We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,300

Open access books available

172,000

International authors and editors

190M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities

WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com

Shear Wave Elastography for Chronic Musculoskeletal Problem

Tomonori Kawai

Abstract

Shear wave elastography is a new noninvasive tool for the analysis of the biomechanical properties of the muscles in healthy and pathological conditions. Shear wave elastography is currently considered as a promising real-time visualization tool for quantifying explicitly the mechanical properties of soft tissues in sports medicine including muscle strain injury (MSI). This chapter shows utilizing diagnostic tools of magnetic resonance imaging, B mode ultrasound (US), and shear wave elastography in both acute and chronic phases. Also, the proposal for this chapter is to indicate the possibility of utilizing shear wave elastography for musculoskeletal injury, not only properties of the muscle but also fascial tissues. It introduces the relationship between previous muscle strain injury and local soft tissue stiffness, and we assessed the mechanical properties of soft tissues from a clinical perspective.

Keywords: shear wave elastography, muscle strain, connective tissue, fascia, chronic injury

1. Introduction

In the sports medicine field, in order to evaluate musculoskeletal conditions such as muscle strain injury (MSI), magnetic resonance imaging (MRI) is commonly used in the diagnosis and prognosis of MSI. MRI uses the power of a magnetic field to determine the amount of water present in cells and tissues in the body.

The basic mechanism of MRI is that water has two hydrogen atoms, which are composed of a central proton and surrounding electrons. When a high-frequency current is pulsed to an object, the protons are stimulated and become imbalanced by acting against the gravitational pull of the magnetic field. When the radiofrequency field is turned off, the MRI sensors can detect the energy emitted when the protons rearrange to the magnetic field.

The time it takes for the protons to realign to a magnetic field depends on the environment and nature of the chemistry of the molecule to detect pathological changes [1]. MRI usually includes two types: T1-weighted and T2-weighted images, which are basically sets of settings. In T1-weighted images, the major adipose tissue appears white and the water and liquid components appear black. On the contrary, adipose tissue and fluid components appear white on T2-weighted images and can be used to detect the presence of pathological or morphological changes. Therefore, it can be

used to assess fibrotic scar tissue when returning to sports or in the chronic phase of muscle injury to show anatomical features of the tissue [2].

While ultrasound (US) is used in musculoskeletal injury, the US uses high-frequency sound waves to evaluate organs and structures including muscle or other soft tissues. High-spatial-resolution modality provides details of a structure especially superficial area. There are some advantages of using both US and MRI evaluation. MRI is better in evaluating morphological changes, such as scar tissue and deep or large areas. On the other hand, the US is excellent at assessing small areas in detail. Because of its excellent contrast, high spatial resolution, and ability to view soft tissues with multiplanar evaluation, MRI currently appears to be the best imaging method for early-phase diagnosis and follow-up cases of muscle injuries. While the US can be a well-detected imaging method to assess adjunct tissues and can determine real-time conditions of muscle injuries.

1.1 Shear wave elastography

There are some kinds of diagnostic US, such as B mode US or shear wave elastography (SWE) for evaluating the musculoskeletal problems. B mode US is easy accessibility and relatively low cost, plus the possibility of real-time evaluation. Therefore, B mode US is widely used in the musculoskeletal field. However, B mode US cannot exactly investigate the biomechanical properties of tissues; therefore, it is difficult to assess the relationship with structural disorganization. In contrast, SWE is a novel noninvasive diagnostic ultrasound modality for analyzing the biomechanical properties of the soft tissues in healthy and pathological conditions.

Acoustic emission impulses are utilized to excite the tissue and measure the distribution of shear wave propagation speed by the shear wave as regards the mechanism of SWE [3]. SWE visualizes shear wave propagation and can quantify tissue stiffness based on the speed of propagation. SWE primarily assesses elasticity, also known as stiffness; the term of stiffness is basically recognized as the extent to which an object resists deformation in response to an applied force, and the speed of shear wave propagation is determined by both the elasticity and viscosity of the tissue [4]. As a result, it evaluates mechanical properties that indicate the deformity as an indicator of the quality of the object's form and shape. Normal muscle is considered a linear relationship between shear wave modulus and muscle tone. Therefore, normal muscle shows optimal stiffness on SWE (**Figure 1**) [5]. However, the score of SWE is influenced by the components of collagenous fiber tissue such as epimysium or endomysium; therefore, the definitive optimal stiffness is difficult to determine.

By contrast, B-mode US uses a monitor to convert the intensity of reflected waves into a two-dimensional tomographic image in the cross section parallel to the direction of the ultrasonic wave.

Because B-mode US is operator-independent, relatively reproducible, and quantitative method, SWE is currently considered as a promising real-time visualization tool for explicitly quantifying the mechanical properties of soft tissues in sports medicine [6].

B-mode US has a limitation that it is difficult to show the biomechanical properties of tissues.

Therefore, there is a difficulty to assess certain relationships between structural disorganization and clinical features [7]. On the other hand, SWE can obtain additional morphological information with elastic value of tissue structures and

Figure 1.
Normal calf muscles are seen with normal echotexture on SWE [3].

mechanical properties in regard to tissue degeneration, tissue healing, or injury in the wide variety of tissues and injury phases.

