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Assessing Muscle Shear Modulus With Shear-Wave Elastography During Neuromuscular Fatigue: A Review

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Abstract

This review explores the use of shear wave elastography (SWE) to assess muscle shear modulus during neuromuscular fatigue. Fatigue generally leads to a decrease in muscle stiffness, as measured by SWE, though responses vary across different muscles and fatigue protocols. Quadriceps muscles consistently show decreased stiffness post-fatigue, while hamstrings, plantar flexors, and trunk muscles exhibit more variable responses. These findings suggest that SWE could be a valuable non-invasive tool for monitoring muscle condition and recovery, with potential applications in optimizing training programs and preventing overuse injuries. However, the variability in findings indicates a need for further research to standardize SWE protocols and clarify the mechanisms underlying changes in muscle stiffness during fatigue. Understanding these mechanisms could enhance the application of SWE in both clinical and sports settings. This review also underscores the importance of accounting for fatigue as a confounding factor in studies of muscle stiffness measurements and highlights future research directions to expand the utility of SWE in assessing neuromuscular function.

Keywords: *Muscle Stiffness, Fatigue Assessment, Neuromuscular Fatigue, Shear Wave Elastography, Neuromuscular Function*

INTRODUCTION

Fatigue is characterized by decreased performance, often involving both physical and mental aspects, and is often accompanied by increased actual or perceived difficulty in performing tasks or exercises (Abd-Elfattah et al., 2015). In the context of muscle activity, fatigue is defined as the inability to maintain the required level of force (Edwards, 1981). While it is often associated with a sudden inability to continue the task, several neurophysiological mechanisms are altered beforehand, sometimes serving as early indicators of fatigue. Neuromuscular fatigue refers to any exercise-induced reduction in force or power, regardless of whether the task can still be sustained

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(Bigland‐Ritchie & Woods, 1984). It is a complex, multifactorial phenomenon influenced by task-specific characteristics such as the type and duration of exercise, as well as the speed and duration of muscle contractions. These factors can be modified in research settings to standardize fatigue induction or adjusted in training programs to optimize performance outcomes (Bigland-Ritchie et al., 1986; De Luca, 1984; Fallentin et al., 1993; Hägg, 1992). In electromyography (EMG) signals, fatigue is indicated by an increase in amplitude and a decrease in spectral frequency characteristics (Kallenberg et al., 2007). The changes in the EMG signal reflect compensatory motor-unit recruitment, slowed conduction velocity due to metabolic stress, and altered neural control strategies. These changes help maintain force output for as long as possible but ultimately signal the onset of muscle exhaustion (Bigland-Ritchie et al., 1986; De Luca, 1984; Fallentin et al., 1993; Hägg, 1992).

Muscle fatigue has been identified as a potential factor of muscle stiffness (Descarreaux et al., 2010; Morisada et al., 2006). This is partly due to the development of resting tension when muscles are unable to fully relax during fatigue (Gong et al., 2000, 2003). Since muscle tension is known to increase muscle stiffness (Dresner et al., 2001), it is reasonable to infer that muscle fatigue elevates resting muscle stiffness. However, some studies found a decrease in muscle stiffness after fatigue, which is possibly explained by fatigue-induced changes in muscle fiber recruitment (e.g., increased reliance on less stiff fast-twitch fibers), a possible creep response in tendons leading to shorter muscle length, and a rise in muscle temperature, which can reduce stiffness by causing the unfolding of myosin and collagen (Vatovec et al., 2022).

The stiffness of muscle is influenced by both its cross-sectional area and its material mechanical properties. However, for most research purposes, it is more appropriate to focus on measures of material properties alone, since muscle cross-sectional area tends to remain relatively stable in the short term (Dieterich et al., 2017; Eby et al., 2015). Shear wave elastography (SWE), an ultrasound-based technique, assesses tissue elasticity by analyzing the speed of propagation of shear waves that are remotely induced (Bercoff et al., 2004; Chen et al., 2009; Palmeri et al., 2008). Unlike traditional ultrasound elastography, SWE does not rely on manual compression or tissue displacement (García-Manso et al., 2011), resulting in more reliable data when conducted with an appropriate experimental setup. SWE determines tissue stiffness based on measurements of shear wave propagation velocity (m/s), which is then converted to shear modulus (in kPa). This technique is non-invasive, quantitative, and provides real-time diagnostic imaging, making it particularly suitable for in vivo studies of skeletal muscle. When applied under controlled conditions that ensure reproducibility, SWE has proven to be a reliable method for exploring muscle biomechanical properties (Dubois et al., 2015; Gennisson et al., 2010; Koo et al., 2014; Kot et al., 2012).

Combining SWE with traditional methods, such as evoked torque/force measurements, could be valuable in examining the relationship between the degree of fatigue in each synergist muscle (Akagi et al., 2017). This review aims to summarize the existing research on how the muscle shear modulus, as measured by SWE, changes during periods of neuromuscular fatigue, thereby addressing critical gaps in our understanding of muscle stiffness and its modulation by fatigue. Understanding this relationship is crucial in research settings where fatigue may be one factor influencing stiffness measurements. Moreover, shear-wave elastography could be further investigated as a marker of fatigue.

METHODS

This narrative review followed a systematic approach to gather, assess, and synthesize relevant literature on the assessment of muscle shear modulus using SWE to assess the effects of neuromuscular fatigue. The primary focus was on studies that employed SWE to obtain muscle stiffness in human subjects under conditions of induced neuromuscular fatigue.

Literature Search

A comprehensive literature search was conducted using electronic databases including PubMed, Scopus, and Web of Science. The search strategy was designed to identify studies published up until December 2024. Keywords and search terms included combinations of the following: "muscle stiffness," "shear wave elastography," "muscle shear modulus," "neuromuscular fatigue," and "fatigue protocol." Boolean operators (AND, OR) were used to refine the search.

Inclusion and Exclusion Criteria

Studies were included if they met the following criteria: (1) original research articles published in peer-reviewed journals, (2) studies involving human participants, (3) use of SWE to measure muscle shear modulus, (4) protocols inducing neuromuscular fatigue, and (5) availability of full-text articles in English. Exclusion criteria were: (1) studies involving animals or in vitro models, (2) articles not directly measuring muscle shear modulus or not inducing fatigue, and (3) reviews, meta-analyses, conference abstracts, or case studies. In addition to the criteria listed above, we excluded studies in which fatigue could not be clearly distinguished from exercise-induced muscle damage, such as prolonged running or multi-hour endurance events. These protocols introduce confounding mechanical and inflammatory processes that prevent the isolation of fatigue-specific effects on shear modulus. We also excluded studies that reported elastography outcomes not expressed as shear modulus or shear-wave velocity, and studies in which stiffness was measured only at the tendon without accompanying muscle measurements.

