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Title: Sports activity resumption after lower-limb muscle and tendon injuries in athletes: The role of shear-wave elastography in diagnosis and healing assessment: A narrative review

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Abstract:

Background: Muscle and tendon injuries of the lower limb are common in athletes and often require prolonged rehabilitation before returning to sport. Shear-wave elastography (SWE) enables quantitative assessment of tissue mechanical properties and may provide information beyond conventional morphological imaging.

Aim: Sports activity resumption after lower-limb muscle and tendon injuries is a key focus of this narrative review, which summarizes current evidence on SWE in diagnosis, monitoring of healing and rehabilitation, and assessment of readiness to return to sport.

Material and methods: Studies evaluating SWE in lower-limb muscle and tendon injuries were reviewed.

Results: Studies demonstrate measurable SWE changes in hamstring and calf muscle injuries, Achilles tendon pathology and rupture, and patellar tendinopathy. However, the direction and magnitude of stiffness changes vary according to tissue type, injury stage, loading conditions, training status, acquisition protocol, and ultrasound system. Serial SWE measurements may therefore be more informative than isolated absolute values, particularly when performed under standardized conditions and interpreted alongside clinical and functional recovery.

Conclusions: At present, SWE should be considered a complementary tool rather than a stand-alone diagnostic or return-to-sport criterion. Universal reference ranges and validated cutoff values are lacking, and the relationship between SWE normalization, re-injury risk, and readiness to return to sport remains uncertain. Further prospective studies using standardized protocols and clinically relevant outcomes are needed.

Key words: athletes; muscle injuries; return to sport; shear-wave elastography; tendon injuries

1. Introduction

Sports activity, particularly involving jumping, rapid acceleration and deceleration, and repetitive mechanical loading, places substantial demands on lower-limb muscles and tendons and may contribute to injury. Hamstring injuries account for approximately 10% of all reported injuries in field-based team sports [1]. Patellar tendinopathy is also common, affecting approximately 18% of athletes, particularly in basketball and volleyball [2]. Achilles tendinopathy is also associated with physical activity and has been reported more frequently in athletes than in amateur exercisers [3].

MRI and ultrasonography are widely used in the evaluation of sports-related muscle and tendon injuries. Ultrasonography offers several practical advantages, including accessibility, real-time imaging, dynamic assessment, and the ability to repeat the examination multiple times during rehabilitation [4,5]. However, conventional ultrasonography provides mainly structural and vascular information and does not allow for direct quantitative assessment of the mechanical properties of tissues [6,7].

Shear-wave elastography (SWE) is an ultrasound technique that allows for the quantitative assessment of tissue stiffness by measuring the propagation velocity of shear waves. These waves travel faster in stiffer tissues, and the results can be expressed as shear wave velocity or as calculated elastic parameters [6,7]. SWE is increasingly being used in the assessment of skeletal muscles and tendons, including the hamstrings, Achilles tendon, and patellar tendon.

Recent studies have investigated SWE-derived mechanical properties in relation to injury risk, acute injury, tendinopathy, and recovery [8–10]. However, measurement results are influenced by factors such as joint position, muscle activation, probe positioning, recent physical activity, and the ultrasound device used. Methodological heterogeneity and the lack of standardized reference values currently limit the routine use of this method in clinical practice [11,12].

The aim of this narrative review is to summarize the current evidence regarding the use of SWE in lower limb muscle and tendon injuries in athletes, with a focus on diagnostic applications, monitoring healing and rehabilitation, and its potential role in assessing readiness to return to sport.

2. Methods

2.1. Literature search and study selection.

A narrative literature review was conducted using PubMed, Scopus, and Web of Science. The search included publications available up to August 2026 and used combinations of terms related to shear-wave elastography, muscle injury, hamstring injury, calf muscle injury, tendinopathy, Achilles tendon, patellar tendon, rehabilitation, and return to sport.

Original studies and relevant review articles evaluating SWE in lower-limb muscles and tendons were considered. Particular emphasis was placed on studies involving athletes or physically active individuals and on publications addressing diagnostic applications, tissue healing and remodeling, rehabilitation monitoring, and return-to-sport assessment. Studies were selected according to their relevance to the predefined thematic areas of the review, with

additional consideration given to methodological studies addressing SWE acquisition, reliability, reproducibility, and interpretation.

Representative clinical studies illustrating the principal applications of SWE in lower-limb muscle and tendon injuries were summarized in Table 1.