Soft tissues, which are referred to muscle, fat, fibrous tissue, blood vessels, or other supporting tissue of the body, are generally recognized viscoelastic, inhomogeneous, and anisotropic [8]. Viscoelastic tissues have both elastic and viscous fluid properties that vary from tissue to tissue [9]. In order to evaluate elasticity, it assumes linear, elastic, solid tissues, a first-order approximation is possible without the force from viscous fluid properties. Elastography systems are based on the prerequisite assumption that object material tissues are elastic, incompressible, homogeneous, and isotropic [10]. Since the elasticity of soft tissues is nonlinear and dependent on the tissue density, strain magnitude, or applied excitation frequency, the evaluation of soft tissues still has been challenging with using diagnostic US.

Utilization of SWE for the musculoskeletal system should be taken into several considerations. Firstly, in order to evaluate shear wave values, a transducer of SWE is put on the surface of the body. As musculoskeletal tissue is heterogeneity, skeletal muscle fibers are surrounded by fascial tissues and passed through by nerve, arteries, veins, and lymphatic vessels. Besides the skin, which is a relatively tight organ, and dermis are superficial to the skeletal muscle fibers [11].

Secondly, the individual muscle fibers are thought to be parallel or oblique to the long axis of the muscle. Muscle fiber types, pennate, unipennate, or multipennate, may affect shear wave measurements; therefore, transducer positioning should be taken according to the muscle fiber architecture.

Thirdly, shear wave value may not change with depth within superficial muscles; however, if the muscle is deeper than 4 cm, the unit of measurement will be difficult to normalize [12].

Lastly, shear wave value, stiffness, can be affected by muscle activities. Changes in SWS measurements with muscle activation are shown during muscle contraction [13].

Plus, SWE measurements are different between active and passive muscles [14]. The more increased tension in the tissue, the more stiffness is measured [15]. Controlling the muscle activation and sustaining the perfect resting positioning are difficult in human in vivo study; therefore, the positioning is special care due to technical errors.

Evaluating for stiffness in MSI used to be difficult because it required a high mechanical load in a view of safety for the participants; however, SWE can have a low invasive approach besides visible in a resting position. In this regard, SWE takes an advantage to other diagnostic tools.

Furthermore, the measurement can be affected by some internal factors. Shear wave values tend to be higher in men than women. In addition, shear wave values are gradually increased according to age [16].

2. Imaging of musculoskeletal injury

2.1 Musculoskeletal injury

The general process of most MSI cases, and it leads to the typical inflammatory process. Muscle inflammation basically occurs in the following three phases: damage, repair, and remodeling; especially repair and remodeling phases happen almost at the same time. Muscle inflammation is a normal and inevitable process, which is healing tissues, and ensures optimal tissue regeneration in order to lead to proper muscle function. In the inflammatory phase, it begins with the destruction of the injured tissue. This reaction leads to an influx of extracellular calcium and the activation of calcium-dependent proteases and phospholipases. Furthermore, this destructed reaction will secrete the serum proteins deriving from disrupted tissue increase as creatine kinase, present in the cytosol of the muscle cell, and found in excessive mechanical stress or muscle degenerative diseases.

In the regeneration phase, the fibrotic scar tissue formation is built and the mature tissue recovers its muscle function as normal reaction [17]. In this phase, an increase in elastography stiffness can occur.

Recovering functional muscle tissue depends on proper joint motion at the remodeling phase. Proper fiber alignment can be one of the important factors for muscle function.

Fibroblasts play an important role in muscle tissue repair by secreting extracellular matrix (ECM) proteins including: collagen types I and III, fibronectin, elastin, proteoglycans, laminin, and growth factors. However, if fibroblasts excessively secrete in ECM, the tissue alters the mechanical characteristics of the muscle, which leads to the development of fibrosis and incomplete muscle recovery [18]. Fibrotic tissue such as fibrotic scar tissue is characterized by the accumulation of ECM, primarily type I collagen. Fibrotic scar tissue is usually induced by chronic connective tissue injuries; however, the relationship between scar tissue and injuries has been still controversial [19]. Therefore, this relationship should be required further investigation and considerations.

2.2 In acute phase on MRI

MRI is commonly used for the diagnosis and recovery of muscle injuries [20].

T2 mapping may be useful from a musculoskeletal injury. Using a series of diffusion-weighted images and subsequent muscle fiber tracking, diffusion tensor imaging provides diffusion quantification of anisotropic tissues such as muscle tissues.

It has been shown that diffusion tensor imaging can be useful for identifying muscle fiber direction, detecting the subclinical changes after a muscle injury, and differentiating injured muscles from normal control muscles [21].