Data Extraction and Synthesis

Data were extracted from each included study regarding study design, sample characteristics, muscles studied, fatigue protocols, and main outcomes related to changes in muscle shear modulus. The studies were then synthesized qualitatively, focusing on the differences and similarities in methodologies, outcomes, and interpretations. Special attention was given to how different fatigue protocols influenced the shear modulus and how these findings varied across different muscle groups. Due to the variability in the study designs, muscles tested, and fatigue protocols, a meta-analysis was not feasible. Instead, a narrative synthesis approach was used to describe trends, highlight consistent findings, and identify areas where results were inconclusive or conflicting. The synthesis aimed to identify gaps in the literature and suggest directions for future research. The included studies varied in the muscle groups assessed, the contraction modes used to induce fatigue, and the specific shear-wave elastography parameters reported; these aspects were documented systematically to ensure that differences in study content were accounted for during the qualitative synthesis.

The included studies were published between 2017 and 2024 (Table 1). All studies used SWE and included a minimum of 9 to a maximum of 54 participants. Seven studies monitored the stiffness of knee extensors muscles (Akagi et al., 2019; Andonian et al., 2016; Chalchat et al., 2020; Chwała & Pogwizd, 2021; Hill et al., 2022; Morel et al., 2019; Siracusa et al., 2019), four studies included knee flexors muscles (Evangelidis et al., 2023; Mendes et al., 2018, 2020; Pimenta et al., 2023), three studies included plantar flexion muscles (Akagi et al., 2017; Chwała & Pogwizd, 2021; Lall et al., 2022) and two studies monitored trunk muscles (Kumamoto et al., 2021; Vatovec et al., 2022). Other muscles and structures included in studies were hip extensors, Achilles tendon, and abductor digiti minimi (Chwała & Pogwizd, 2021; Hill et al., 2022; Morel et al., 2019; Pimenta et al., 2023). The fatigue protocol varied between studies. Most studies involved varying numbers of muscle contractions between 10 and 60 % maximal voluntary contraction (MVC), maximal voluntary isometric contraction (MVIC) or maximal voluntary torque (MVT) and tasks until failure. Other fatigue protocols in the studies included ultra-distance running trail, the Biering - Sorensen test, and drop jumps.

RESULTS

Three studies investigating knee flexor muscle stiffness found that the active stiffness of the semitendinosus (ST) muscle after fatigue was higher than that of the long head of biceps femoris (BFlh) and the other hamstring muscles, or that the stiffness of the BFlh did not change significantly after fatigue (Mendes et al., 2018, 2020; Pimenta et al., 2023). In two studies, the semitendinosus displayed the most pronounced stiffness response to fatigue, showing the highest active stiffness at 20% MVIC compared with the biceps femoris long head and other hamstring muscles (Mendes et al., 2018; Pimenta et al., 2023). A study examining MVT of the knee flexors under different conditions found that the average relative torque maintained during the task was lower at CON than at ISO and ECC, but the absolute torque was similar. On average, the BFlh-SWV tended to increase under ISO conditions, while it decreased under ECC conditions. The ST-SWV decreased in CON, while it remained unchanged in ISO and ECC. SM-SWV decreased in CON but was unchanged in ISO and variable in ECC (Evangelidis et al., 2023). In one study, the focus was on between-participant differences, and it was unclear whether stiffness changed as a consequence of fatigue (Pimenta et al., 2024).

In all studies in which the knee extensor muscles were examined, there was a statistically significant decrease in the shear modulus of the quadriceps muscle after fatigue (Akagi et al., 2019; Andonian et al., 2016; Chalchat et al., 2020; Chwała & Pogwizd, 2021; Hill et al., 2022; Morel et al., 2019; Siracusa et al., 2019). In one study comparing the effects of fatigue on muscle stiffness between men and women, the fatigue-induced decrease in maximum muscle strength was more pronounced in men than in women. Only VL shear modulus increased in men after the fatigue task, and a gender difference was observed in the percentage change in VL shear modulus before and after the fatigue task. The fatigue-induced decrease in evoked torque was greater in males than in females, but not in VA% (Akagi et al., 2019). The opposite was found in a study (Hill et al., 2022) in which fatiguing exercise produced similar reductions in muscle torque, dynamic balance, and VL stiffness at rest in men and women. The use of vibration treatment to enhance muscle relaxation after exercise significantly reduced post-exercise muscle stiffness scores and proved more effective than passive rest. In the DB group, the recovery of muscle stiffness scores from pre-exercise was significantly slower than in the DW group (Chwała & Pogwizd, 2021).

Studies with plantar flexor muscles showed that the percentage change in shear modulus before and after the fatigue task and the alternating muscle activity during the fatigue task were significantly higher in MG than in SOL. The contraction-induced change in shear modulus and the alternating muscle activity of the LG, which showed the lowest muscle activation of all plantar flexors during the fatigue task, did not differ significantly from those of the other muscles (Akagi et al., 2017). The comparison of the MG and LG muscles shows that the resting stiffness of both the MG and LG increased significantly immediately, 24 hours, and 48 hours after muscle fatigue, while during the MVC, the stiffness of the MG decreased, and that of the LG showed no change. When the stiffness of the MG and LG was compared before and after MFP, the changes in MG stiffness were significantly greater than those in LG (Lall et al., 2022). Another study found a decrease in MG stiffness following intermittent submaximal contractions, with the magnitude of the decline correlated with the decline in MVF (Vincent et al., 2024).

Different fatigue effects were found in two studies examining the trunk muscles. MVF decreased after fatigue and passive shear modulus was significantly decreased after fatigue in the MF muscle, but not in the ES muscle. The active shear modulus at low contraction was not affected by fatigue, while it decreased at high contraction in both muscles. The shear modulus of the ES muscle was significantly decreased in men but not in women, while the shear modulus of the superficial MF muscle was statistically significantly decreased in women but not in men (Vatovec et al., 2022). In the second study, combining isometric fatiguing and back extension exercises, the shear modulus of the multifidus muscle was significantly lower after the standing back extension exercise in the fatigue + exercise group compared to the fatigue-only group (Kumamoto et al., 2021).

The authors of a study examining the abductor digiti minimi muscle also concluded that active muscle stiffness decreased following fatiguing exercise with intermittent submaximal isometric contractions (Morel et al., 2019). While hip extension and knee flexion exercises appear to have a different active shear modulus response pattern to a submaximal isometric contraction at 20% of MVIC. The hip extension task produced a similar behaviour across all hamstring muscles, and the knee flexion task resulted in a Δ decrease of the ST, an Δ increase of the BFlh and a similar Δ of the semimembranosus, which showed that the active shear modulus pattern is changed with a submaximal isometric fatigue protocol (Pimenta et al., 2023).