2.2. AI

ChatGPT (OpenAI) and Claude (Anthropic) were used to support manuscript structuring, language editing, and improvement of clarity and readability. All tools were used under human supervision. The authors reviewed and verified all scientific content, interpretations, and references and take full responsibility for the final manuscript.

3. Shear-Wave Elastography: Principles and Measurement Considerations

3.1. Basic Principles of Shear-Wave Elastography

SWE is an ultrasound technique that provides quantitative information about the mechanical properties of soft tissues [6]. Unlike conventional B-mode imaging, SWE uses acoustic radiation force to generate shear waves within the examined tissue. Their propagation is then tracked using ultrafast ultrasound imaging, allowing the local shear wave velocity to be calculated. Because shear waves travel faster in stiffer tissues, their velocity can be used as an indirect indicator of tissue stiffness [6,13].

In musculoskeletal applications, SWE is used to assess both skeletal muscles and tendons [6,7]. Its main advantage is the ability to obtain quantitative measurements in a specific region of interest while simultaneously visualizing tissue morphology in a B-mode image. However, muscles and tendons are anisotropic and mechanically complex structures. As a result, SWE measurements are influenced not only by tissue composition but also by fiber orientation and the mechanical state of the tissue at the time of examination [7,13].

3.2. Shear-Wave Velocity, Tissue Stiffness, and Elastic Modulus

SWE results can be reported directly as shear wave velocity in meters per second or converted to elastic parameters in kilopascals. Studies have shown that SWE values increase with increasing mechanical load and correlate with changes in muscle stiffness, particularly when the ultrasound transducer is aligned with the muscle fibers [14].

Converting shear wave velocity to elastic modulus requires assumptions regarding the mechanical properties of the tissue. These assumptions are relatively straightforward for homogeneous and isotropic materials; however, skeletal muscle and tendons do not fully meet these conditions due to their anisotropic and viscoelastic structure [13]. Therefore, values reported in meters per second and kilopascals should not always be considered directly comparable between studies, especially when different devices or computational models are used. In some musculoskeletal applications, direct reporting of shear wave velocity may therefore be more appropriate [15]

3.3. Physiological Determinants of Elastography Measurements

In skeletal muscle, SWE values vary depending on muscle length, joint position, and the degree of muscle activation [16,17]. Passive stretching increases tension within the musculotendinous unit, while voluntary contraction leads to a significant increase in measured stiffness [17]. Transducer positioning is also important, as shear waves propagate differently along and across muscle fibers. Experimental studies have shown poorer wave propagation when measurements are taken perpendicular or oblique to the fiber direction [14].

3.4. Effects of Exercise and Training on Elastographic Measurements

Physical activity represents an additional source of variability in SWE results in athletes. Acute eccentric exercise can induce transient increases in muscle stiffness, which may persist into the early recovery period before returning toward baseline values [18]. Eccentric and intensive exercise may also induce muscle microdamage and delayed-onset muscle soreness during the recovery period [19]. Studies of exercise-induced muscle damage have frequently reported increases in shear modulus immediately after eccentric exercise and for several days thereafter, although the magnitude and temporal pattern of these changes vary between studies [20].

Baseline tissue stiffness may also vary according to training status [21]. Acute exercise may induce individual-specific changes in tissue stiffness; therefore, recent physical activity should be considered when interpreting SWE measurements in athletes [22]. The time interval between physical activity and elastography should also be taken into account when comparing measurements over time or between athletes. In longitudinal monitoring, measurements should, whenever possible, be performed under comparable pre-test conditions.

3.5. Interpretation and Reporting of SWE Measurements

Interpretation of SWE results requires consideration of both the properties of the tissue being examined and the measurement conditions. Higher or lower stiffness values should not automatically be considered pathological, as SWE parameters depend on factors such as muscle activation, joint position, tissue loading, fiber orientation, and the measurement technique [13,14]. Furthermore, values expressed as shear wave velocity and values converted to elastic modulus are not always directly comparable, particularly in anisotropic tissues such as muscles and tendons [13,23].

Therefore, in SWE studies, the unit of measurement, anatomical location, limb and joint position, transducer orientation, region of interest, and the ultrasound device used should be precisely defined. For muscle, direct reporting of shear wave velocity may be more appropriate than converting it to elastic modulus because such conversion requires making assumptions that are not fully valid in anisotropic and viscoelastic tissues [13,15,23]. Consistent reporting of acquisition conditions is essential for correct interpretation and comparison of SWE results between studies.