In the general clinical practice especially in sports medicine, MRI observation is suggested to monitor recovery following the injury and decide to return to play. It is basically observed increased signal intensity on fluid-sensitive sequences consistent with edema may persist after resolution of clinical symptoms 6 weeks after the onset of injury. However, even though almost all athletes that are clinically recovered and successfully returned to play showed increased signal intensities on fluid-sensitive sequences, MRI feature only should not be the decision to return to play because it is moderate correlation between clinical assessment using functional tests and MRI findings, plus it showed that functional testing was more accurate than MRI assessment [22].

2.3 In acute phase on B mode US and SWE

B mode US offers dynamic muscle assessment in acute musculoskeletal injury. It is a fast, relatively inexpensive, easier tool for the injuries. And also, it allows serial evaluation for the healing process, and it can be used to perform real-time interventions. In addition, B mode US takes an advantage to MRI in regard that it can demonstrate relevant anatomy surrounding an injury. In acute injury, it is sometimes difficult to show the tissues on MRI images due to inflammation reactions such as an edema [23].

Normal muscle fibers are properly arranged in parallel to fibrofatty septa. The muscle fibers and fascicles are usually hypo echogenicity compared with adjacent fascial tissues. Thick hyperechoic areas are dense fibrous content, which basically contains collagen fiber.

B mode US shows that normal muscle is hypoechoic muscle bundles and the linear hyperechoic perimysium are arranged in layers (**Figure 2**).

From a clinical perspective, in grade 1 MSI injuries, B mode US images may be either negative or exhibit focal or diffuse areas of increased echogenicity within the muscle at the site of injury. As Grade 1 MSI is known with or without actual fiber disruption, it may include injuries exhibiting minimal focal fiber disruption occupying less than 5% of the cross-sectional area of the muscle. The site of injury is represented by a well-defined focal hypoechoic or anechoic area within the muscle. However, there is no consensus about this definition. Therefore, the exact classification is unclear between grade 1 and grade 2 MSI [24]. In grade 2 MSI, the presence of areas of partial fiber disruption is less than 100% of the cross-sectional area of the muscle. Discontinuous fiber arrangement is usually seen in the echogenic perimysium striae around either the myotendon junction or the myofascial junction. Obvious intramuscular hematoma is normally seen in grade 2 MSI in initial almost 24–48 h. In this inflammation phase, hematomas may solidify and display increased echogenicity in comparison to the surrounding muscle. Up to 48 h, hematomas will develop into a well-defined hypoechoic fluid collection with an echogenic margin. In grade 3 MSI, total disruption or discontinuous fiber arrangement is observed on the B mode US. Perifascial fluid may be depicted on the B mode US and with hypoechoic area, which is the presence of extravascular blood in the inflammation phase.

The evaluation of B mode US should be careful because the linear configuration of the septae makes them susceptible to anisotropy artifact leading to decreased echogenicity or absence of conspicuity of septae.

Figure 2.
Normal calf muscles are seen with proper layered fiber arrangement on B mode US [3].

The evaluation of SWE, when MSI occurred, the stiffness as shear wave value is decreased for 4–8 weeks. Then the stiffness is gradually increased, and it can generally return to a similar value as the uninjured side. This phenomenon is well explained that muscle tissue is properly in the acute phase of the healing process (**Figures 3 and 4**) [25].

Furthermore, another study shows that the stiffness of the postoperative tendon initially decreases and gradually increases following the recovery phases [26].

Improper healing tissue can be potential for re-injury; therefore; these results will be the parameter for return to play [27].

After MSI injury, MRI evaluation is basically used for injury evaluation in the acute phase.

Importantly, the T2 value is highest at 5 days on MRI while shear wave value is highest at 2 days on SWE.

2.4 In chronic phase on MRI

In the early stages of MSI, scar tissue formation can be visible as low signal intensity on T1-weighted images and high signal intensity on fluid-sensitive MRI. Scar tissue is observed almost 6 weeks after MSI, which can display low signal intensity on T1-weighted and high signal intensity on fluid-sensitive MRI at early stages.

It is typical for scar tissue to display as low signal intensity with MRI pulse sequences at the late stages. In the clinical practice, it may be misdiagnosed due to residual scar tissue and lead to over- or under-identification of new injuries [28].

During the healing phase up to a couple of months after MSI, differences in the hydrogen and proton environment due to obtained structural tissue changes including

Figure 3.
The healing process of gastrocnemius muscle imaging B mode US [25].

Figure 4.
The healing process of gastrocnemius muscle imaging and SWE [25].

hemorrhage may contribute to susceptibility artifacts. It may be observed during follow-up evaluation. A study shows that MRI could evaluate morphologic changes of musculotendon remodeling following MSI by using quantification of the scar tissue volumes [29].

2.5 In chronic phase on B mode US

The US can observe the healing process of injured tissues depending on the nature of the original injury. The B mode US may appear hyperechogenic during the healing phase. Normal tissue healing is considered a reduction in size or resolution of the region of increased echogenicity [30]. Even though the B mode US can evaluate the chronic phase of injured tissue, it is less sensitive than MRI to residual morphologic changes after MSI for the higher soft-tissue contrast and high to extracellular fluid in MRI [31]. In clinical practice, the detection of small echogenic scar tissue by using the B mode US is difficult for a less experienced practitioner. As mentioned above, the

relationship between demonstration of scar tissue and re-injury is still controversial. However, excessive scar tissue may be symptomatic that is described as “feeling tight.” It may disturb neural tension, which leads to re-injury [32].