Table 1
Details of Included Studies

Authors/Reference	Participant's characteristics			Muscles included	Fatigue	Fatigues analysis/Tasks performed	Outcome measures	Main findings
	Numerus	**Age in years (mean ± SD)**	**Sex (m/f)**					
Siracusa et al., 2019	n = 15	29.0 ± 2.5	Only males	Knee extensors (VL)	60 repetitions of 5-s MVC	MVC, EMG, Evoked Torque	MVC: -38.4 ± 12,6% VLμ: from 10th MVC -12.4 ± 7.7 to end -34.7 ± 6.7%; p < 0.001 MVC: -38.4 ± 12,6% VLμ: from 10th MVC -12.4 ± 7.7 to end -34.7 ± 6.7%; p < 0.001	Progressive decrease in resting VLμ during fatiguing exercise may contribute to peripheral fatigue by reducing force transmission efficiency.
Chalchat et al., 2020	n = 12	29.0 ± 4.5	Only males	Knee extensors (VL)	6 sets × 10 repetitions of 5-s MVIC	Voluntary and evoked torque, MVC	Voluntary, evoked torque: -37%; P < 0.01 Resting VLμ: -57.9 ± 5.4%; P < 0.001 Resting VLη: +179.0 ± 123%; P < 0.01 Active muscle stiffness index decreased with fatigue (P < 0.05) 20 min post-fatigue: no significant differences from the pre- exercise VLη and active muscle stiffness index, contrary to the resting VLμ.	Fatigue significantly reduces VL muscle stiffness, both at rest and during activity, leading to increased muscle compliance and viscosity. The observed shear wave dispersion highlights the importance of frequency-dependent changes in muscle tissue mechanics.
Andonian et al., 2019	n = 50	43.0 ± 9.1	46/4	Knee extensors (RF, VL, VM, global)	330 km-long ultra-distance running trail	Blood biomarker levels	QMμ decrease (global): finish: 3.31±0.61 kPa, p<0.00; baseline: 3.56±0.63 kPa; +48 h after: 3.45±0.6 kPa, p = 0.002 RFμ decrease: p = 0.003; VMμ: p = 0.033; VR: p = 0.001	SWE effectively tracks changes in muscle stiffness under extreme mechanical stress, providing insights into muscle mechanics. Despite prolonged ECC contractions during an ultra-long race, muscle damage and inflammation remained moderate, aligning with previous findings.

Table 1 (Continued)

Authors/Reference	Participant's characteristics			Muscles included	Fatigue	Fatigues analysis/Tasks performed	Outcome measures	Main findings
	Numerus	Age in years (mean ± SD)	Sex (m/f)					
Akagi et al., 2019	n = 41		18/23	Knee extensors (VL)	Sustained contraction at 20% peak torque during MVIC of KE until the endurance limit	Evoked torque, voluntary activation, MVC	RFμ: −3.4 ± 19.6% (m), −4.6 ± 18.6% (w) VLμ: 21.7 ± 32.4% (m), 0.4 ± 20.4% (w) VMμ: 1.6 ± 16.5% (m), −0.8 ± 14.2% (w) Significant muscle × sex interaction (P = 0.024, ηp2 = 0.092) % change in the VLμ significantly higher than other muscles μ for men (RF vs VL: P < 0.001; RF vs VM: P = 1.000; VL vs VM: P = 0.020), no significant difference in % changes in μ for women (RF vs VL: P = 0.922; RF vs VM: P = 1.000; VL vs VM: P = 1.000) The fatigue-induced decreased ratio was greater for men than for women in evoked torque, but not in VA%	Men experience a greater fatigue-induced decline in maximal muscle strength than women, primarily due to a larger increase in VLμ and greater peripheral fatigue. While both central and peripheral fatigue contributed to strength reduction in both sexes, the observed sex differences were mainly attributed to variations in peripheral fatigue of the VL muscle.
Morel et al., 2019	n = 9	24.0 ± 4.0	Only males	Knee extensors (VL), abductor digiti minimi	15 min intermittent submax, isometric contractions at 60% MVC (4s on, 4s off)	MVC	MVC VL, ADM: -22% ± 7% and -32% ± 15%; P < 0.001 VLμ: -12% ± 15%; P < 0.03 ADMμ: - 44% ± 19%; P < 0.001	Active muscle stiffness decreases following a fatiguing task involving intermittent submaximal ISO contractions, observed in both VL and ADM muscles.

Table 1 (Continued)

Authors/Reference	Participant's characteristics			Muscles included	Fatigue	Fatigues analysis/Tasks performed	Outcome measures	Main findings
	Numerus	Age in years (mean ± SD)	Sex (m/f)					
Hill et al., 2022	n = 16	24.8 ± 5.0	Only males	Knee extensors (VL), plantar flexors (LG), achilles tendon	Five sets of 20-drop jumps	MVC, muscle torque, dynamic balance	Reductions in muscle torque after fatigue: d=0.45–0.80 (m); d = 0.46–0.52 (w) Dynamic balance: d = 0.45–0.74 (m); d = 0.47–0.79 (w) Resting VLμ: d = 0.46 (m); d = 0.36 (w) (all p < 0.05) Quiet standing balance, fatigue induced an increase in postural sway metrics: d = 0.64–1.28 and reduction in resting GLμ: in m: d = 0.40 (both p < 0.001); w: p > 0.05	Similar changes in dynamic stability, muscle torque, and VL stiffness in men and women after repeated maximal effort contractions. However, men exhibited increased postural sway and reduced LG stiffness, unlike women.
Chwala et al., 2021	n = 42	20-24	Only males	Knee and hip extensors and flexor plantaris	20x alternate flexion and extension of lower limbs joints on the leg press at 75% MVC without rest		EG (vibration massage recovery): significantly lower levels of μ after each stage of post-exercise regeneration compared to CG (passive rest) 1. regeneration stage: -16% Δσ_r1-s; p < 0.05 in EG 2. regeneration stage: -14% Δσ_r2-s; p < 0.005 in EG	Vibration treatment significantly enhances post-exercise muscle relaxation, reducing muscle stiffness more effectively than passive rest. Recovery of pre-exercise stiffness was notably slower in the CG.
Pimenta et al., 2023	n = 15	23.3 ± 3.5	Only males	Knee flexors (SM, ST, BFlh, BFsh) and gluteus maximus	Knee flexion, hip extension task until failure	Joint Torque during MVIC	Active μ: task × muscle interaction (p = 0.002; η2p = 0.401); muscle contribution: BFlh-SM: p = 0.006; d = 1.10; BFlh-ST: p = 0.001; d = 1.35; SM-ST: p = 0.020; d = 0.91 Between task comparison: SM: p = 0.025; d = 0.60; ST: p = 0.026; d = 0.60; BFlh: p = 0.062; d = 0.46	Hip extension and knee flexion exercises elicit different active shear modulus response patterns in the hamstring muscles during submaximal isometric contractions.