3.6. Reliability, Reproducibility, and Measurement Standardization

Studies have demonstrated generally good intra- and interobserver reliability of SWE measurements in lower-limb muscles and tendons when standardized protocols are used,

although reliability may vary depending on the tissue and measurement conditions [24,25]. However, SWE measurements may be influenced by technical factors such as transducer pressure and orientation, measurement depth, location of the region of interest, joint positioning, and the ultrasound device used [15,26]. In muscle assessment, repeatability may be improved by using minimal transducer pressure, measurement depths below 4 cm, and reporting shear wave velocity in m/s rather than calculated elastic modulus in kPa [15]. Standardization is therefore particularly important when SWE is used for repeated assessments during rehabilitation. Whenever possible, subsequent examinations should be performed at the same anatomical site, with the same limb position, probe orientation, and using the same device and acquisition settings. Despite good reproducibility under controlled conditions, differences between devices and examination protocols, as well as the lack of universally accepted reference values, continue to limit direct comparison of results and broader clinical application of SWE [15,26].

4. Shear-Wave Elastography in Sports-Related Muscle Injuries

4.1. Acute Muscle Strain Injuries

Acute muscle injuries involve muscle fiber damage, swelling, bleeding, and subsequent tissue remodeling. These processes alter the mechanical properties of the injured area and can influence SWE results. Reduced SWE-derived mechanical parameters have been observed in injured muscles during the early post-injury phase compared with the contralateral limb [9,27].

However, these changes do not necessarily follow a consistent pattern during healing. As regeneration progresses, tissue stiffness can be influenced by scar formation, extracellular matrix remodeling, and the gradual recovery of load-bearing capacity. Longitudinal studies indicate that stiffness can increase during rehabilitation and remain altered even upon return to sport [28]. Therefore, SWE should be considered primarily as a method for monitoring changes over time, rather than as a parameter that always changes in a single direction after injury.

4.2. Hamstring Injuries

Hamstring injuries are among the most common muscle injuries in athletes, particularly in sports involving high-speed running, sprinting, jumping, and rapid changes of direction. The long head of the biceps femoris is most frequently affected [29]. Alterations in its mechanical properties may persist beyond clinical recovery [28,30].

Crawford et al. demonstrated reduced shear wave velocity in the injured limb during the acute phase of injury, but no significant differences were observed between limbs upon return to sport [9]. However, other studies indicate increased stiffness in later stages of recovery. Kawai et al. described increased fascial stiffness in professional rugby players with a history of hamstring injuries [30], while Kukuchi et al. demonstrated that passive stiffness of the biceps femoris long head increased during rehabilitation and remained elevated at return to sport [28].

These differences highlight the importance of timing and location of measurement. In the acute phase, the results may reflect edema and fiber disruption, whereas later on, remodeling processes and changes in connective tissue may become more important [9]. Therefore, the current data suggest that SWE may be useful in longitudinal assessment of hamstring

regeneration, but they do not yet allow for the definition of a single characteristic pattern of stiffness changes for all injuries [9,28,30].

4.3. Calf Muscle Injuries

Calf muscle injuries often involve the medial head of the gastrocnemius muscle, particularly near the musculotendinous junction [31]. SWE studies have demonstrated regional differences in gastrocnemius stiffness depending on the measurement site and ankle joint position, which may help explain the greater susceptibility of specific musculotendinous regions to injury [32].

Prospective data also suggest that SWE may be useful for monitoring muscle healing. You et al. found lower SWE-derived speed-of-sound (C) values in acutely injured triceps surae muscles than in the contralateral limb, followed by a gradual increase during recovery, with values approaching those of the healthy side after 12 weeks [27].

Available evidence on SWE in calf muscle injuries remains limited compared with that for hamstring injuries. SWE appears promising for monitoring changes in muscle mechanical properties, but its clinical and prognostic significance requires further study in athletic populations.

5. Shear-Wave Elastography in Sports-Related Tendon Pathology

5.1. Achilles Tendon

The Achilles tendon is one of the most commonly assessed tendons in the lower limb using SWE [12,33]. In tendinopathy, structural changes visible on conventional ultrasound may be accompanied by measurable changes in mechanical properties [12,33,34]. However, the direction and severity of these changes are not consistent across studies, which may be partially due to differences in the stage of the disease, measurement site, ankle joint position, and SWE methodology used [12].

