AT, to allow a larger portion of the stored ESE to be reused during propulsion (78). Evidence on training-induced changes in tendon hysteresis in sprint athletes or sprint-related activities (i.e., plyometric training) remains limited and somewhat conflicting. For example, Kubo et al. (2017) reported no meaningful change in tendon hysteresis (-2.0–0.6%) following 12-weeks of plyometric or isometric training in untrained participants (52). Whereas Fouré et al. (2010) found the

effects of 14-weeks of plyometric training to significantly decrease hysteresis in the AT (-35%; $p < 0.05$) of amateur athletes participating in regular sport practices (79). Intriguingly, Weisinger et al. (2017) observed significantly lower AT hysteresis values in ski jumpers (12.0 ± 5.6%) and endurance runners (11.8 ± 3.1%) compared to controls (17.3 ± 5.1%; $p = 0.017$), indicating a better energy conservation capacity in athletes whose tendons are regularly used in a spring-like fashion (80). The lack of consensus across these studies may be related to the lower strain rate and mechanical loading demands during isometric contractions relative to sprinting or sprint-like activities.

No significant relationship between AT stiffness and 100-m sprint performance was reported. However, a moderate positive correlation ($r = 0.50$, $p < 0.05$) was found between AT stiffness and 30-m sprint time, inferring that a more compliant tendon was superior for 30-m sprint performance, whereas greater AT stiffness, associated with high muscle forces, may be superior for reaching and maintaining maximal velocity.

Quadriceps Tendon Mechanical Properties in Sprinters

In contrast to the AT, faster sprinters (mean 100-m time of 10.58–11.04-s) displayed greater VL tendon compliance (1.42–1.91 x 10^{-2} mm/N) (50), elongation (29.3–41.3 mm) (50, 51, 57), and strain (9.0%) (57) compared to both slower sprinters (57), and untrained men (50, 51). Interestingly, Kubo et al. (50) observed significant differences only at low contraction intensities (10–20% MVC); however, this induced a considerably greater maximal elongation (41.3 ± 2.6 mm) and relative elongation at all force levels at and above 50% MVC. Greater compliance of the VL tendon at low force levels is likely attributed to toe-region mechanics of the stress-strain curve depicted in tendon research, specifically the crimping of collagen fibres, where compliance is highest (81). Since the energy storage capacity of the tendon is not strictly related to the straightening out of the crimp but instead to the elasticity of the straightened taut collagen fibres (82), the observed compliance likely reflects the potential elastic capacity of the tendon, though this may comprise only one component of the overall mechanism influencing sprint performance (83). For instance, Danielsen and Andreassen (1988) described how the cross-link pattern, structure, and/or packing of the collagen fibres can influence the viscoelastic behaviour and intrinsic mechanical properties of tendons (84), signifying important structural determinants of tendon mechanics.

Another important finding from the earlier work of both Kubo et al. (50) and Stafilidis and Arampatzis (56) was the significant negative correlation between 100-m sprint time and both tendon compliance ($r = -0.76$) and maximal elongation ($r = -0.57$; $r^2 = 0.32$) (57). However, conflicting results were later reported by Kubo (51) who found no significant association between 100-m time and both maximal tendon compliance (stiffness) ($r = -0.19$) or maximal tendon elongation ($r = -0.25$). These inconsistent results could be explained by the wide range of 100-m race times indicative of different athletic ability; therefore, further investigation is warranted.

Neuromuscular Mechanical Properties: Active and Passive Muscle Stiffness

The total stiffness of a muscle can be classified into two components: the mechanical component, combining passive and active stiffness, and the neural component, involving the reflex action that produces involuntary activation of the muscle (85). In the context of neuromuscular actions involving the SSC, in activities such as sprinting, the regulation of muscle stiffness is primarily regulated by two mechanisms: 1) central pre-activation of muscle fibres, and 2) short-latency stretch-reflex activation (86).

Central pre-activation refers to a feedforward process involving the pre-programmed recruitment of motor units, initiated 50–100-ms before touchdown during sprinting. This anticipatory activation increases initial levels of muscle stiffness, occurring in leg muscles that are involved in generating propulsive force (i.e., vastus lateralis, biceps femoris and gastrocnemius) and in particular the biarticulate muscles (i.e., biceps femoris, rectus femoris and gastrocnemius) throughout the entire running cycle (87–89). This pre-contact activity potentiates the functional role of stretch reflexes and appears to be a preparatory requirement of the musculotendinous system to withstand the high-impact demands at the onset of ground contact (87).

The short-latency stretch-reflex, reflected in mean electrical activity occurring within the 30–60-ms after landing (86), is a feedback mechanism, mediated by muscle spindle Ia afferents, detecting rapid eccentric muscle stretch and eliciting additional α-motoneuron activation, permitting further increases in muscle stiffness during the initial stages of the SSC (87). This reflex response simultaneously modulates and heightens programmed muscle activity to facilitate effective SSC actions (89).

Together, these mechanisms have important implications for sprint performance, including enhancing force production during the braking/propulsive phases, supporting sudden increases in running velocity, joint stability during the stance phase, and providing adequate compensation for unexpected perturbations or surface irregularities (89).