Table 1 (Continued)

Authors/Reference	Participant's characteristics			Muscles included	Fatigue	Fatigues analysis/Tasks performed	Outcome measures	Main findings
	Numerus	Age in years (mean ± SD)	Sex (m/f)					
Mendes et al., 2018	n = 12	24.5 ± 8.63	9/3	Knee flexors (ST, BFlh)	15-s knee flex. isometric contraction (10, 20, 30, 40, 50 and 60% MVC)	MVIC, EMG	μ at 20% MVIC: STμ (80.6 ± 21.1 kPa), BFμ (63.2 ± 21.6 kPa, *d* = 0.81, p = 0.022), SMμ (54.6 ± 16.7 kPa, *d* = 1.36, *p* = 0.005), BFlhμ (48.5 ± 15.5 kPa, *d* = 1.73, *p* = 0.001) Between limbs comparison: p = 0.12	Ultrasound-based SWE provides reliable and repeatable measurements of hamstring muscle stiffness during submaximal ISO contractions. A high correlation was found between shear modulus and myoelectric activation in the BFlh, but not in the ST, possibly due to methodological factors. The study also highlights a nonlinear response in muscle stiffness, with the BFlh showing higher stiffness during higher contraction intensities, potentially explaining its higher injury rate in activities like sprinting.
Mendes et al., 2020	n = 12	23.3 ± 2.1	Only males	Knee flexors (ST, BFlh)	Submaximal isometric knee flexion at 20% of MVIC until exhaustion	MVIC, knee flexor torque	Time to exhaustion: day 1: 443.8 ± 192.5 s; day 2: 474.6 ± 131.7 s; p = 0.323 Active STμ: 40% of the task time to exhaustion: -2.2 to -13.3%, p = 0.027; end of the task: -16.1 to -22.9%, p = 0.012; (BFlh: p = 0.77); immediately after: − 11.8 to − 17.8%, p < 0.001; (BFlhμ: p = 0.551)	Sustained knee flexor ISO contraction at 20% of MVIC alters the hamstring muscles' active stiffness pattern, with consistent inter-individual responses across sessions. ST stiffness decreased midway through the fatigue task, while BFlh remained unchanged.

Table 1 (Continued)

Authors/Reference	Participant's characteristics			Muscles included	Fatigue	Fatigues analysis/Tasks performed	Outcome measures	Main findings
	Numerus	Age in years (mean ± SD)	Sex (m/f)					
Evangedelis et al., 2023	n = 9	21.8 ± 4.2	Only males	Knee flexors (ST, SM, BFlh)	99 contractions of 5 s at 50% MVT	MVT, SWV, MRI - T2	MVT: − 18.4 to − 33.6%, all conditions Average relative torque sustained during the task: lower in CON than ISO and ECC, absolute torque was similar BFlh SWV: ISO: +0.4 m/s, 4.5%, p = 0.064; ECC: -0.8 m/s, -7.7%, p < 0.01 ST SWV: CON: -1.1 m/s, − 9.0%, p < 0.01, unchanged in ISO and ECC SM SWV: CON: -0.8 m/s, -8.1%, p < 0.01, unchanged in ISO, variable in ECC	ECC fatigue primarily affects BFlh, potentially explaining its high strain injury risk, while BFlh remains the least fatigued during ISO tasks. CON knee flexions induce the most significant mechanical and metabolic changes, mainly impacting ST and SM.
Akagi et al., 2017	n = 19	22.0 ± 1.0	Only males	Plantar flexors (MG, LG, SOL)	1-h sustained contraction at 10% peak torque during MVIC plantar flexion	MVC, EMG, Evoked Torque	% change in μ before/after fatigue: MG: 16.7 ± 12.0%, SOL: −4.1 ± 13.9% Alternate muscle activity during fatigue task (MG: 33 [20–51] times, SOL: 30 [17–36] times) were significantly higher in MG than in SOL. The contraction-induced change in μ (7.4 ± 20.3%) and the alternate muscle activity (37 [20–45] times) of LG with the lowest magnitude of muscle activation during the fatiguing task among the plantar flexors were not significantly different from those of the other muscles	Increase in muscle shear modulus during prolonged contraction corresponds to the frequency of alternate muscle activity, particularly in the later stages of fatigue. The findings indicate that MG exhibits more frequent alternate activity than SOL due to its greater fatigue progression.

Table 1 (Continued)

Authors/Reference	Participant's characteristics			Muscles included	Fatigue	Fatigues analysis/Tasks performed	Outcome measures	Main findings
	Numerus	Age in years (mean ± SD)	Sex (m/f)					
Lall et al., 2022	n = 35		20/15	Plantar flexors (MG, LG)	3 sets of 50 eccentric contractions of the calf muscles (dominant leg)	MVC	Resting MGμ, LGμ increased: immediately, 24 h, 48 h after fatigue ($p < 0.05$) MGμ during MVC decreased ($p < 0.05$); LGμ no change ($p > 0.05$) Comparison MGμ and LGμ before/after MFP: greater changes in MG ($p < 0.05$).	MG stiffness decreased after eccentric exercise, while LG stiffness showed no change. Resting stiffness increased immediately, 24 h, and 48 h after exercise, and active stiffness during maximal voluntary contraction decreased only in the MG.
Kumamoto et al., 2021	n = 33	23.5 ± 6.6	Only males	Trunk muscles (multifidus)	Biering-Sorensen test - 60-s, followed by 5 sets of extension exercise		Extension exercise caused reductions in μ after prior fatigue; however, the effect of fatigue alone cannot be discerned from the available data. Between-group differences before exercise suggest that fatigue increased μ.	Performing repeated SBEE exercises can improve the elastic modulus of fatigued multifidus muscles, potentially helping to prevent fatigue-related LBP.
Vatovec et al., 2022	n = 22	20-40	11/11	Trunk muscles (Erector spinae, superficial, deep multifidus)	2x6 min + 1x3 min intermittent submax. trunk extensions	MVF	MVF: -8.64%; $p = 0.003$ Passive MFμ: $p = 0.006–0.022$; $d = 0.40–46$; ESμ: $p = 0.867$ Active μ low-level contr.: $p = 0.697–0.701$; high-level: $p = 0.011$; $d = 0.29–0.34$	ISO fatigue can reduce both passive and active shear moduli in trunk extensor muscles. While the underlying mechanisms remain unclear, fatigue should be accounted for as a confounding factor in muscle stiffness research. Additionally, observed sex-specific responses highlight the importance of considering sex differences in future studies.

Table 1 (Continued)

Authors/Reference	Participant's characteristics			Muscles included	Fatigue	Fatigues analysis/Tasks performed	Outcome measures	Main findings
	Numerus	Age in years (mean ± SD)	Sex (m/f)					
Pimenta et al., 2024	n = 54	23.5 ± 3.6		Knee flexors (ST, SM, BFlh, BFsh)	10 × 30 m repeated sprint protocol		No significant differences were observed in active hamstring shear modulus changes between competitive levels and positions among soccer players, with unclear main time effect.	It was not possible to distinguish football players from different competitive levels and positions when analysing the sprint performance, hamstring shear modulus and peak torque after a repeated sprint task. However, there was a lack of main effect of fatigue in this study.
Vincent et al., 2024	n = 12	27.3 ± 5.5		Plantar flexors (MG)	60 isometric contractions 4-s with a 1-s rest interval)		A decline was observed in active stiffness and peak torque. Furthermore, significant correlation was identified between the decrease of the peak torque of PF and the active stiffness of the GM ($r = 0.6$; $p < 0.05$).	Isometric fatiguing exercises modify the mechanical properties of both the contractile and elastic components. The decline in stiffness was positively correlated with decline in peak torque, supporting the utility of SWE in fatigue assessment.