Scar tissue is often shown as irregular thickening of the fascial tissue compared with the uninjured side on the B mode US [33].

Skeletal muscles are also composed of connective tissue, which resists and transmits the force generated by myofibrils to the tendon and bone structures to generate physical movement. When skeletal muscles are injured, any one of these components including fascial tissue can be damaged [18].

2.6 In chronic phase on SWE

SWE can take an advantage to evaluate tissue properties in chronic phase compared with B mode US. SWE can evaluate the absolute elasticity value of soft tissue structures and obtain useful quantitative information about the mechanical properties in the chronic phase.

In the chronic phase of MSI, the stiffness is significantly higher in the chronic phase compared with the acute phase [25].

In the chronic phase of tendon rupture injury, the stiffness of the tissue gradually increased following the healing process with or without surgical repair [34].

From these results, SWE can be a useful tool for evaluating in the phase of transition of acute to chronic phase.

Tendinopathy is considered to occur from mechanical, degenerative, and overuse diseases. It is associated with degeneration and disorganization of the collagenous structure, changes in the proteoglycan and water contents, increased cellularity, fatty infiltration, and neovascularization due to repetitive mechanical stress [35]. A study of tendinopathy shows tendon stiffness is correlated with the patients' symptom scores, demonstrating the promise of shear wave elastography during follow-up for tendinopathies [36].

Interestingly, by evaluating SWE, injured area of fascial tissue increased stiffness between injured leg and uninjured leg in 11 injured professional rugby players, mean average of shear wave modulus on injured side (17.34 ± 9.04 kPa) and maximum shear wave modulus on injured side (33.53 kPa) compared with mean average of shear wave modulus on uninjured side (12.7 ± 4.96 kPa) and maximum shear wave modulus on uninjured side (20.86 kPa) (**Figures 5 and 6**) [37].

Chronic cumulative injury can affect the fascial tissue in addition to the chronic phase of direct trauma. Cumulative mechanical stress leads to fibrotic tissue, thickness of tendinous tissue could be related to the injury [38]. Repetitive cumulative stress, especially eccentric contraction, causes microscopic tissue damage and increases inflammation. ECM of tissue changes plays an important role in tissue stiffness changes [39]. Change in property of ECM by cumulative stress may affect the stiffness in the chronic musculoskeletal injury.

Considering the results, in chronic musculoskeletal injury, it affects not only the muscle tissue but also a wide variety of tissues including fascial tissue. Even though a wide variety of ultrasound imaging has been used in fascial tissue, there is a lack of standardization [40]. SWE can be a more accurate diagnostic tool compared with B-mode, and the combination of SWE and B-US can be a strong diagnostic tool for fascial pathology [41].

To measure the fascial tissue, SWE provides the images reflecting the shear wave value as a tightness of the area of interest.

Figure 5.
The stiffness of fascial tissue of injured side by using Q box trace mode, and the unit was given automatically by machine in kilopascal units. Injured side stiffness is higher than that of uninjured side.

Figure 6.
The stiffness of fascial tissue of uninjured side by using Q box trace mode, and the unit was given automatically by machine in kilopascal units.

As considering the tissue property depending on viscoelastic property, utilization of SWE can be a useful tool for evaluating a wide variety of tissues in chronic musculoskeletal injury.

To explain fascial tissue, the term Fascia is used to be recognized as “a sheet or band of soft connective tissue that attaches, surrounds and separates internal organs and skeletal muscles.” However, according to the recognition of physiological and

pathophysiological behaviors of a range of connective tissues, the definition is widely considered. With current understanding of mechanical aspects of connective tissue function, fascia is considered in the view of micro to macro as fibril to fascial system. From a morphological view, fascia is described as a sheet or any other dissectible aggregations of connective tissue that forms beneath the skin to attach, enclose, and separate muscles and other internal organs.

There are several types of fascial tissues in the fascial system. The fascial system consists of adipose tissue, adventitia, neurovascular sheaths, aponeuroses, deep and superficial fasciae, dermis, epineurium, joint capsules, ligaments, membranes, meninges, myofascial expansions, periosteum, retinacula, septa, tendons. The fascial system is also considered to be included endotendon, peritendon, epitendon, and paratendon, visceral fasciae, and all the intramuscular and intermuscular connective tissues, including endomysium, perimysium, epimysium. The fascial system consists of various components, and it is built on three-dimensional soft seamless collagenous fibers. The loose and dense fibrous connective tissue fills the whole body and allows the integration of body systems.