Active Muscle Stiffness

In this review, active muscle stiffness (i.e., muscle stiffness measured during a contraction) was assessed in four studies. The active stiffness of the plantar flexors (MG) was examined in three studies (53, 58, 59), while the knee extensors (VL) were examined in a single study (55). Given the limited number of studies and the methodological heterogeneity for assessing active stiffness, findings are reported and discussed by measurement approach.

Isokinetic Dynamometry

Using real-time ultrasound and an isokinetic dynamometer, Kubo et al. (2017) examined the active short-range stiffness of the MG in sprinters. Short-range stiffness, a mechanical sub-factor of classic muscle stiffness modelling, is a phenomenon that occurs when bound cross-bridges in its sarcomere are placed under sudden stretch (before active muscle lengthening), causing them to generate larger yet transient levels of force compared to steady state muscle lengthening (as described by the force-length

relationship) (90). The contribution of short-range stiffness relates to damping initial movement perturbations, limiting angular excursion and velocities of MTUs and joints (91).

With short-range stiffness in mind, Kubo and colleagues applied a passive dorsi-flexion stretch to the ankle joint at five submaximal torque levels (10–90% MVC in 20% increments) with the applied stretch reaching an angular velocity of approximately 250°/s. The active stiffness reported in this study was considered to represent the intrinsic muscular component, as the values excluded the initial 60-ms after the onset of stretch, as measured by EMG. However, no statistical difference ($p > 0.05$) was found with sprinters exhibiting comparable active short-range stiffness values to untrained men (92.4 N/mm vs. 90.4 N/mm). Interestingly, the relationship between active short-range stiffness and relative and absolute force production was highly significant ($p < 0.001$) and was independent of the populations studied (59). These findings align with our current understanding of the force-velocity behaviours of muscle described by Huxley's model (1957) of cyclic interaction between actin and myosin filaments. With increasing central neural drive, a greater number of cross-bridges form between actin and myosin protein filaments, generating higher intrinsic muscle stiffness (92). The determination of cross-bridge stiffness scales near linearly with the number of attached myosin heads; therefore, increases in neuromuscular activation enhance the mechanical stiffness of the muscle by increasing the number of bound cross-bridges. In sprinting, this likely acts as a functional strategy both before and during ground contact. Increased pre-activation leads to muscle stiffness, slowing the mechanical response, limiting excessive strain, allowing time for the central nervous system to react and stabilise joints during SSC activities. Furthermore, increases in mechanical load would also generate higher muscle activation and, subsequently, additional cross-bridge formation, thereby increasing active stiffness. Thus, active muscle stiffness is proportional to both the load/force generated and the amount of EMG activity of the muscle. This is particularly relevant for sprinting, where faster running speeds elicit greater force demands on the active muscles coupled with greater muscular pre-activation.

In later research, Kubo et al. (2020) employed a similar ultrasound-dynamometer set-up, examining the active stiffness of the MG by applying passive dorsi-flexion stretches to the ankle joint at various angular velocities of 100, 200, 300, 500, and 600°/s during submaximal isometric contractions of 50% MVC. The researchers found sprinters had significantly greater active muscle stiffness (65.7–71.7 N/mm; $p < 0.05$) compared to untrained controls, yet only under high angular velocities of applied stretch (500 and 600°/s; $d = 0.68–0.74$) (53). The authors hypothesized that active stiffness in sprinters would be altered by the stretch reflex, as muscle stiffness increases with increases in stretch velocity; however, the EMG data reported show no detectable short-latency stretch-reflex effects at any velocity.

The discrepancies in reported outcomes across these studies may be attributed to the relatively low angular velocities applied in Kubo's earlier work. The relationships found at higher angular velocities (500–600°/s) more closely resemble the ankle plantar and dorsi-flexion characteristics observed at touchdown during sprinting, where faster sprinters were found to have angular velocities of approximately 675–800°/s toward the maximal velocity portion (strides 6–13) of a 50-m sprint (93). Alternatively, these findings may reflect specific training-induced adaptations related to the load and

velocity characteristics typical of sporting events. For instance, Kubo et al. (2015) previously reported that active muscle stiffness, measured under low angular velocities (250°/s) was significantly higher in endurance runners compared with untrained men ($p < 0.001$) (94). As the angular velocity of ankle dorsiflexion during endurance running has been reported to be similar (approximately 200–300°/s), a possible explanation is active muscle stiffness is highly specific to the training demands; however, additional longitudinal investigation is required to support such a contention.

Shear-wave Elastography

SWE, also called dynamic elastography, is a modern and increasingly used technique used to evaluate the elasticity of various musculoskeletal tissues (e.g., muscles and tendons). The basic physics of SWE can be explained in 3-steps: 1) shear waves are generated using acoustic radiation force, propagating perpendicularly to the primary ultrasound wave; 2) rapid plane excitation is used to track displacement and velocity, calculated via a speckle tracking algorithm; and, 3) displacement of the measured tissues are used to determine shear wave velocity and shear modulus (95). The current literature indicates greater stiffness of contracted muscles and tendons (active stiffness) propagate faster shear waves (shear-wave velocity (m/s)) compared to those that are relaxed (passive stiffness) (95).