Crawford et al. demonstrated lower shear wave speed in the symptomatic free tendon compared with the contralateral side, but found no significant differences in the soleus or gastrocnemius aponeuroses [34]. This suggests that changes in mechanical properties may be localized and not encompass the entire musculotendinous unit. Other studies have also demonstrated differences in elastic properties between healthy Achilles tendons and tendons affected by tendinopathy [33].

These results suggest that SWE can complement B-mode imaging and Doppler imaging by providing quantitative information about the mechanical properties of the tendon [12,33,34]. However, at present, this method should be considered an adjunct tool, as a single stiffness value does not reliably characterize the full spectrum of Achilles tendon pathology [12].

5.2. Patellar Tendon

Patellar tendinopathy is particularly common in athletes exposed to repetitive jumping loads [35]. SWE has also been extensively studied in this condition. Contrary to some findings regarding the Achilles tendon, increased patellar tendon stiffness has been reported in symptomatic athletes. Breda et al. demonstrated significantly higher patellar tendon stiffness in

athletes with tendinopathy compared with healthy controls, with excellent intra-observer and good inter-observer reliability [10].

The diagnostic value of SWE also depends on the measurement site and knee position. Devran et al. demonstrated the highest diagnostic accuracy when assessing the proximal patellar tendon at 30° of knee flexion [36]. This finding further emphasizes that stiffness values should always be interpreted in the context of the testing protocol used.

Longitudinal studies also suggest that SWE can detect changes in mechanical properties during treatment. Zhang et al. described changes in the morphology and stiffness of the patellar tendon following shockwave therapy in volleyball players with tendinopathy [37]. In another study, reduced patellar tendon stiffness during exercise therapy was associated with greater clinical improvement, although the baseline value alone did not predict treatment outcome [38].

Notably, Achilles tendon and patellar tendon tendinopathy may be characterized by different elastographic patterns [33]. Therefore, the assumption that a pathological tendon is always softer or stiffer than a healthy one is an oversimplification. SWE results should be interpreted taking into account the specific tendon, the type of pathology, the area being examined, and the measurement protocol.

5.3. Tendon Rupture and Post-Injury Changes

The most extensive data regarding the use of SWE after tendon rupture relate to the Achilles tendon. Acute rupture causes significant disruption of the tendon's continuity and mechanical properties, followed by gradual remodeling during the healing process. Longitudinal studies have demonstrated gradual changes in elastic properties after rupture, suggesting that SWE can be used to noninvasively monitor mechanical recovery [39,40].

Yoshida et al. observed progressive changes in SWE parameters after both conservative and surgical treatment of Achilles tendon ruptures, with values becoming comparable to the uninjured tendon at different time points between groups [40]. Previous studies have also indicated that the mechanical properties of the healed tendon may remain reduced long after restoration of its continuity [41]. These findings indicate that restoration of tendon continuity does not necessarily correspond to complete recovery of its mechanical properties.

More recent longitudinal data further support this observation. Sukanen et al. demonstrated that shear wave velocity in the injured Achilles tendon increased during the first year after conservative treatment and reached values similar to the contralateral side after approximately six months. Symmetry of wave velocity was also associated with symmetry of plantarflexion maximal voluntary torque, suggesting a possible relationship between recovery of tendon mechanical properties and functional improvement [42].

Overall, SWE appears to be capable of detecting mechanical changes associated with tendinopathy and tendon rupture, which are not always fully captured by classical morphological imaging. However, the variability of results between different tendons and healing stages indicates the need for longitudinal evaluation and the use of standardized protocols rather than interpreting single absolute values.

6. Shear-Wave Elastography for Monitoring Healing and Rehabilitation

6.1. Muscle Healing and Remodeling

Muscle healing is a dynamic process involving inflammation, regeneration of muscle fibers, connective tissue formation, and subsequent remodeling [43]. These biological processes are accompanied by phase-dependent changes in tissue mechanical properties that can be detected using SWE. Across hamstring and triceps surae injuries, acute injury has generally been associated with reduced SWE-derived mechanical parameters, whereas later stages of rehabilitation may be characterized by normalization or an increase in stiffness as tissue regeneration and remodeling progress. Importantly, mechanical recovery does not appear to follow a uniform pattern, and SWE values may either approach those of the contralateral limb or remain altered at return to sport depending on the injured tissue and stage of healing. Therefore, serial measurements interpreted in relation to the phase of recovery may be more informative than isolated SWE values. [9,27,28].