With injured fascial tissues, it will have a very similar healing process to muscle injury. Micro or macro changes occurred by excessive or repetitive loading or direct trauma of fascial tissue. The pathological changes will modify mechanical function that compromises initial tissue or function. In the acute inflammation phase of fascial tissue, immune response proceeds by phagocytosis from the injured cell. It releases proinflammatory cytokines and macrophages to promote immune cell infiltration. If the excessive loading is chronically prolonged, continuing inflammation develops, which leads to the presence of cytotoxic cytokines affected tissues. From this reaction, interleukin-1 β , tumor necrosis factor (TNF) and transforming growth factor beta (TGF β -1) can promote fibrosis by excessive fibroblast proliferation and collagen matrix deposition that consequently develops fibrotic tissue. A study indicates that substance P stimulates TGF β -1, which leads to fibrotic tissue development [42]. That phenomenon shows in the chronic phase of fascial injury.

Most pathological cases of fascial tissue demonstrated that a decreased tissue stiffness is present, while some cases demonstrated an increased stiffness due to fibrotic tissues.

However, the viscoelasticity is varied from tissue to tissue. The stiffness of tissue can be affected by the viscoelastic properties of ECM, especially the aponeurotic tissue containing loose connective tissue in which the ECM has ground substances, such as glycosaminoglycans (GAGs) especially hyaluronan (HA)-containing fluid between each layer [43]. The fascial component of the ECM is the main site of the inflammatory responses that occur in tissues. Thus, when the tissue reacts to an inflammatory response, the viscosity of the tissue can be increased, which could lead to increased viscoelasticity of the fascial tissue.

Evaluation of the stiffness of fascial tissue using SWE is considered as viscoelastic, inhomogeneous tissues [44]. The shear modulus value, stiffness, of fascial tissue is affected not only by the fibrotic tissue itself, but also ground substances and fluid components [45]. Therefore, stiffness is affected not only by pure elastic properties, but also by viscosity properties in the fascial tissue [46].

Fascial tissue can be affected by viscoelastic properties more than muscle [47].

Fascial tissue should include loose connective tissue, which contains rich ground substances between each layer. These properties affect the movement of loose connective tissue within and under the tissues [48].

In the chronic condition of MSI, the concentration and molecular weight of HA are altered. In this regard, binding interactions with other macromolecules may affect the sliding movement of fascial tissues [49]. Generally speaking, elastic tissues are hydrophilic and function using a tissue sliding system. However, fibrotic tissues exhibit an altered tissue sliding system, which affects the rehydration and expansion [50]. Therefore, in chronic MSI with scar tissue, there may be less function of rehydration; consequently, it will be stiffer tissue than healthy tissue. Even though SWE is considered not operator-dependent, the viscosity component will affect the results of measurement. Therefore, viscoelastic tissue such as fascial tissue must take special consideration in chronic musculoskeletal conditions.

This phenomenon may affect our daily activities for some reasons.

First, fascial tissues are rich in nerve receptors and free and encapsulated nerve endings including Pacinian corpuscles and Ruffini endings. Those receptors detect and react to mechanical stimulations [51]. As the tissue is stimulated, the nerve endings react and provide sensory feedback that translates into the human ability to detect and coordinate movement and achieve neuromuscular control. Chronic musculoskeletal issues, especially with fibrotic scar tissue, can alter the movement in daily activities.

Secondly, changes in the viscoelasticity of the tissues, basically modulated by ground substances, alter pain sensitivity as activation of nociceptors [48]. The more adhered tissue such as an inflamed tissue, the less lubricated that leads to the alteration of the tissue sliding. Thus, nociceptors can translate mechanical stimuli into pain sensation; consequently, incorrect sensory feedback will modify proprioceptors to nociceptors. Finally, myofascial network transmits to other tissues for muscle force [52]. Stiffened tissue affects this transmission and may change muscle mechanics [53]. Therefore, impaired myofascial force transmission by stiffened tissue may have a negative effect on the proper muscle biomechanics.

3. Conclusion

SWE is a newly developed diagnostic tool and is widely used in the musculoskeletal system.

SWE is a promising diagnostic modality for MSI and the accurate measurement of muscle and fascial tissues' properties, which has a major impact in clinical practice. In this chapter, diagnostic tools of magnetic resonance imaging, B mode ultrasound, and shear wave elastography in both acute and chronic phases are compared. There are pros and cons for utilization between the tools; however, there is new insight by using SWE in MSI not only properties of muscle but also fascial tissues. SWE generally evaluates tissue stiffness as viscoelasticity. SWE visualizes the propagation of shear waves and can quantify tissue "stiffness" by the speed of propagation. In the chronic MSI cases, viscoelasticity comes from ground substances, which are contained more in fascial tissue. The stiffness increases in fascial tissue more than muscle; therefore, in the chronic case of MSI, not only muscle but also a wide variety of connective tissues can be considered. However, utilization of SWE should be careful due to technical pitfalls or internal factors. All in all, SWE is a promising diagnostic modality for MSI and the accurate measurement of muscle and fascial tissues properties, which has a major impact in clinical practice. There are few studies that investigate for chronic musculoskeletal problem including fascial tissue problem by using SWE especially in clinical trials. Furthermore, the shear wave value is different according to active

muscle contraction. Therefore, further studies for chronic musculoskeletal problem will be expected in a wide variety of conditions.

Conflict of interest

The authors declare no conflict of interest.