The research using SWE is relatively novel, particularly in the realm of sprinting, with just four studies being included in this review: two of which assessed active muscle stiffness. The active muscle stiffness of the VL was quantified in a single study by Miyamoto et al. (2019) who showed that long-distance runners exhibited higher active muscle stiffness (11.48 ± 1.04 m/s) than both sprinters (10.52 ± 1.15 m/s; $d = 0.56$; $p < 0.05$) and controls ($d = 1.28$; $p < 0.01$) measured during sustained 7-8-s isometric contractions at 50% MVC. Surprisingly, the authors found 100-m sprint time to be positively correlated with active muscle stiffness ($r = 0.47$; $p < 0.05$). Conflictingly, Yamazaki et al. (2022) observed shear-wave speed (m/s) at 50% (8.91 ± 0.97 m/s) and 80% (11.56 ± 1.31 m/s) MVC to have a positive correlation with ankle joint stiffness during sub-maximal quasi-isometric contractions at a fixed angular velocity of 500°/s, which in turn showed a negative correlation with 100-m race time ($r = -0.526$; $p < 0.01$) (58).

A possible explanation for greater active stiffness in the long-distance running group might be related to the effects of endurance training inducing a slow-twitch (ST) fibre type shift; a pattern found across multiple studies noting phenotype shifts toward ST, type I fibres (+ 6.2–12%) and a concomitant reduction in fast-twitch (FT), type II fibres (-4–24%) following 6-and-13 weeks of running and cycling in sedentary and novice athletes (96, 97). Researchers studying isolated muscle fibres and single motor units have found lower short-range stiffness and dynamic stiffness in FT fibres compared to ST fibres (98, 99), while simple modelling presented ST fibres as 30% stiffer than FT fibres (100). Additionally, greater muscle stiffness has been related to a decrease of FT fibres following endurance training (101); however, it is important to note that these collective findings were based on animal studies and are yet to be confirmed in vivo and with whole muscle.

Furthermore, it has been proposed that muscle architectural features may be the primary determinant of short-range stiffness (100). This is relevant as short-range stiffness is inversely related to muscle fibre fascicle length, an established morphological characteristic associated with sprint performance (102, 103). Increases in fascicle length result in a greater number of serially connected sarcomeres, enhancing the maximal length range of muscle excursion and contraction shortening velocity, yet reducing the optimal force and total stiffness of the muscle (100, 104). This evidence may help explain the positive correlation between 100-m sprint performance and greater active muscle stiffness in long-distance runners reported by Miyamoto et al. (55).

Passive Muscle Stiffness

The passive muscle stiffness of sprinters was examined in three studies using SWE; each investigating different muscles, including the MG (58), VL (55), and the BF-LH (56). In the only between-group study, Miyamoto et al. (2019) reported that sprinters exhibited lower passive VL stiffness (2.69 ± 0.30 m/s; $p < 0.05$) compared with both long-distance runners (2.91 ± 0.21 m/s) and untrained men (2.93 ± 0.20 m/s). Despite the absence of direct between-group comparisons available for the MG, Yamazaki et al. (2022) reported passive MG stiffness (2.71 ± 0.13 m/s) comparable to that of the VL in sprinters. Notably, the passive stiffness of both the MG and VL showed moderate but significant negative correlations with 100-m sprint performance (MG:$r = -0.58$, $p < 0.05$; VL: $r = -0.47$), suggesting that passive muscle stiffness may be an important mechanical factor influencing sprint performance.

More recently, Miyamoto et al. (2024) studied the effects of short-term training cessation on passive BF-LH stiffness in sprinters and discovered that shear-wave speed increased (greater muscle stiffness) following a two-week de-training period (before: 4.75 ± 0.77 m/s, after: 5.00 ± 0.88 m/s; $p < 0.001$, $d = 0.31$), providing evidence that passive muscle stiffness in sprint populations has a distinctive sensitivity to mechanical changes in daily and habitual training patterns. Accordingly, the passive stiffness of specific muscles has been shown to acutely, and chronically decrease with eccentrically focused resistance training at long muscle lengths (105), following 4 weeks of static stretching (106), and 8 weeks of high-volume plyometric training (107). Sprint training regularly involves eccentric exercises, stretched positions, long-ranged isometric contractions, and regular bouts of plyometric activity; therefore, the cessation of such exercise modalities associated with training could plausibly result in changes in passive muscle stiffness. Although based on limited data, the observation of lower passive muscle stiffness in sprinters corroborates these findings and likely suggest a multifactorial influence of both structural and functional mechanisms.

First, the increased stiffness in long-distance runners is likely attributed to intra-muscular tissue adaptation, specifically the relatively large, crimped and lattice-like cross-linked formation of fibrils associated with the perimysium (108). The perimysium is the middle layer of fascia (encompassing fascicles/bundles of muscle fibres), known for its load bearing function in the prevention of muscles from being overstretched and potential active role in muscle stiffness linked to myofibroblast density, although this is outside the scope of the review. Interestingly, tonic muscles (e.g., the soleus, used heavily in distance running) contain greater amounts of perimysium compared to phasic FT muscles

(109), and respond aptly to changes in mechanostimulation related to magnitude and amplitude of stretch (108). Therefore, the increased compliance of muscle in sprinters could at least partially be explained by the amount, type and structure of intramuscular connective tissue.