Note. VL = vastus lateralis, MVC = maximal voluntary contraction, EMG = electromyography, MVF = maximal voluntary force , RF = rectus femoris, VM = vastus medialis, μ = shear wave modulus, SM = semimembranosus, ST = semitendinosus, BFlh = biceps femoris long head, BFsh = biceps femoris short head, MVIC = *maximal voluntary isometric contraction*, F-Ex = fatigue-exercise, F-nEx = fatigue-non-exercise, nF-Ex = non-fatigue-exercise, MG = medial gastrocnemius, LG = lateral gastrocnemius, SOL = soleus, KE = knee extensors, VA = voluntary activation, MVT = maximal voluntary torque, SWV = shear wave velocity, MRI - T2 = magnetic resonance imaging T2 sequence, CON = concentric, ECC = eccentric, ISO = isometric, w = women, m = men, EG = experimental group, CG = control group, ADM = abductor digiti minimi, SBEE = Standing back extension exercise, LBP = low back pain.

DISCUSSIONS

This review aimed to summarize the current research on assessing muscle shear modulus using SWE during neuromuscular fatigue. The main findings indicate that muscle stiffness, as measured by shear modulus, generally decreases following fatiguing tasks, with notable variations across muscle groups and fatigue protocols. While quadriceps muscles consistently exhibited a decrease in stiffness post-fatigue, the responses in hamstring, plantar flexor, and trunk muscles were more heterogeneous. Given these findings across different muscle groups and protocols, further research is needed to clarify the conditions under which SWE can reliably serve as a non-invasive marker for monitoring muscle condition during and after fatiguing exercise.

The underlying mechanisms responsible for changes in muscle shear modulus during fatigue are complex and not fully understood. One possible explanation involves the redistribution of load between synergistic muscles during fatiguing contractions, as seen in lower limb muscles, which might reduce the shear modulus in some muscles while leaving others unaffected or even increasing their stiffness (Mendes et al., 2020; Morel et al., 2019). Additionally, the fatigue-induced decrease in shear modulus could be attributed to tendon creep, resulting in a shorter muscle length and a consequent decrease in shear modulus (Koo & Hug, 2015; Pearson et al., 2007). However, given the relatively short tendons in some muscles, such as the multifidus and erector spinae, this mechanism may not fully account for the observed changes.

Moreover, muscle fiber type composition could play a significant role, as slow-twitch fibers are typically stiffer than fast-twitch fibers (Goubel & Marini, 1987; Kovanen et al., 1984). Fatigue could lead to a greater recruitment of fast-twitch fibers as slow-twitch fibers become fatigued, but this would only reduce the active shear modulus during contraction, while it does not explain why the passive shear modulus also decreases. Additionally, it is important to note that muscle fiber stiffness can change independently of muscle tension (Bernabei et al., 2020), suggesting other factors, such as muscle temperature, could contribute to the observed reductions in stiffness. For instance, an increase in muscle temperature due to prolonged contractions may cause unfolding of myosin and collagen, leading to a decrease in both passive and active shear modulus (Nocella et al., 2013; Tornberg, 2005). However, given the relatively modest temperature changes likely to occur in vivo, temperature changes alone may not fully explain the decrease in shear modulus observed in fatigued muscles. Finally, Ca2+ depletion during fatigue could reduce the number of attached cross-bridges, thereby decreasing the noncontractile stiffness contributed by titin and other passive structures within the sarcomere (Colombini et al., 2016; Nocella et al., 2012).

While the majority of studies suggest that shear modulus, obtained by SWE, tends to decrease following fatiguing tasks, some evidence points towards situations where muscle stiffness might increase instead. This counterintuitive response could be associated with the onset of muscle damage, which often occurs alongside or as a result of fatigue. When muscles undergo intense or unaccustomed exercise, especially eccentric contractions, they can sustain microtrauma that leads to increased passive stiffness (Ličen & Kozinc, 2022). The damage-induced increase in stiffness is primarily attributed to inflammatory processes and to the disruption of structural proteins such as titin and desmin, which contribute to the muscle's passive elastic properties (Lieber & Fridén, 1993; Proske & Morgan, 2001). Muscle damage may lead to cytoplasmic calcium accumulation, which can enhance titin binding to actin filaments, thereby increasing muscle stiffness (Labeit et al., 2003). Additionally, edema resulting from muscle damage can contribute to increased stiffness by expanding the muscle tissue and increasing intramuscular pressure (Chleboun et al., 1998). This dual effect of fatigue and damage might explain the variability in shear modulus changes across different muscles and fatigue protocols, with some studies reporting increases in stiffness under specific conditions, such as following high-intensity eccentric exercise or during the early recovery phase, when muscle damage is predominant.

Another explanation for the heterogeneous findings is that SWE reflects local muscle properties rather than the stiffness of the whole muscle or muscle-tendon unit. Region-specific responses may have occurred and could be undetected with a single-point measurement. Many studies have demonstrated muscle-specific and even muscle-region-specific differences in shear modulus in response to muscle-damaging exercise protocols (Lacourpaille et al., 2014, 2017). Additionally, SWE has been shown to be more sensitive to detecting muscle damage when muscles are assessed in a lengthened position (Goreau et al., 2022; Lacourpaille et al., 2017; Xu et al., 2019), likely due to the increased mechanical strain on passive structures such as titin and collagen fibers. It could be that the effect of fatigue on muscle stiffness varies by muscle region, as some areas may experience greater mechanical strain, metabolic stress, or preferential recruitment of specific fiber types. Furthermore, variations in the ultrasound probe's position, even within the same muscle, could contribute to discrepancies in stiffness measurements (Pałac & Linek, 2022). These factors suggest that future research should consider multi-site SWE assessments and standardized measurement locations to enhance the reliability of fatigue-induced stiffness changes.

Limitations

Several limitations should be acknowledged when interpreting the findings of this review. First, the available studies show substantial heterogeneity in fatigue protocols, including differences in contraction mode, intensity, task duration, and criteria for task failure. This variability limits the comparability of results across studies and may partly explain the inconsistent stiffness responses observed in certain muscle groups. Second, the evidence base is unevenly distributed, with the quadriceps and hamstring muscles examined more frequently than the plantar flexors or trunk muscles, which restricts the generalizability of conclusions across the entire musculoskeletal system. Third, most studies assessed stiffness at a single anatomical location per muscle, despite known regional variations in shear modulus, which may obscure localized fatigue responses. Fourth, because SWE measurements are influenced by joint position, probe orientation, and muscle activation level, minor methodological discrepancies across studies may have contributed to variability in reported stiffness changes. Finally, the cross-sectional nature of most existing studies precludes strong inferences about causal mechanisms underlying fatigue-related stiffness changes.

CONCLUSION

In conclusion, SWE shows promise as a non-invasive method for monitoring muscle stiffness and neuromuscular fatigue, with potential applications in optimizing training programs and preventing injuries. By assessing muscle readiness and recovery, SWE could inform decisions about training load and rehabilitation timing. However, the variability in responses across different muscles and fatigue protocols highlights the need for further research. Future studies should focus on standardizing SWE protocols, exploring the mechanisms underlying changes in muscle stiffness, and investigating sex-specific responses. This research will enhance the utility of SWE in both clinical and athletic settings.