Author details

Tomonori Kawai

Faculty of Human Sciences, Department of Sports and Health Sciences, University of East Asia, Ichinomiya, Yamaguchi, Japan

*Address all correspondence to: tomochiro@toua-u.ac.jp

IntechOpen

© 2022 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/3.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

References

- [1] Berger A. Magnetic resonance imaging. *BMJ*. 2002;**324**(7328):35. DOI: 10.1136/bmj.324.7328.35
- [2] Verrall GM, Slavotinek JP, Barnes PG, Fon GT, Esterman A. Assessment of physical examination and magnetic resonance imaging findings of hamstring injury as predictors for recurrent injury. *The Journal of Orthopaedic and Sports Physical Therapy*. 2006;**36**(4):215-224. DOI: 10.2519/jospt.2006.36.4.215
- [3] Taljanovic MS, Gimber LH, Becker GW, et al. Shear-wave elastography: Basic physics and musculoskeletal applications. *Radiographics*. 2017;**37**(3):855-870. DOI: 10.1148/rg.2017160116
- [4] Chan O, Del Buono A, Best TM, Maffulli N. Acute muscle strain injuries: A proposed new classification system. *Knee Surgery, Sports Traumatology, Arthroscopy*. 2012;**20**:2356-2362. DOI: 10.1007/s00167-012-2118-z
- [5] Eby SF, Song P, Chen S, Chen Q, Greenleaf JF, An K-N. Validation of shear wave elastography in skeletal muscle. *Journal of Biomechanics*. 2013;**46**:2381-2387
- [6] Finnoff JT, Hall MM, Adams E, et al. American Medical Society for Sports Medicine (AMSSM) position statement: Interventional musculoskeletal ultrasound in sports medicine. *PM&R*. 2015;**7**:151-168. DOI: 10.1016/j.pmrj.2015.01.003
- [7] Docking SI, Ooi CC, Connell D. Tendinopathy: Is imaging telling us the entire story? *The Journal of Orthopaedic and Sports Physical Therapy*. 2015;**45**:842-852. DOI: 10.2519/jospt.2015.5880
- [8] Bercoff J, Tanter M, Muller M, Fink M. The role of viscosity in the impulse diffraction field of elastic waves induced by the acoustic radiation force. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*. 2004;**51**:1523-1536. DOI: 10.1109/tuffc.2004.1367494
- [9] Bercoff J, Tanter M, Fink M. Supersonic shear imaging: A new technique for soft tissue elasticity mapping. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*. 2004;**51**:396-409. DOI: 10.1109/tuffc.2004.1295425
- [10] Barr RG, Ferraioli G, Palmeri ML, Goodman ZD, et al. Elastography assessment of liver fibrosis: Society of radiologists in ultrasound consensus conference statement. *Radiology*. 2015;**276**:845-861. DOI: 10.1148/radiol.2015150619. Epub 2015 Jun 16
- [11] Chino K, Kawakami Y, Takahashi H. Tissue elasticity of in vivo skeletal muscles measured in the transverse and longitudinal planes using shear wave elastography. *Clinical Physiology and Functional Imaging*. 2017;**37**(4):394-399. DOI: 10.1111/cpf.12315. Epub 2015 Dec 22
- [12] Alfuraih AM, O'Connor P, Hensor E, et al. The effect of unit, depth, and probe load on the reliability of muscle shear wave elastography: Variables affecting reliability of SWE. *Journal of Clinical Ultrasound*. 2018;**46**(2):108-115. DOI: 10.1002/jcu.22534
- [13] Nordez A, Gennisson JL, Casari P, et al. Characterization of muscle belly elastic properties during passive stretching using transient elastography. *Journal of Biomechanics*. 2008;**41**:2305-2311. DOI: 10.1016/j.jbiomech.2008.03.033. Epub 2008 Jun 9