Second, considering that sprinters are typically characterized by greater percentage area of FT fibres (110), and longer fascicle lengths associated with concurrent reductions in stiffness (103), the baseline level of passive stiffness is theoretically lower; However, the regulation of passive stiffness does not rely solely on resting (static) tissue mechanics (85). The passive stiffness of a joint has both a static and a dynamic component, the latter depending highly on the amplitude and duration of an imposed demand (85). For example, when rapid displacement occurs over a short period of time (i.e., as seen immediately on touch down in the sprint cycle), passive force would increase suddenly until a plateau of stretch. Therefore, by mechanical demand, sprinters likely experience higher dynamic passive stiffness during sprinting than is demonstrated at rest under quasi-static conditions experienced using SWE in the aforementioned studies.

With respect to the association between muscle stiffness and sprinting, it remains unclear how the stiffness of passive and active muscles affect performance; however, based on these findings, it's possible that the active muscle stiffness of sprinters is more closely linked to the centrally driven force generative capacity of muscle, while the passive stiffness is affected by the duration and velocity of an imposed stretch rather than solely morphological features such as fibre-type composition or fascicle length, despite remaining essential to elite sprint performance. A more detailed explanation of the association between active/passive muscle stiffness and sprint performance would hold significance for coaches and researchers alike, contributing to the advancement in the understanding of the role of material mechanical properties towards elasticity.

Measurement Considerations

While traditional B-mode ultrasound has been used to assess in vivo tendon length changes since the mid-1990's, (adopted by the majority of research groups in the included studies), fine tuning the methodological details involving the assessment of musculotendinous stiffness is still ongoing, with recent evidence showing considerable variance in muscle-tendon junction displacement and strain of the AT by adding only 1–3 cm of aponeurosis above the precise muscle-tendon junction location (111). It is important to note that the ultrasound-based measurements are largely considered reliable (112), and the ability to detect mechanical changes in muscle and tendon properties is substantial (78); however, the broad range of approaches used by different researchers in this review has led to variable measurement and physiological practices, most likely reflected in the inconsistencies reported across studies, especially with respect to tendon stiffness (22.7–804.5 N/mm) and active muscle stiffness (65.7–92.4 N/mm).

A key issue in understanding the physiology of tendon stiffness is the wide variety of calculations used by researchers. Tendon viscoelastic properties display non-linear force-elongation behaviours; as such,

tendon stiffness is typically measured as the slope of the tendon force-elongation curve within the highest force/stress intervals (approximately 50–100% MVC) to minimise the influence of the more compliant toe-region (112). However, the reviewed studies utilised a variety of contraction intensities and calculated tendon stiffness from data collected at various positions along the force-elongation curve (20–100% MVC). Measuring the slope in the quasi-linear region (50–100% MVC) excludes the compliant toe region, leading to higher stiffness values and making comparisons between studies, problematic.

Another central consideration in the various isometric (sustained/ramped) and quasi-isometric (applied stretch and ballistic contraction types) testing conditions is the viscous, non-linear, time- and rate-dependent behaviour (i.e., stress-relaxation and creep) of tendons (112, 113). When a tendon is placed under constant strain, stress decreases (stress-relaxation). Similarly, when stress is continually or cyclically imposed, increased strain (creep) can be observed (112). Research on the mechanical stabilisation of these phenomena indicates that tendons should be subjected to ≥ 5 cyclical tensile loads to account for tendon “conditioning” (113), a concept that only a single included study explicitly accounted for (54).

Additionally, because the muscle and tendon forces are determined directly by the set-up of the dynamometer (via calculations with moment arm length), some muscular contraction is virtually unavoidable, causing misalignment between the joint axis of rotation and the dynamometer axis (78). While most studies corrected for joint rotation using normalised electromyography activity, electro-goniometer, laser-guided potentiometer, or passive joint correction, the variability in these approaches only heightens the complexity when drawing final conclusions. To improve the reliability of mechanical stiffness assessment and, more so, the comparison between studies, particular attention should be paid to isometric familiarisation, the definition of tendon stiffness calculation, time- and rate-dependent tendon conditions, and standardised joint correction factors.

Finally, several known potential errors have been recognized when obtaining biomechanical information of the in vivo measurement of musculotendinous mechanical properties and include; the selected tissue, the site-location on the muscle or tendon, scanning and tracking error, management of technical factors (transducer pressure, region of interest size, image acquisition time/depth), signal synchronization and very importantly, estimation of tendon force (78, 112, 114).

Practical Implications

Could Tendon Compliance Enhance Force Transmission During the Stance Phase?

Considering these findings, compliant tendon structures of the knee extensors may be beneficial to sprinting performance. If we consider the observed compliance as a maximal velocity stance-phase-specific mechanism, a more compliant VL tendon, and therefore, an elastic contribution, could help generate higher vertical ground reaction forces (v-GRF) when the foot is in contact with the ground.