6.2. Tendon Healing and Remodeling

Tendon healing involves progressive collagen reorganization, structural remodeling, and gradual restoration of load-bearing capacity, although the original mechanical properties of the tendon may not be fully recovered [44]. Longitudinal SWE studies of Achilles tendon rupture indicate that mechanical properties change progressively during healing, with increasing stiffness or shear-wave velocity over time and partial or complete convergence toward values observed in the contralateral tendon. However, the timing and magnitude of these changes vary according to treatment strategy and stage of recovery, and residual mechanical abnormalities may persist despite restoration of tendon continuity. These findings suggest that serial SWE assessment may provide information on tendon remodeling that is not captured by morphological healing alone [39–42].

6.3. Monitoring Response to Therapeutic Loading and Rehabilitation

SWE may also be useful for monitoring changes in muscle and tendon mechanical properties in response to rehabilitation. In patellar tendinopathy, longitudinal studies have demonstrated changes in tendon stiffness during both shockwave therapy and exercise-based rehabilitation, with greater reductions in stiffness during exercise therapy being associated with greater clinical improvement. Importantly, baseline stiffness alone did not predict treatment outcome, suggesting that longitudinal changes may be more informative than isolated pre-treatment measurements [37,38]. Similar observations have been reported in other tendinopathies, where SWE detected treatment-related changes that were not fully reflected by conventional B-mode or Doppler imaging. However, elastographic changes should be interpreted together with symptoms and functional recovery rather than used as an independent marker of rehabilitation progress [45].

Overall, current longitudinal evidence does not indicate a single universal pattern of stiffness changes during recovery. The clinical value of SWE may therefore lie primarily in repeated measurements performed in the same patient under standardized conditions, with changes interpreted alongside clinical and functional improvement rather than on the basis of isolated absolute values [9,27,28,38–40,42].

7. Shear-Wave Elastography and Return-to-Sport Decision-Making

7.1. Current Principles of Return-to-Sport Assessment

Return to sport is a multifactorial process rather than a single endpoint. Current concepts describe a continuum encompassing return to participation, return to sport, and return to performance [46]. Decisions should consider biological healing, symptoms, muscle strength, range of motion, functional ability, sport-specific demands, and individual risk of re-injury. Rehabilitation progression and return to activity should be guided by functional recovery and the athlete's response to gradually increasing physical demands [47]. Psychological, social, and contextual factors should also be considered in return-to-sport decision-making [46,48].

Within this framework, imaging represents only one component of the overall assessment. SWE may provide additional information on tissue mechanical properties, but its findings should be interpreted in the context of clinical and functional recovery.

7.2. Evidence from Muscle Injuries

Evidence directly linking SWE findings with return-to-sport readiness in muscle injuries remains limited. In hamstring injuries, longitudinal studies have shown that between-limb differences in SWE parameters may diminish by the time of return to sport, whereas altered passive stiffness may also persist despite clinical recovery. These findings indicate that normalization of SWE parameters is not a consistent prerequisite for return to sport and that persistent mechanical asymmetry may coexist with functional recovery [9,28].

Currently, no validated SWE thresholds have been established for return-to-sport decision-making, and evidence linking residual stiffness abnormalities to subsequent re-injury risk remains lacking [49,50].

7.3. Evidence from Tendon Injuries

Evidence directly linking SWE parameters with return-to-sport readiness in tendon injuries remains limited. Following Achilles tendon rupture, longitudinal studies have shown progressive recovery of mechanical properties during rehabilitation, with increasing similarity between the injured and contralateral tendon over time. However, restoration of mechanical symmetry does not necessarily coincide with complete functional recovery, and persistent abnormalities may remain despite clinical improvement [39–42].

In patellar tendinopathy, changes in tendon stiffness during exercise-based rehabilitation have been associated with clinical improvement, whereas baseline stiffness alone did not predict treatment outcome. These findings support the use of serial SWE measurements for monitoring recovery but do not provide validated criteria for determining readiness to return to sport [38].

7.4. Integration with Clinical, Functional, and Conventional Imaging Assessment

The potential value of SWE lies in complementing, rather than replacing, established return-to-sport assessment methods. Clinical findings, strength testing, range of motion, and functional and sport-specific tests remain essential components of return-to-sport decision-

making [46,48], while conventional imaging provides complementary structural information [4].