PRACTICAL IMPLICATIONS

The findings of this review suggest several practical applications of SWE in both sports and clinical settings. First, SWE could serve as a supplementary tool for monitoring neuromuscular fatigue in athletes, providing objective, real-time information about muscle mechanical state that complements traditional performance measures such as force output or perceived exertion. Given that quadriceps stiffness consistently decreases following fatiguing tasks, serial SWE measurements of the vastus lateralis or rectus femoris could help practitioners track accumulated fatigue during training blocks or tournament schedules, and inform decisions about training load adjustments or recovery interventions. Second, SWE may support return-to-sport and rehabilitation decisions by offering a non-invasive means of assessing whether muscle mechanical properties have returned to baseline following intense exercise. This could be particularly relevant in injury-prone muscle groups such as the hamstrings, where fatigue-induced changes in the relative stiffness of individual synergists may have implications for strain injury risk. Finally, researchers should account for fatigue as a potential confounding factor when using SWE to assess baseline muscle stiffness, as even moderate prior physical activity may meaningfully alter shear modulus values. Standardizing measurement conditions — including time since last exercise, joint position, and probe placement — will be essential for ensuring the reproducibility and interpretability of SWE data across studies and clinical assessments.

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Authors' Contribution

Both authors conceptualized the idea and performed the literature review and extracted the data from the included studies. First author wrote the first draft of the manuscript. Both authors worked on finalizing the manuscript.

Declaration of Conflict Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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REFERENCES

Abd-Elfattah, H. M., Abdelazeim, F. H., & Elshennawy, S. (2015). Physical and cognitive consequences of fatigue: A review. *Journal of Advanced Research, 6*(3), 351–358. https://doi.org/10.1016/j.jare.2015.01.011

Akagi, R., Fukui, T., Kubota, M., Nakamura, M., & Ema, R. (2017). Muscle Shear Moduli Changes and Frequency of Alternate Muscle Activity of Plantar Flexor Synergists Induced by Prolonged Low-Level Contraction. *Frontiers in Physiology, 8,* 708. https://doi.org/10.3389/fphys.2017.00708

Akagi, R., Sato, S., Yoshihara, K., Ishimatsu, H., & Ema, R. (2019). Sex difference in fatigability of knee extensor muscles during sustained low-level contractions. *Scientific Reports, 9*(1), 16718. https://doi.org/10.1038/s41598-019-53375-z

Andonian, P., Viallon, M., Le Goff, C., de Bourguignon, C., Tourel, C., Morel, J., Giardini, G., Gergelé, L., Millet, G. P., & Croisille, P. (2016). Shear-Wave Elastography Assessments of Quadriceps Stiffness Changes prior to, during and after Prolonged Exercise: A Longitudinal Study during an Extreme Mountain Ultra-Marathon. *PloS One, 11*(8), e0161855. https://doi.org/10.1371/journal.pone.0161855

Bercoff, J., Tanter, M., & Fink, M. (2004). Supersonic shear imaging: a new technique for soft tissue elasticity mapping. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 51*(4), 396–409. https://doi.org/10.1109/tuffc.2004.1295425

Bernabei, M., Lee, S. S. M., Perreault, E. J., & Sandercock, T. G. (2020). Shear wave velocity is sensitive to changes in muscle stiffness that occur independently from changes in force. *Journal of Applied Physiology (Bethesda, Md. : 1985), 128*(1), 8–16. https://doi.org/10.1152/japplphysiol.00112.2019

Bigland-Ritchie, B., Furbush, F., & Woods, J. J. (1986). Fatigue of intermittent submaximal voluntary contractions: central and peripheral factors. *Journal of Applied Physiology, 61*(2), 421–429. https://doi.org/10.1152/jappl.1986.61.2.421

Bigland‐Ritchie, B., & Woods, J. J. (1984). Changes in muscle contractile properties and neural control during human muscular fatigue. *Muscle & Nerve, 7*(9), 691‐699. https://doi.org/10.1002/mus.880070902

Chalchat, E., Gennisson, J.-L., Peñailillo, L., Oger, M., Malgoyre, A., Charlot, K., Bourrilhon, C., Siracusa, J., & Garcia-Vicencio, S. (2020). Changes in the Viscoelastic Properties of the Vastus Lateralis Muscle With Fatigue. *Frontiers in Physiology, 11*, 307. https://doi.org/10.3389/fphys.2020.00307

Chen, S., Urban, M. W., Pislaru, C., Kinnick, R., Zheng, Y., Yao, A., & Greenleaf, J. F. (2009). Shearwave dispersion ultrasound vibrometry (SDUV) for measuring tissue elasticity and viscosity. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 56*(1), 55–62. https://doi.org/10.1109/TUFFC.2009.1005

Chleboun, G. S., Howell, J. N., Conatser, R. R., & Giesey, J. J. (1998). Relationship between muscle swelling and stiffness after eccentric exercise. *Medicine and Science in Sports and Exercise, 30*(4), 529–535. https://doi.org/10.1097/00005768-199804000-00010

Chwała, W., & Pogwizd, P. (2021). Effects of vibration and passive resting on muscle stiffness and restitution after submaximal exercise analyzed by elastography. *Acta of Bioengineering and Biomechanics, 23*(2), 3–11. https://doi.org/10.37190/ABB-01778-2020-02

Colombini, B., Nocella, M., & Bagni, M. A. (2016). Non-crossbridge stiffness in active muscle fibres. *The Journal of Experimental Biology, 219(Pt 2)*, 153–160. https://doi.org/10.1242/jeb.124370

De Luca, C. J. (1984). Myoelectrical manifestations of localized muscular fatigue in humans. *Critical Reviews in Biomedical Engineering, 11*(4), 251–279. Retrieved from: https://pubmed.ncbi.nlm.nih.gov/6391814/

Descarreaux, M., Lafond, D., & Cantin, V. (2010). Changes in the flexion-relaxation response induced by hip extensor and erector spinae muscle fatigue. *BMC Musculoskeletal Disorders, 11*, 112. https://doi.org/10.1186/1471-2474-11-112

Dieterich, A. V, Andrade, R. J., Le Sant, G., Falla, D., Petzke, F., Hug, F., & Nordez, A. (2017). Shear wave elastography reveals different degrees of passive and active stiffness of the neck extensor muscles. *European Journal of Applied Physiology, 117*(1), 171–178. https://doi.org/10.1007/s00421-016-3509-5

Dresner, M. A., Rose, G. H., Rossman, P. J., Muthupillai, R., Manduca, A., & Ehman, R. L. (2001). Magnetic resonance elastography of skeletal muscle. *Journal of Magnetic Resonance Imaging : JMRI, 13*(2), 269–276. https://doi.org/10.1002/1522-2586(200102)13:2<269::aid-jmri1039>3.0.co;2-1