Theoretically, tendon compliance could have an even greater positive effect on sprint performance than the results demonstrate, because the extensor moment at the knee joint during sprinting is markedly larger than the force generated during the isometric contraction from which these data were obtained (115). According to v-GRF-time waveforms in composite modelling, a part of what separates the fastest sprinters is the application of greater forces during the early portion of the stance phase (10). As this eccentric force acts on the muscle, the MTU lengthens, as does the tendon, relative to the force acting on the system. By accommodating a significant portion of the eccentric stretch before concentric muscle action, a more compliant tendon would hypothetically elongate to a greater extent, increase strain energy, and thereby increase energy return, peak power, and mechanical efficiency (36). From a muscular standpoint, increased tendon compliance may limit (or delay (116)) muscle fibre displacement (117), cross-bridge detachment in activated muscle fibres, and enable reduced muscle shortening velocities to approach near-isometric due to enhanced elastic recoil in the activated muscles (118). Potentiation of concentric muscle force, through a more optimal muscle length-tension and force-velocity relationship, is, therefore, very likely.

Could Tendon Stiffness-Compliance Serve a Dual Role Purpose?

It is plausible that the observed findings reflect a non-uniform dynamic balance between stiffness and compliance, serving a task-specific dual role. Based on work by Miyashiro et al., faster maximal sprinting speeds will be accompanied by greater peak angular velocity (1185–1397°/s) (119) and excursion ranges (114°) (120) by the knee joint during the early swing-phase. To maximise efficiency in such vast joint moments, greater VL tendon compliance may serve a protective function, acting as a mechanical buffer for the quadriceps and hip flexors by limiting peak strain rates of active muscle (116). In contrast, an overly compliant tendon, combined with insufficient joint control, could delay force transmission and timing of limb repositioning during recovery (121). Across different gait conditions, different amounts of tendon compliance and muscle fascicle lengths are generated to maximise efficiency (117). Thus, the mechanical contributions of the working muscles and tendons likely vary across the gait cycle, demanding finely tuned coordination and phase-specific modulation of joint-level stiffness, muscle activation, and tendon stiffness or compliance. This balance ensures effective force transmission and sufficient tendon strain to accommodate the high velocities of stretching and shortening, joint excursion ranges, and timing of force application. These findings lead to speculation that the structural composition of the VL tendon may differ between sprinters and non-sprinters; however, the mechanisms underlying this remain experimentally unestablished.

Limitations and Future Research

While the main objectives of this review were fulfilled, several important limitations must be recognised. Notably, we only included studies that met our population-specific inclusion criteria. Although it would have lowered the quality of our assessment, we could have widened the scope to include all investigations of musculotendinous mechanical stiffness in sprint populations, without restrictions on

participant or performance reporting. However, inconsistent classification of what defines elite and world-class performers (i.e., race time, level of competition, training status) throughout the sprint-specific literature is evident, and without regulation, the ability to confidently interpret these findings would be even more limited. Future research should aim to provide clear, sufficiently detailed inclusion criteria which accurately classifies population samples, thereby improving the comparability and accuracy of elite sprint-related research.

Although the overall quality of the evidence was moderate, with only a few studies exhibiting low risk-of-bias, there was an element of subjectivity in our quality appraisal. Other researchers may take a different approach to assessing quality using the JBI appraisal tool. Moreover, several studies did not provide numeric values for a multitude of musculotendinous mechanical stiffness measures, requiring the authors to manually extract data from figures, potentially affecting the reliability of results, albeit to a minimal degree. Thus, the readers should be aware that the conclusions drawn from this review are constrained by variable study quality. Similarly, the wide variety of study designs, measurements, and outcomes made meta-analyses impossible.

Furthermore, despite consistency amongst sprint participant characteristics (permitting simple comparative analysis between studies), future researchers should quantify the normative musculotendinous mechanical stiffness characteristics across joints in truly elite sprinters. Most of the musculotendinous outcomes presented in this review displayed a clear lack of consistency. In conjunction with many of the included cohorts being comprised of sub-elite sprinters, alongside a scarcity of female athletes, and a complete absence of hip-joint specific measures of mechanical stiffness, a comprehensive examination of the mechanical stiffness characteristics of male and female sprinters, who are recognized as world-class performers in accordance with McKay's' framework, is warranted. This would be a major step towards identifying the optimal mechanical stiffness profile of the world's fastest athletes and how these differ to sub-elite athletes.

While isometric assessment provides a feasible, lab-based method for measuring musculotendinous mechanical stiffness characteristics, the magnitude of force, rate of imposed stretch and duration of effort is considerably different during localised isometric contractions than perceived in real-time during sprinting or sprint-related training activities. Along with standard ultrasound imaging and SWE, the use of additional technologies may provide further objective insights into the musculotendinous mechanical characteristics of sprinters, including force-plates, inertial measurement units, and visual kinematic software/motion capture analysis systems, which are at the forefront of utility in this area. Employing such tools could lead to more practically relevant examinations of mechanical behaviours of MTU's in relation to force-velocity demands, task orientation, and SSC activity during sprinting.