Serial SWE assessment may add quantitative information on changes in tissue mechanical properties during recovery. However, persistent mechanical asymmetry does not necessarily indicate incomplete clinical recovery, while normalization of an individual SWE parameter should not be interpreted as evidence of complete recovery in the presence of persistent functional deficits [41,42]. SWE findings should therefore be interpreted as one component of a broader clinical, functional, and imaging assessment.

7.5. Limitations of Shear-Wave Elastography as a Stand-Alone Return-to-Sport Criterion

Several factors currently prevent SWE from being used as an independent criterion for return-to-sport decision-making. Measurements are influenced by joint position, muscle activation, probe orientation, measurement site, acquisition protocol, and ultrasound system, while baseline tissue properties may also differ according to training status [13,15,26,51].

Moreover, validated SWE cutoff values for distinguishing adequate from inadequate mechanical recovery have not been established, and the relationship between normalization of tissue stiffness and subsequent re-injury risk remains unclear. SWE should therefore be considered a complementary source of quantitative information rather than a stand-alone return-to-sport criterion, with final decisions based on integrated clinical, functional, sport-specific, and imaging assessment [46,48,49].

Representative clinical studies addressing the main applications of SWE in lower-limb muscle and tendon injuries are summarized in Table 1.

Table 1. Representative clinical studies on shear-wave elastography in lower-limb muscle and tendon injuries

Study	Population condition	Main SWE findings	Clinical relevance
Crawford et al., 2024 [9]	Collegiate athletes with acute hamstring strain injury	SWS was lower in the injured limb at the time of injury, with no significant between-limb differences at RTS or 12 weeks after RTS	SWS may complement conventional imaging in monitoring mechanical changes during hamstring injury recovery.
Kukuchi et al., 2026 [28]	Male track-and-field athletes with biceps femoris long head strain injury	Passive BFlh stiffness increased during rehabilitation and remained elevated at return to sport; previously	Persistent increases in passive muscle stiffness may indicate lasting mechanical alterations after hamstring strain

		injured limbs also showed higher stiffness than contralateral uninjured limbs	injury, including at RTS.
You et al., 2026 [27]	Patients with acute unilateral triceps surae muscle injury	SWE-derived speed-of-sound values were reduced in the injured muscle at baseline and progressively increased during rehabilitation, approaching contralateral values by 12 weeks.	SWE may support serial monitoring of calf muscle healing and treatment response.
Crawford et al., 2022 [34]	Patients with chronic midportion Achilles tendinopathy	SWS was lower in the symptomatic free tendon, with no significant differences in the soleus or gastrocnemius aponeuroses	SWE may detect region-specific mechanical alterations in Achilles tendinopathy and complement conventional ultrasound assessment.
Coombes et al., 2018 [33]	Adults with Achilles or patellar tendinopathy and healthy controls	Achilles tendinopathy showed lower SWV at the distal Achilles tendon insertion, whereas patellar tendinopathy showed higher SWV in both examined regions compared with healthy controls.	Achilles and patellar tendinopathy may show opposite, tendon-specific changes in mechanical properties, limiting universal interpretation of SWE values.
Breda et al., 2022 [38]	Athletes with patellar tendinopathy undergoing exercise therapy	Patellar tendon stiffness decreased during treatment, and greater reductions were associated with better clinical outcomes; baseline stiffness did not predict treatment outcome	Longitudinal changes in SWE may be more informative for monitoring rehabilitation than a single baseline stiffness measurement.

Frankewycz et al., 2020 [39]	Patients with acute Achilles tendon rupture treated non-operatively	Elastographic stiffness increased during healing, with a marked rise in the first 6 weeks and a second increase between 3 and 6 months	SWE may support longitudinal monitoring of changes in Achilles tendon mechanical properties during healing.
Yoshida et al., 2023 [40]	Patients with acute Achilles tendon rupture treated conservatively or surgically	SWE values became comparable with the uninjured tendon at 12 weeks after conservative treatment and at 4 weeks after surgical treatment; the surgical group showed higher SWE values up to 24 weeks.	SWE may support non-invasive monitoring of Achilles tendon healing during rehabilitation.
Sukanen et al., 2026 [42]	Patients with unilateral Achilles tendon rupture treated non-operatively	SWV progressively increased during the first year, reached values comparable with the uninjured tendon by 6 months, and SWV symmetry correlated with plantarflexion maximal voluntary torque symmetry.	SWE may support monitoring of Achilles tendon mechanical recovery and its relationship with plantarflexion maximal voluntary torque.