- [14] Chernak LA, DeWall RJ, Lee KS, et al. Length and activation dependent variations in muscle shear wave speed. *Physiological Measurement*. 2013;**34**(6):713-721. DOI: 10.1088/0967-3334/34/6/713
- [15] Yavuz A, Bora A, Bulut MD, Batur A, et al. Acoustic radiation force impulse (ARFI) elastography quantification of muscle stiffness over a course of gradual isometric contractions: A preliminary study. *Medical Ultrasonography*. 2015;**17**(1):49-57. DOI: 10.11152/mu.2013.2066.171.yvz
- [16] Eby SF, Cloud BA, Brandenburg JE, et al. Shear wave elastography of passive skeletal muscle stiffness: Influences of sex and age throughout adulthood. *Clinical Biomechanics*. 2015;**30**:22-27. DOI: 10.1016/j.clinbiomech.2014.11.011
- [17] Järvinen TA, Järvinen M, Kalimo H. Regeneration of injured skeletal muscle after the injury. *Muscle, Ligaments and Tendons Journal*. 2014;**3**:337-345
- [18] Kääriäinen M, Järvinen T, Järvinen M, et al. Relation between myofibers and connective tissue during muscle injury repair. *Scandinavian Journal of Medicine & Science in Sports*. 2000;**10**:332-337. DOI: 10.1034/j.1600-0838.2000.010006332.x
- [19] Reurink G, Almus E, Goudswaard GJ, et al. No association between fibrosis on magnetic resonance imaging at return to play and hamstring reinjury risk. *American Journal of Sports Medicine*. 2015;**43**:1228-1134. DOI: 10.1177/0363546515572603. Epub 2015 Mar 6
- [20] Kerkhoffs GMMJ, van Es N, Wieldraaijer T, et al. Diagnosis and prognosis of acute hamstring injuries in athletes. *Knee Surgery, Sports Traumatology, Arthroscopy*. 2013;**21**:500-509. DOI: 10.1007/s00167-012-2055-x. Epub 2012 May 24
- [21] May DA, Disler DG, Jones EA, et al. Abnormal signal intensity in skeletal muscle at MR imaging: Patterns, pearls, and pitfalls. *Radiographics*. 2000;**20**:S295-S315. DOI: 10.1148/radiographics.20.suppl_1.g00oc18s295
- [22] Schneider-Kolsky ME, Hoving JL, Warren P, et al. A comparison between clinical assessment and magnetic resonance imaging of acute hamstring injuries. *The American Journal of Sports Medicine*. 2006;**34**:1008-1015. DOI: 10.1177/0363546505283835
- [23] Connell DA, Schneider-Kolsky ME, Hoving JL, et al. Longitudinal study comparing sonographic and MRI assessments of acute and healing hamstring injuries. *AJR. American Journal of Roentgenology*. 2004;**183**(4):975-984. DOI: 10.2214/ajr.183.4.1830975
- [24] Lee JC, Mitchell AW, Healy JC, Thorstensson A. Imaging of muscle injury in the elite athlete. *The British Journal of Radiology*. 2012;**85**(1016):1173-1185. DOI: 10.1259/bjr/84622172. Epub 2012 Apr 11
- [25] Yoshida K, Itoigawa K, Maruyama Y, et al. Healing process of gastrocnemius muscle injury on ultrasonography using B-mode imaging, power doppler imaging, and shear wave elastography. *Journal of Ultrasound in Medicine*. 2019;**38**(12):3239-3246. DOI: 10.1002/jum.15035. Epub 2019 Jun 4
- [26] Zhang L, Wan W, Wang Y, et al. Evaluation of elastic stiffness in healing achilles tendon after surgical repair of a tendon rupture using in vivo ultrasound shear wave elastography. *Medical Science Monitor*. 2016;**22**:1186-1191. DOI: 10.12659/MSM.895674

- [27] Eming SA, Martin P, Tomic-Canic M. Wound repair and regeneration: Mechanisms, signaling, and translation. *Science Translational Medicine*. 2014;**6**(265):265sr6. DOI: 10.1126/scitranslmed.3009337
- [28] Blankenbaker DG, Tuite MJ. Temporal changes of muscle injury. *Seminars in Musculoskeletal Radiology*. 2010;**14**(2):176-193. DOI: 10.1055/s-0030-1253159
- [29] Slider A, Heiderscheit BC, Thelen DG, Enright T, Tuite MJ. MR observations of longterm musculotendon remodeling following a hamstring strain injury. *Skeletal Radiology*. 2008;**37**(12):1101-1109. DOI: 10.1007/s00256-008-0546-0. Epub 2008 Jul 23
- [30] Takebayashi S, Takasawa H, Banzai Y, et al. Sonographic findings in muscle strain injury: Clinical and MR imaging correlation. *Journal of Ultrasound in Medicine*. 1995;**14**(12):899-905. DOI: 10.7863/jum.1995.14.12.899
- [31] Petersen J, Thorborg K, Nielsen MB, et al. The diagnostic and prognostic value of ultrasonography in soccer players with acute hamstring injuries. *The American Journal of Sports Medicine*. 2014;**42**(2):399-404. DOI: 10.1177/0363546513512779. Epub 2013 Dec 11
- [32] Brukner P. Hamstring injuries: Prevention and treatment—An update. *British Journal of Sports Medicine*. 2015;**49**(19):1241-1244. DOI: 10.1136/bjsports-2014-094427
- [33] Drakonaki EE, Sudół-Szopińska I, Sinopidis C. High resolution ultrasound for imaging complications of muscle injury: Is there an additional role for elastography? *Journal of Ultrasonography*. 2019;**19**(77):137-144. DOI: 10.15557/JoU.2019.0020. Epub 2019 Jun 28
- [34] Frankewycz B, Henssler L, Weber J, et al. Changes of material elastic properties during healing of ruptured achilles tendons measured with shear wave elastography: A pilot study. *International Journal of Molecular Sciences*. 2020;**21**(10):3427. DOI: 10.3390/ijms21103427
- [35] Aubry S, Nueffer JP, Tanter M, et al. Viscoelasticity in Achilles tendonopathy: Quantitative assessment by using real-time shear-wave elastography. *Radiology*. 2015;**274**:821829. DOI: 10.1148/radiol.14140434. Epub 2014 Oct 17
- [36] Dirrichs T, Quack V, Gatz M, et al. Shear wave elastography (SWE) for the evaluation of patients with tendinopathies. *Academic Radiology*. 2016;**23**:1204-1213. DOI: 10.1016/j.acra.2016.05.012. Epub 2016 Jun 16
- [37] Kawai T, Takahashi M, Takamoto K, et al. Hamstring strains in professional rugby players result in increased fascial stiffness without muscle quality changes as assessed using shear wave elastography. *Journal of Bodywork and Movement Therapies*. 2021;**27**:34-41. DOI: 10.1016/j.jbmt.2021.03.009. Epub 2021 Mar 20
- [38] Paluch L, Nawrocka-Laskus E, Wieczorek J, et al. Use of ultrasound elastography in the assessment of the musculoskeletal system. *Polish Journal of Radiology*. 2016;**81**:240-246. DOI: 10.12659/PJR.896099. eCollection 2016
- [39] Kjaer M, Magnusson P, Krogsgaard M, et al. Extracellular matrix adaptation of tendon and skeletal muscle to exercise. *Anatolia*.