Lastly, although indirect, proxy measures of mechanical stiffness have been widely researched, very little has been published on musculotendinous mechanical stiffness characteristics in elite sprinters. While it does exist, the body of literature fails to fully capture the contribution of muscles and tendon towards more elite levels of sprint performance. However, the review has revealed exciting research possibilities

and questions surrounding the role of independent musculotendinous mechanical stiffness characteristics towards optimising specific features of sprinters and sprint performance, including:

1. Does musculotendinous mechanical stiffness at a single joint, or across multiple joints demonstrate a distinct relationship with indirect measures of mechanical function relating to joint, leg and vertical stiffness in sprint populations. This is particularly relevant given the association between higher mechanical stiffness and faster maximal sprint velocity.
2. Can musculotendinous mechanical stiffness predict or correlate with spatiotemporal sprint kinematics (e.g., stride length/rate, contact time, flight time) during various sprint phases (i.e., 0–5/10/20/40/100-m race splits). This information could help inform coaches whether components of musculotendinous mechanical stiffness are associated with determinants of mechanical sprint performance (i.e., AT stiffness is more important during maximal velocity than acceleration) and spatiotemporal sprinting kinematics.
3. Does an optimal balance exist between tendon stiffness and compliance relative to the force required to produce tendon strain, level of muscle activation and the angle and velocity of load?
4. To what extent do inter-individual neuromuscular, morphological and skeletal factors influence optimal musculotendinous mechanical stiffness? Exploring this may help explain why some sprinters show greater power, creating advantage during acceleration, while others are more elastic and attain greater maximal velocities.

Conclusions

Determining the mechanical stiffness of individual MTUs may facilitate a greater level of understanding towards the contribution of stiffness at each joint and, consequently, to global stiffness of the leg-spring system. However, a limited number of studies investigated MTU characteristics in sprint populations when constrained by appropriate scientific criteria. Despite the scarcity and questionable quality of sprint-related research in this area, widespread generalised notions of MTU mechanical characteristics (i.e., tendon stiffness is uniformly greater in sprinters) by strength and conditioning practitioners and track coaches in the community are commonly assumed. Yet, as illustrated in this review, the veracity of the optimal mechanical profile of the elite sprinter is unclear. Most likely, a dynamic and individualised optimal mechanical profile does exist for maximal sprinting distinguished by sufficient stiffness to transfer rapid force efficiently, yet adequate compliance to induce strain and utilise ESE effectively. However, without further research to help define the optimal and individualised musculotendinous mechanical factors that contribute to the success of sprinting, drawing conclusions from the current data is highly speculative. With the small number of studies included, broad range in assessment techniques, and questionable reliability, consistent methodological practice and better reporting are needed. It is recommended that future research should look to replicate and expand on these findings in elite sprint populations.

Abbreviations

AT – Achilles tendon

BF-LH – Biceps femoris-long head

B-mode – Brightness mode

CR – Coefficient of repeatability

CV – Coefficient of variation

EMG – Electromyography

ESE – Elastic strain energy

FT – Fast-twitch

IAAF – International Association of Athletics Federations

ICC – Intraclass correlation coefficient

JBI – Joanna Briggs Institute

MG – Medial gastrocnemius

MTU – Musculotendinous unit

MVC – Maximal voluntary contraction

SMM – Spring-mass model

SSC – Stretch–shortening cycle

ST – Slow-twitch

SWE – Shear-wave elastography

VL – Vastus lateralis

V-GRF – Vertical ground reaction force

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and material

The data underlying this review are in available in the article text and table formats. The data can also be accessed in each individual study.

Competing interests

David I. Sturrock is the owner and employee of Method Performance and Rehab, a private sports performance and physiotherapy clinic.

John B. Cronin, and Dustin J. Oranchuk declare that they have no competing conflicts of interest relevant to the content of this review.

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Authors' contributions

The concept of the review was formed by DIS and JBC who contributed practical and theoretical insights in refining the topic and primary research question. DIS and DJO performed the initial literature search, title / full text screening, data extraction and determined inclusion, quality and risk of bias. DIS wrote the initial draft of the title, abstract, introduction, methods, results and discussion sections. All authors contributed to the final draft and approved the final version of the manuscript prior to publication.