Abbreviations: BFlh, biceps femoris long head; RTS, return to sport; SWE, shear-wave elastography; SWS, shear wave speed; SWV, shear wave velocity.

8. Discussion

8.1. Clinical Value of Shear-Wave Elastography in Sports Medicine

Current evidence suggests that the main clinical value of SWE in sports medicine lies in its ability to provide quantitative information on tissue mechanical properties and to track their changes over time. This may complement conventional B-mode and Doppler imaging, particularly when repeated measurements are performed during rehabilitation under standardized conditions.

The available literature indicates that longitudinal changes in SWE parameters may be more informative than isolated absolute values, as tissue stiffness is influenced by the type of tissue, stage of injury, loading conditions, training status, and technical aspects of acquisition.

In athletes, these factors are particularly relevant because chronic sport-specific loading may modify baseline tissue mechanical properties [51].

SWE should therefore be considered a complementary method rather than a replacement for conventional imaging or functional assessment. Its clinical interpretation depends on the specific injury, stage of recovery, and the athlete's functional status, and the significance of an individual SWE value remains limited when considered outside this broader context [11,49].

8.2. Interpretation of Increased and Decreased Tissue Stiffness

A major challenge in SWE interpretation is the absence of a consistent direction of stiffness changes across different tissues and pathological conditions. Both increased and decreased values have been reported. This is particularly evident in tendon pathology, where Achilles tendinopathy has been associated with lower shear-wave velocity in selected regions, whereas patellar tendinopathy may demonstrate increased values compared with healthy controls [33]. Systematic evidence likewise demonstrates substantial variability between studies evaluating pathological tendons [11].

Consequently, increased or decreased stiffness should not be interpreted as a direct marker of disease severity or recovery. In muscle injury, lower values during the acute phase may reflect disruption of normal fiber tension, edema, or structural damage, whereas later increases may be related to tissue remodeling, scar formation, or recovery of load-bearing capacity [9,27,28]. In tendons, interpretation is further influenced by chronic loading, collagen organization, degenerative changes, and measurement location.

For these reasons, SWE findings should be interpreted primarily in relation to the specific tissue, stage of injury, and longitudinal clinical course. Changes over time and their relationship to symptoms and functional recovery appear more informative than the direction of stiffness change alone.

8.3. Methodological Heterogeneity and Cross-Platform Variability

Methodological heterogeneity remains a major barrier to the broader clinical use of SWE in sports medicine. Measurements can be influenced by joint position, muscle activation, transducer pressure and orientation, measurement depth, anatomical location, and region-of-interest placement, all of which may affect the comparability of results between studies [12,13,15,23,26].

Cross-platform variability represents an additional limitation. Studies have demonstrated very good inter-operator agreement while showing significant differences in shear-wave velocity between devices from different manufacturers, and significantly different shear-wave speed values have also been obtained from the same muscle samples using different SWE systems [52,53]. These findings indicate that absolute values obtained on one platform should not be assumed to be directly transferable to another.

This variability is particularly relevant in longitudinal and multicenter studies. Repeated measurements should, whenever possible, be performed using the same device, transducer, anatomical location, limb position, and acquisition settings. In multicenter research, differences between systems may introduce variability unrelated to biological changes in the tissue. Current

reviews therefore continue to emphasize the need for standardized acquisition and reporting protocols to improve comparability across studies and clinical settings [50].

8.4. Lack of Universal Reference Values and Diagnostic Cut-Offs

Despite the quantitative nature of SWE, universal reference ranges for lower-limb muscles and tendons have not been established. This reflects both methodological variability and physiological differences between individuals, including age, sex, training status, recent physical activity, measurement location, and current mechanical loading. In athletes, chronic training adaptations may further shift baseline tissue properties compared with nonathletic populations [13,14,22,51].

The presence of different elastographic patterns across tendon pathologies further limits the usefulness of a single diagnostic threshold. For example, Achilles and patellar tendinopathy may demonstrate opposite directions of change in SWE parameters, while absolute values may also vary between ultrasound systems [33,52,53].

Accordingly, currently available evidence does not support the use of universal SWE cutoff values for diagnosis or return-to-sport qualification. No validated threshold has been established that reliably distinguishes sufficient mechanical recovery from a state associated with increased re-injury risk. At present, longitudinal assessment of the same athlete under standardized conditions appears more informative than comparison with a universal reference value.