Dubois, G., Kheireddine, W., Vergari, C., Bonneau, D., Thoreux, P., Rouch, P., Tanter, M., Gennisson, J.-L., & Skalli, W. (2015). Reliable protocol for shear wave elastography of lower limb muscles at rest and during passive stretching. *Ultrasound in Medicine & Biology, 41*(9), 2284–2291. https://doi.org/10.1016/j.ultrasmedbio.2015.04.020

Eby, S. F., Cloud, B. A., Brandenburg, J. E., Giambini, H., Song, P., Chen, S., LeBrasseur, N. K., & An, K.-N. (2015). Shear wave elastography of passive skeletal muscle stiffness: influences of sex and age throughout adulthood. *Clinical Biomechanics (Bristol, Avon), 30*(1), 22–27. https://doi.org/10.1016/j.clinbiomech.2014.11.011

Edwards, R. H. (1981). Human muscle function and fatigue. *Ciba Foundation Symposium, 82*, 1–18. https://doi.org/10.1002/9780470715420.ch1

Evangelidis, P. E., Shan, X., Otsuka, S., Yang, C., Yamagishi, T., & Kawakami, Y. (2023). Fatigue-induced changes in hamstrings' active muscle stiffness: effect of contraction type and implications for strain injuries. *European Journal of Applied Physiology, 123*(4), 833–846. https://doi.org/10.1007/s00421-022-05104-0

Fallentin, N., Jorgensen, K., & Simonsen, E. B. (1993). Motor unit recruitment during prolonged isometric contractions. *European Journal of Applied Physiology and Occupational Physiology, 67*(4), 335–341. https://doi.org/10.1007/BF00357632

Friedman, J. H., Brown, R. G., Comella, C., Garber, C. E., Krupp, L. B., Lou, J.-S., Marsh, L., Nail, L., Shulman, L., Taylor, C. B., & Working Group on Fatigue in Parkinson's Disease. (2007). Fatigue in Parkinson's disease: a review. *Movement Disorders : Official Journal of the Movement Disorder Society, 22*(3), 297–308. https://doi.org/10.1002/mds.21240

García-Manso, J. M., Rodríguez-Ruiz, D., Rodríguez-Matoso, D., de Saa, Y., Sarmiento, S., & Quiroga, M. (2011). Assessment of muscle fatigue after an ultra-endurance triathlon using tensiomyography (TMG). *Journal of Sports Sciences, 29*(6), 619–625. https://doi.org/10.1080/02640414.2010.548822

Gennisson, J.-L., Deffieux, T., Macé, E., Montaldo, G., Fink, M., & Tanter, M. (2010). Viscoelastic and anisotropic mechanical properties of in vivo muscle tissue assessed by supersonic shear imaging. *Ultrasound in Medicine & Biology, 36*(5), 789–801. https://doi.org/10.1016/j.ultrasmedbio.2010.02.013

Gong, B., Legault, D., Miki, T., Seino, S., & Renaud, J. M. (2003). KATP channels depress force by reducing action potential amplitude in mouse EDL and soleus muscle. American Journal of Physiology. *Cell Physiology, 285*(6), C1464-74. https://doi.org/10.1152/ajpcell.00278.2003

Gong, B., Miki, T., Seino, S., & Renaud, J. M. (2000). A K(ATP) channel deficiency affects resting tension, not contractile force, during fatigue in skeletal muscle. American Journal of Physiology. *Cell Physiology, 279*(5), C1351-8. https://doi.org/10.1152/ajpcell.2000.279.5.C1351

Goreau, V., Pigne, R., Bernier, N., Nordez, A., Hug, F., & Lacourpaille, L. (2022). Hamstring muscle activation strategies during eccentric contractions are related to the distribution of muscle damage. *Scandinavian Journal of Medicine & Science in Sports, 32*(9), 1335–1345. https://doi.org/10.1111/sms.14191

Goubel, F., & Marini, J. F. (1987). Fibre type transition and stiffness modification of soleus muscle of trained rats. *Pflugers Archiv : European Journal of Physiology, 410*(3), 321–325. https://doi.org/10.1007/BF00580283

Hägg, G. M. (1992). Interpretation of EMG spectral alterations and alteration indexes at sustained contraction. *Journal of Applied Physiology (Bethesda, Md. : 1985), 73*(4), 1211–1217. https://doi.org/10.1152/jappl.1992.73.4.1211

Hill, M., Rosicka, K., & Wdowski, M. (2022). Effect of sex and fatigue on quiet standing and dynamic balance and lower extremity muscle stiffness. *European Journal of Applied Physiology, 122*(1), 233–244. https://doi.org/10.1007/s00421-021-04831-0

Kallenberg, L. A. C., Schulte, E., Disselhorst-Klug, C., & Hermens, H. J. (2007). Myoelectric manifestations of fatigue at low contraction levels in subjects with and without chronic pain. *Journal of Electromyography and Kinesiology, 17*(3), 264–274. https://doi.org/10.1016/j.jelekin.2006.04.004

Koo, T. K., Guo, J.-Y., Cohen, J. H., & Parker, K. J. (2014). Quantifying the passive stretching response of human tibialis anterior muscle using shear wave elastography. *Clinical Biomechanics (Bristol, Avon), 29*(1), 33–39. https://doi.org/10.1016/j.clinbiomech.2013.11.009

Koo, T. K., & Hug, F. (2015). Factors that influence muscle shear modulus during passive stretch. *Journal of Biomechanics, 48*(12), 3539–3542. https://doi.org/10.1016/j.jbiomech.2015.05.038

Kot, B. C. W., Zhang, Z. J., Lee, A. W. C., Leung, V. Y. F., & Fu, S. N. (2012). Elastic modulus of muscle and tendon with shear wave ultrasound elastography: variations with different technical settings. *PloS One, 7*(8), e44348. https://doi.org/10.1371/journal.pone.0044348

Kovanen, V., Suominen, H., & Heikkinen, E. (1984). Mechanical properties of fast and slow skeletal muscle with special reference to collagen and endurance training. *Journal of Biomechanics, 17*(10), 725–735. https://doi.org/10.1016/0021-9290(84)90103-9

Kumamoto, T., Seko, T., Matsuda, R., & Miura, S. (2021). Repeated standing back extension exercise: Influence on muscle shear modulus change after lumbodorsal muscle fatigue. *Work (Reading, Mass.), 68*(4), 1229–1237. https://doi.org/10.3233/WOR-213452

Labeit, D., Watanabe, K., Witt, C., Fujita, H., Wu, Y., Lahmers, S., Funck, T., Labeit, S., & Granzier, H. (2003). Calcium-dependent molecular spring elements in the giant protein titin. *Proceedings of the National Academy of Sciences of the United States of America, 100*(23), 13716–13721. https://doi.org/10.1073/pnas.2235652100

Lacourpaille, L., Nordez, A., Hug, F., Couturier, A., Dibie, C., & Guilhem, G. (2014). Time‐course effect of exercise‐induced muscle damage on localized muscle mechanical properties assessed using elastography. *Acta Physiologica, 211*(1), 135‐146. https://doi.org/10.1111/apha.12272