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Figures

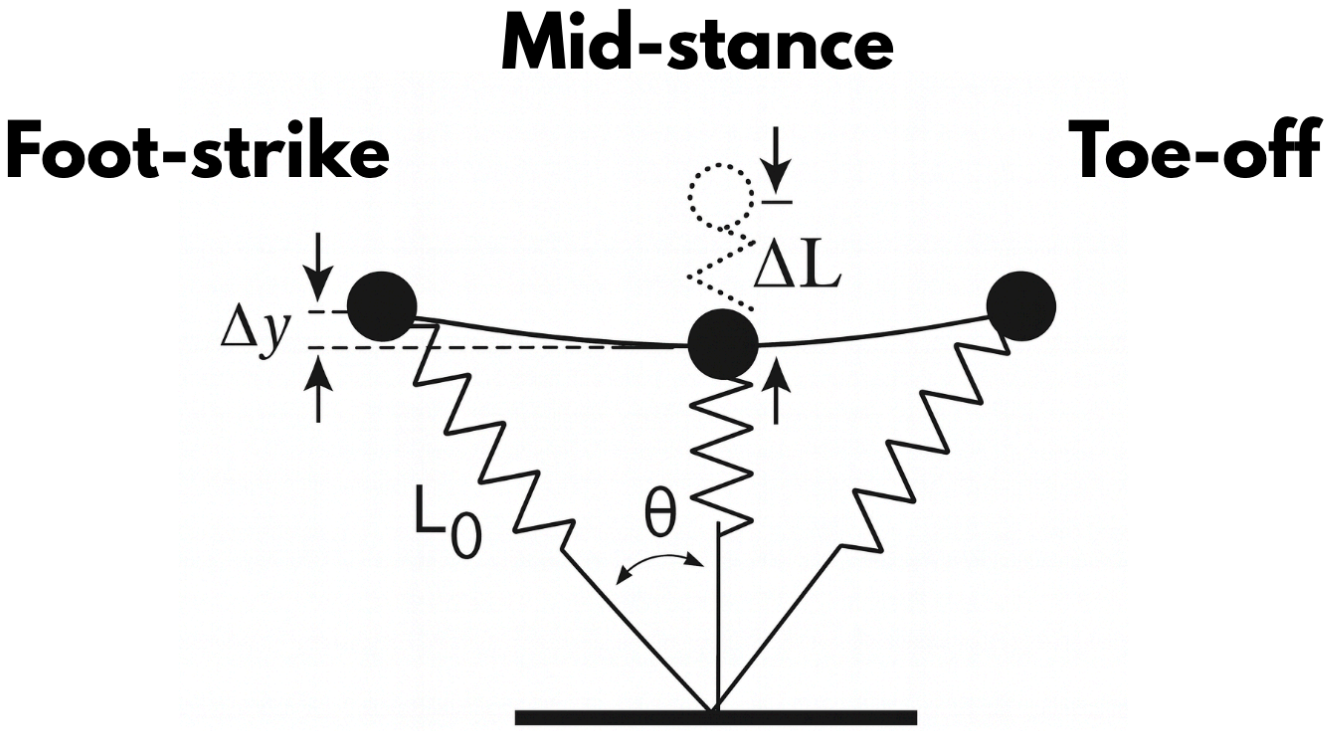


Figure 1

Spring mass model: A representation of running modelled as a simple spring-mass system (adapted and modified from Farley and Gonzalez 1996 (21)). The figure illustrates the beginning (foot-strike), middle (mid-stance), and end (toe-off) of the ground-contact phase. The leg is depicted as a single-leg spring with L_0 as the initial leg length. ΔL denotes the maximal compression of the leg-spring while Δ*y* represents the vertical displacement of the centre of mass. θ denotes half the angle swept by the leg spring in this spring-loaded inverted pendulum behaviour of running.