8.5. Current Evidence Gaps

Several important evidence gaps continue to limit the clinical interpretation of SWE in sports-related muscle and tendon injuries. Many available studies involve relatively small samples, single-center populations, and a single ultrasound platform, while differences in acquisition protocols, reported parameters, and participant characteristics further reduce comparability across studies [11,50].

The evidence base is also uneven across conditions. Hamstring injuries and Achilles tendon pathology are relatively well represented, whereas data on calf muscle injuries and other lower-limb muscle groups remain limited. In addition, many studies include healthy volunteers, asymptomatic athletes, or patients with chronic tendinopathy rather than prospectively following athletes from acute injury through rehabilitation and return to sport.

Most importantly, the relationship between SWE findings and clinically relevant outcomes remains insufficiently defined. Associations have been reported between changes in tissue stiffness and clinical improvement or recovery of strength, but evidence linking SWE parameters with time to return to sport, re-injury risk, symptom recurrence, or restoration of pre-injury performance is still limited [38,42,49,50].

Current literature therefore demonstrates the sensitivity of SWE to changes in tissue mechanical properties more clearly than its ability to predict long-term clinical outcomes.

Another limitation is the frequent use of the contralateral limb as a reference. Although this approach reduces inter-individual variability, it does not provide a true pre-injury baseline and may be influenced by bilateral training-related adaptations in athletes. Prospective pre-

season or pre-injury measurements would provide a stronger reference for longitudinal assessment, although such study designs are more difficult to implement.

8.6. Future Research Directions

Future research should focus on methodological standardization and longitudinal clinical validation. Protocols should be developed separately for individual muscles and tendons and should clearly define joint position, degree of muscle activation, transducer orientation, measurement site, region-of-interest placement, number of repeated measurements, and preferred SWE reporting parameters. Standardized acquisition and reporting are essential for improving reproducibility and comparability across studies [23,49,50].

Large prospective studies in athletic populations are also needed. Ideally, these should include pre-season or pre-injury measurements, serial post-injury assessments, standardized rehabilitation time points, return-to-sport evaluation, and longer-term follow-up for re-injury and recovery of pre-injury performance. Such designs would allow assessment of whether SWE provides prognostic information beyond conventional imaging and functional testing.

Reference values should be developed for specific muscles and tendons and should account for factors such as age, sex, sport discipline, training status, and recent physical activity. These values should be validated in independent populations and across different ultrasound platforms; if substantial inter-device variability persists, system-specific reference ranges may be necessary.

Future studies should also evaluate SWE within multimodal return-to-sport assessment rather than as an isolated marker. Combining serial SWE measurements with conventional ultrasound, strength testing, functional and sport-specific assessments, and patient-reported outcomes may help determine whether SWE provides clinically meaningful incremental information. The key question is therefore not whether SWE can independently determine readiness to return to sport, but whether it can improve decision-making when integrated with established clinical and functional criteria.

9. Conclusions

Shear-wave elastography is a promising ultrasound technique for the quantitative assessment of mechanical properties of lower-limb muscles and tendons in athletes. Current evidence supports its potential role in the evaluation of muscle injuries, tendinopathy, tendon rupture, and longitudinal monitoring of tissue remodeling during rehabilitation.

The greatest clinical value of SWE appears to lie in serial assessment performed under standardized conditions rather than in the interpretation of isolated absolute values. Measurements are influenced by physiological, technical, and device-dependent factors, and no universal reference ranges or validated cutoff values for diagnosis or return-to-sport decision-making have yet been established.

SWE should therefore be considered a complementary tool alongside clinical examination, functional testing, and conventional imaging rather than a stand-alone diagnostic or return-to-sport criterion. Further prospective studies using standardized protocols and clinically relevant outcome measures are needed to determine whether longitudinal SWE

assessment can provide meaningful additional value in rehabilitation monitoring and return-to-sport decision-making.

Disclosure

Supplementary Materials

None.

Author Contributions

Conceptualization, K.S. and K.O.; methodology, K.S., K.O., and M.K.; investigation, K.S., K.O., M.K., and M.D.; data curation, K.S., K.O., M.K., and M.D.; writing - original draft preparation, K.S., K.O., M.K., and M.D.; writing - review and editing, K.S., K.O., M.K., M.D., and E.M.; visualization, K.S. and M.D.; project administration, K.S. All authors have read and agreed to the published version of the manuscript.

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Declaration of generative AI and AI-assisted technologies in the writing process

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