2006;**208**(4):445-450. DOI: 10.1111/j.1469-7580.2006.00549.x

[40] Mc Auliffe S, Mc Creesh K, Purtill H, et al. A systematic review of the reliability of diagnostic ultrasound imaging in measuring tendon size: Is the error clinically acceptable? *Physical Therapy in Sport*. 2017;**26**:S146630207-S146630203. DOI: 10.1016/j.ptsp.2016.12.002. Epub 2016 Dec 8

[41] Gatz M, Ljudmila Bejder L, Quack V, et al. Shear wave elastography (SWE) for the evaluation of patients with plantar fasciitis. *Academic Radiology*. 2020;**27**(3):363-370. DOI: 10.1016/j.acra.2019.04.009. Epub 2019 May 30

[42] Frara N, Fisher PW, Zhao Y, et al. Substance P increases CCN2 dependent on TGF-beta yet collagen type I via TGF-beta1 dependent and independent pathways in tenocytes. *Connective Tissue Research*. Jan 2018;**59**(1):30-44. DOI: 10.1080/03008207.2017.1297809. Epub 2017 Apr 12

[43] Stecco A, Stecco C, Raghavan P. Peripheral mechanisms contributing to spasticity and implications for treatment. *Current Physical Medicine and Rehabilitation Reports*. 2014;**2**:121-127. DOI: 10.1007/s40141-014-0052-3

[44] Urban M, Chen S, Fatemi M. A review of shearwave dispersion ultrasound vibrometry (SDUV) and its applications. *Current Medical Imaging*. 2012;**8**:27-36. DOI: 10.2174/157340512799220625

[45] Andonian P, Viallon M, Le Goff C, et al. 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*. 2016;**11**:e0161855. DOI: 10.1371/journal.pone.0161855. eCollection 2016

[46] Davis LC, Baumer TG, Bey MJ, et al. Clinical utilization of shear wave elastography in the musculoskeletal system. *Ultrasonography*. 2019;**38**:2-12. DOI: 10.14366/usg.18039. Epub 2018 Aug 23

[47] Gao Y, Waas AM, Faulkner JA, et al. Micromechanical modeling of the epimysium of the skeletal muscles. *Biomechanics*. 2008;**41**:1-10. DOI: 10.1016/j.jbiomech.2007.08.008. Epub 2007 Sep 27

[48] Stecco C, Stern R, Porzionato A, et al. Hyaluronan within fascia in the etiology of myofascial pain. *Surgical and Radiologic Anatomy*. 2011;**33**:891-896. DOI: 10.1007/s00276-011-0876-9. Epub 2011 Oct 2

[49] Cowman MK, Schmidt TA, Raghavan P, et al. Viscoelastic properties of hyaluronan in physiological conditions. *F1000Research*. 2015;**4**:622. DOI: 10.12688/f1000research.6885.1. eCollection 2015

[50] Głowacki A, Olczyk K, Sonecki P, et al. Glycosaminoglycans of normal and scarred fascia. *Acta Biochimica Polonica*. 1994;**41**:166-169

[51] Turrina A, Martínez-González MA, Stecco C. The muscular force transmission system: Role of the intramuscular connective tissue. *Journal of Bodywork and Movement Therapies*. 2013;**17**:95-102. DOI: 10.1016/j.jbmt.2012.06.001

[52] Stecco C, Macchi V, Porzionato A, et al. The ankle retinacula: Morphological evidence of the proprioceptive role of

the fascial system. Cells, Tissues, Organs.
2010;**192**:200-210. DOI: 10.1159/
000290225. Epub 2010 Feb 27

[53] Huijing PA, Baan GC. Myofascial
force transmission causes interaction
between adjacent muscles and connective
tissue: Effects of blunt dissection and
compartmental fasciotomy on length
force characteristics of rat extensor
digitorum longus muscle. Archives
of Physiology and Biochemistry.
2001;**109**:97-109. DOI: 10.1076/
apab.109.2.97.4269