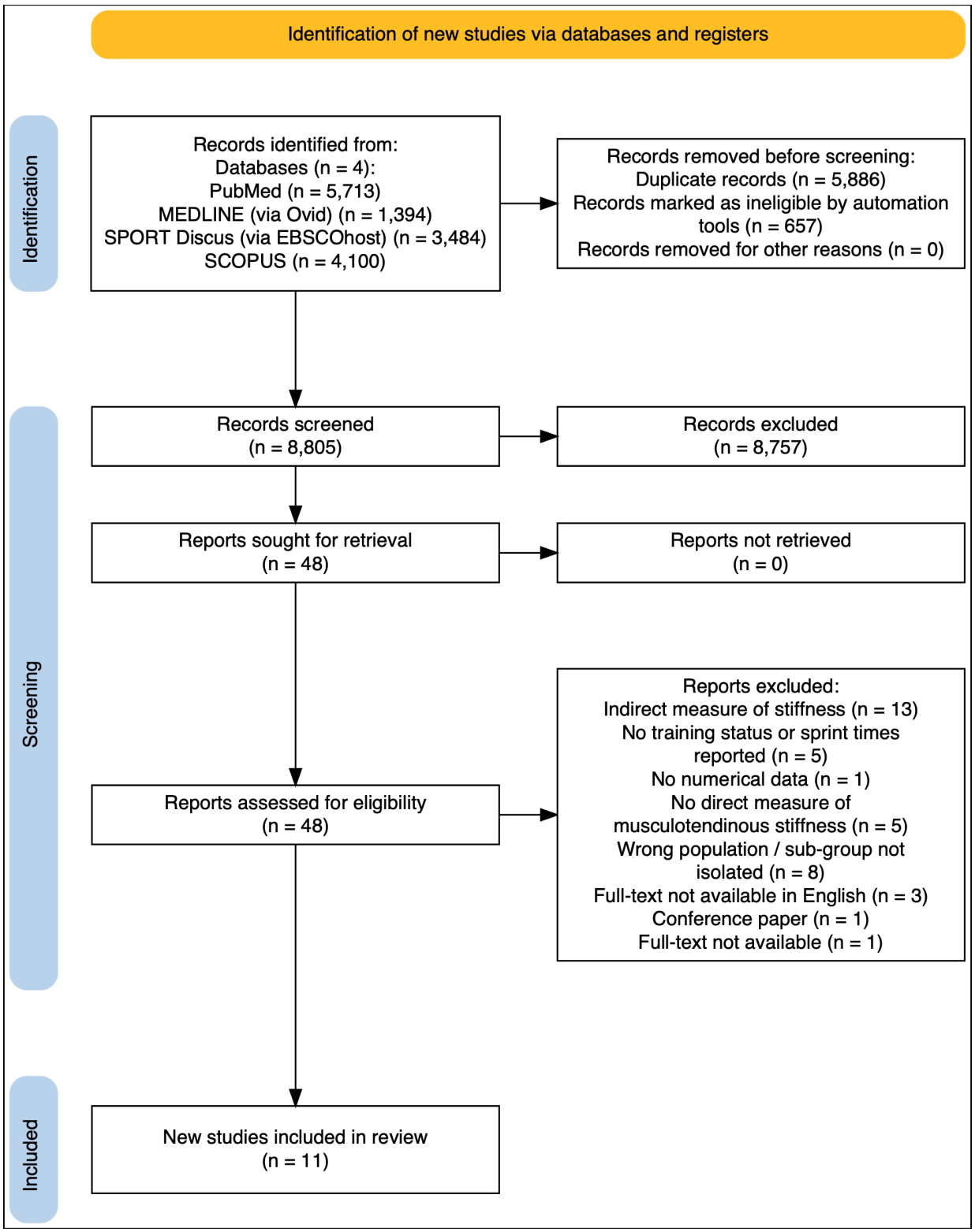


Figure 2

PRISMA Flow Diagram

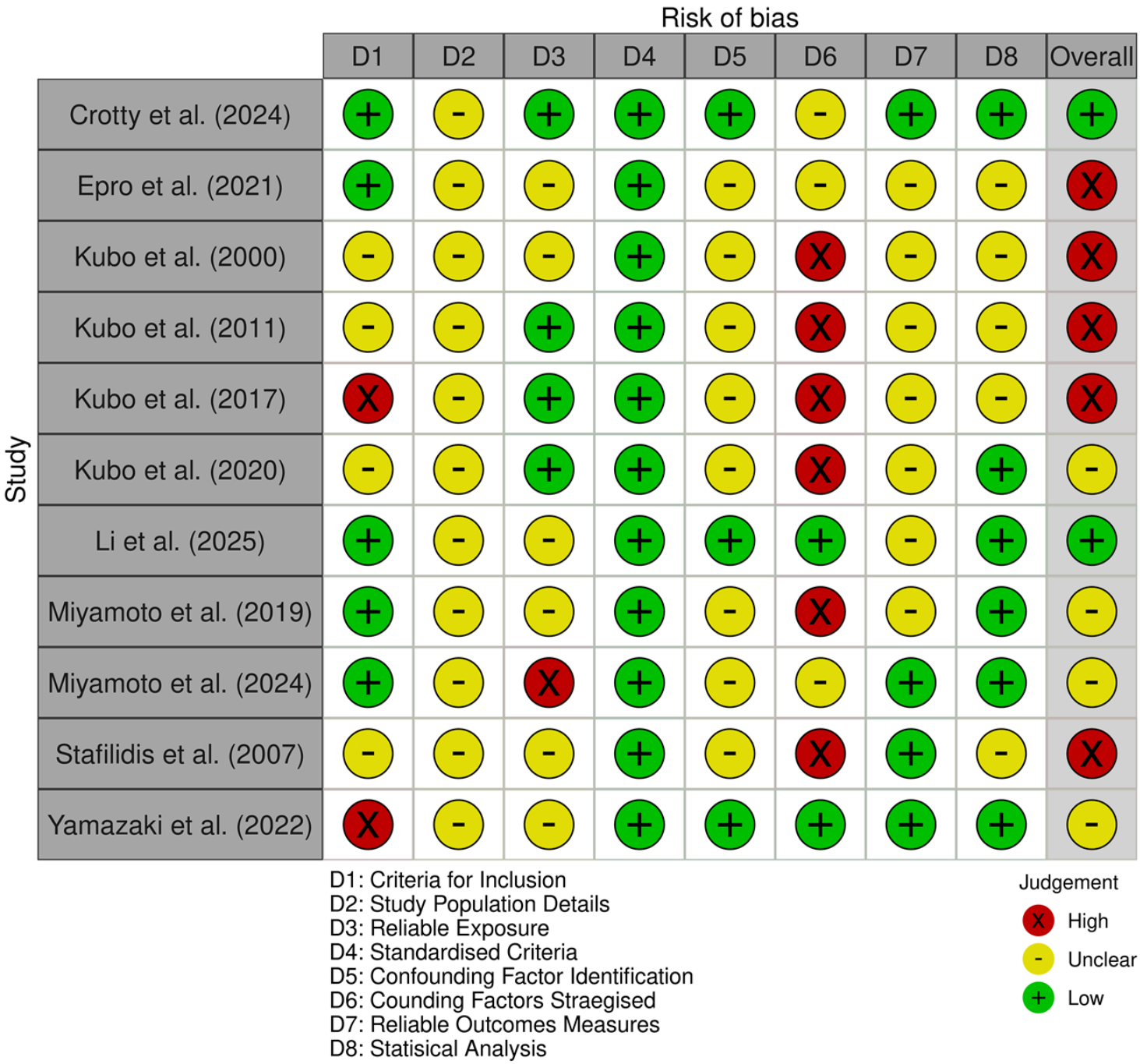


Figure 3

Risk-of-bias summary according to JBI Critical Appraisal tool.