Lacourpaille, L., Nordez, A., Hug, F., Doguet, V., Andrade, R., & Guilhem, G. (2017). Early detection of exercise-induced muscle damage using elastography. *European Journal of Applied Physiology, 117*(10), 2047–2056. https://doi.org/10.1007/s00421-017-3695-9

Lall, P. S., Alsubiheen, A. M., Aldaihan, M. M., & Lee, H. (2022). Differences in Medial and Lateral Gastrocnemius Stiffness after Exercise-Induced Muscle Fatigue. *International Journal of Environmental Research and Public Health, 19*(21). https://doi.org/10.3390/ijerph192113891

Ličen, U., & Kozinc, Ž. (2022). Using Shear-Wave Elastography to Assess Exercise-Induced Muscle Damage: A Review. *Sensors (Basel, Switzerland), 22*(19). https://doi.org/10.3390/s22197574

Lieber, R. L., & Fridén, J. (1993). Muscle damage is not a function of muscle force but active muscle strain. *Journal of Applied Physiology (Bethesda, Md. : 1985), 74*(2), 520–526. https://doi.org/10.1152/jappl.1993.74.2.520

Lorist, M. M., Kernell, D., Meijman, T. F., & Zijdewind, I. (2002). Motor fatigue and cognitive task performance in humans. *The Journal of Physiology, 545*(1), 313–319. https://doi.org/10.1113/jphysiol.2002.027938

Mendes, B., Firmino, T., Oliveira, R., Neto, T., Cruz-Montecinos, C., Cerda, M., Correia, J. P., Vaz, J. R., & Freitas, S. R. (2020). Effects of knee flexor submaximal isometric contraction until exhaustion on semitendinosus and biceps femoris long head shear modulus in healthy individuals. *Scientific Reports, 10*(1), 16433. https://doi.org/10.1038/s41598-020-73433-1

Mendes, B., Firmino, T., Oliveira, R., Neto, T., Infante, J., Vaz, J. R., & Freitas, S. R. (2018). Hamstring stiffness pattern during contraction in healthy individuals: analysis by ultrasound-based shear wave elastography. *European Journal of Applied Physiology, 118*(11), 2403–2415. https://doi.org/10.1007/s00421-018-3967-z

Morel, B., Hug, F., Nordez, A., Pournot, H., Besson, T., Mathevon, L., & Lapole, T. (2019). Reduced Active Muscle Stiffness after Intermittent Submaximal Isometric Contractions. *Medicine and Science in Sports and Exercise, 51*(12), 2603–2609. https://doi.org/10.1249/MSS.0000000000002080

Morisada, M., Okada, K., & Kawakita, K. (2006). Quantitative analysis of muscle hardness in tetanic contractions induced by electrical stimulation in rats. *European Journal of Applied Physiology, 97*(6), 681–686. https://doi.org/10.1007/s00421-006-0225-6

Nocella, M., Cecchi, G., Bagni, M. A., & Colombini, B. (2013). Effect of temperature on crossbridge force changes during fatigue and recovery in intact mouse muscle fibers. *PloS One, 8*(10), e78918. https://doi.org/10.1371/journal.pone.0078918

Nocella, M., Colombini, B., Bagni, M. A., Bruton, J., & Cecchi, G. (2012). Non-crossbridge calcium-dependent stiffness in slow and fast skeletal fibres from mouse muscle. *Journal of Muscle Research and Cell Motility, 32*(6), 403–409. https://doi.org/10.1007/s10974-011-9274-5

Pałac, M., & Linek, P. (2022). Intra-Rater Reliability of Shear Wave Elastography for the Quantification of Respiratory Muscles in Adolescent Athletes. *Sensors, 22*(17), 6622. https://doi.org/10.3390/s22176622

Palmeri, M. L., Wang, M. H., Dahl, J. J., Frinkley, K. D., & Nightingale, K. R. (2008). Quantifying hepatic shear modulus in vivo using acoustic radiation force. *Ultrasound in Medicine & Biology, 34*(4), 546–558. https://doi.org/10.1016/j.ultrasmedbio.2007.10.009

Pearson, S. J., Burgess, K., & Onambele, G. N. L. (2007). Creep and the in vivo assessment of human patellar tendon mechanical properties. *Clinical Biomechanics (Bristol, Avon), 22*(6), 712–717. https://doi.org/10.1016/j.clinbiomech.2007.02.006

Pimenta, R., Almeida, P., Correia, J. P., Bruno, P. M., & Vaz, J. R. (2023). Effects of fatigue on hamstrings and gluteus maximus shear modulus in hip extension and knee flexion submaximal contraction task. *Sports Biomechanics*, 1–14. https://doi.org/10.1080/14763141.2023.2195827

Pimenta, R., Antunes, H., Bruno, P., & Veloso, A. P. (2024). Hamstrings mechanical properties profiling in football players of different competitive levels and positions after a repeated sprint protocol. *Frontiers in Physiology, 14*, 1315564 https://doi.org/10.3389/fphys.2023.1315564

Proske, U., & Morgan, D. L. (2001). Muscle damage from eccentric exercise: mechanism, mechanical signs, adaptation and clinical applications. *The Journal of Physiology, 537*(Pt 2), 333–345. https://doi.org/10.1111/j.1469-7793.2001.00333.x

Siracusa, J., Charlot, K., Malgoyre, A., Conort, S., Tardo-Dino, P.-E., Bourrilhon, C., & Garcia-Vicencio, S. (2019). Resting Muscle Shear Modulus Measured With Ultrasound Shear-Wave Elastography as an Alternative Tool to Assess Muscle Fatigue in Humans. *Frontiers in Physiology, 10*, 626. https://doi.org/10.3389/fphys.2019.00626

Tornberg, E. (2005). Effects of heat on meat proteins - Implications on structure and quality of meat products. *Meat Science, 70*(3), 493–508. https://doi.org/10.1016/j.meatsci.2004.11.021

Vatovec, R., Kozinc, Ž., & Voglar, M. (2022). The Effects of Isometric Fatigue on Trunk Muscle Stiffness: Implications for Shear-Wave Elastography Measurements. *Sensors (Basel, Switzerland), 22*(23). https://doi.org/10.3390/s22239476

Vincent, L., Zidi, M., Portero, P., Belghith, K., Serhal, R. B., Guihard, M., & Maktouf, W. (2024). Quantifying Active and Passive Stiffness in Plantar Flexor Muscles Following Intermittent Maximal Isometric Contractions Using Shear Wave Elastography. *Ultrasound in Medicine & Biology, 50*(12), 1987–1994. https://doi.org/10.1016/j.ultrasmedbio.2024.09.004

Xu, J., Fu, S. N., Zhou, D., Huang, C., & Hug, F. (2019). Relationship between pre‐exercise muscle stiffness and muscle damage induced by eccentric exercise. *European Journal of Sport Science, 19*(4), 508‐516. https://doi.org/10.1080/17461391.2018.1535625