Palpation entails feeling the stiffness of soft tissues with the hands. Hippocrates made manual palpation – as a method for clinical examination – popular in ancient Greece. However, this time-honoured practice\textsuperscript{1} is not without limitation. It is limited to superficial tissues and it provides a qualitative and subjective outcome. Since their introduction in the 1990s, elastography techniques have enabled measurement of the stiffness of localised areas of soft tissues. Although elastography is widely used for diagnosis of breast cancer, liver fibrosis and thyroid nodules, applications for the musculoskeletal system are just beginning to be explored. Quantifying the stiffness of a localised region of muscle, tendon and nerve provides the opportunity for a deeper understanding of changes in the mechanical properties of these tissues with disease progression, rehabilitation and sport training. The main advantages of recent elastography techniques are that they provide real-time, non-invasive, quantitative, reliable and fast measurements. In addition, deep tissues, for which palpation can be difficult, can be assessed.

A WIDE RANGE OF ELASTOGRAPHY TECHNIQUES

There is a wide range of elastography techniques, each of which works in a different way\textsuperscript{2}. An important consideration when choosing an elastography technique is whether it provides a quantitative value of tissue stiffness or only a display of the variation in stiffness within an image. With quasi-static techniques, a constant compression is applied to the tissue. The associated displacement/strain is calculated from conventional ultrasound images as the difference between the reference and the compressed image. As the stress applied to the tissue cannot be accurately quantified (and thus standardised), this technique does not provide the precise quantification of muscle stiffness required to test the effect of an intervention and/or to make comparisons between individuals. Quantitative elastography techniques measure tissue elasticity by calculating the velocity of the shear waves resulting from mechanical perturbations applied...
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to the tissue. This propagation velocity is directly related to the shear modulus of the tissue, i.e. the stiffer the tissue, the faster the shear wave propagation. The velocity of the shear waves can be estimated from subtle tissue displacements measured using medical imaging such as magnetic resonance imaging or ultrasound. Magnetic resonance elastography offers excellent spatial resolution, however the acquisition time is relatively long (up to several minutes for two-dimensional measurements), which limits its use for tissue loading conditions, for example muscle contraction or stretching. In addition, magnetic resonance imaging is expensive. Conversely, ultrasound provides an almost instantaneous measurement of shear wave velocity and is a much cheaper method. One such ultrasound shear wave elastography technique called supersonic shear wave imaging (SSI; Supersonic Imagine, Aix en Provence, France) provides real-time, quantitative and reliable imaging of stiffness. Measures are made with an ultrasound probe placed over the tissue under consideration, as for conventional ultrasound measurements. Two-dimensional maps of the shear modulus (stiffness) are obtained in real time (1 image/s). To date, many of the studies of musculoskeletal applications of elastography have used SSI. However, it is important to note that similar quantitative techniques such as the combo-push ultrasound shear elastography (CUSE) are being developed.

Elastography has been validated for diagnosis of breast cancer, liver fibrosis and thyroid nodules. For example, quantification of tissue elasticity using SSI provides complementary information to traditional ultrasound to assist in distinguishing between benign and malignant breast lesions. Its use in musculoskeletal applications is relatively new. Although promising results have been published, some methodological limitations need to be considered.

ELASTOGRAPHY AND MUSCLE FUNCTION

There is evidence that muscle stiffness estimated using elastography is linearly related to both active and passive muscle force. It therefore provides the opportunity for new insights into changes in muscle tension associated with musculoskeletal conditions and their associated treatment/rehabilitation programmes.

Using an animal model, Lv et al. reported increased muscle stiffness subsequent to a muscle crush injury. Lacourpaille et al. reported increased muscle stiffness associated with more subtle muscle damage in humans, i.e. exercise-induced muscle damage. Interestingly, increased stiffness was observed 1 hour after eccentric exercise in the absence of both muscle soreness and oedema. More recent results (unpublished data) suggest that this increase in stiffness is positively correlated to the amount of damage observed 2 days after eccentric exercise. Therefore, early assessment of muscle stiffness following strenuous exercise might help coaches to estimate the amount of muscle damage. Further, the ability to accurately quantify the increase in passive stiffness associated with muscle injury and to isolate the muscle that is damaged from its synergists, might help the clinician to target interventions to the most affected muscle or muscle region. In this way, Le Sant et al. compared the stiffness among hamstring muscles during passive knee extensions performed at different hip angles. The long head of the biceps femoris was stiffer than the semimembranosus and the semimembranosus was stiffer than the

Figure 1: Representative example of the shear modulus (stiffness) maps obtained in vastus lateralis at rest (a) and during 5% of maximal voluntary isometric contraction (b). The map of shear modulus is superposed onto a B-mode image, with the scale depicting graduation of shear modulus (stiffness). kPa = kilopascals
Elastography may help identify stiffer muscle such that stretching interventions may target this muscle using an optimal joint configuration. Quantification of muscle stiffness also provides insight into the possible mechanisms underlying treatments and rehabilitation programmes and, ultimately, assess their efficacy. Interventions such as massage, taping, dry needling and stretching each aim to alter muscle stiffness. However, their mechanical effect has not yet been quantified. For example, taping techniques are often used to alter local muscle tension. Their effect on muscle tension was mainly inferred from myoelectrical activity measured using electromyography. Because myoelectrical activity does not account for either change in muscle length or passive tension, it cannot be used to accurately estimate change in muscle tension. Using SSI, Hug et al. quantified the effect of deloading tape; a technique that aims to reduce tension on an injured/painful region. They showed that deloading tape applied to the skin directly over the rectus femoris muscle reduced tension in the underlying muscle region when the muscle was loaded (during muscle stretch and contraction). This mechanical effect of tape has been recently confirmed by magnetic resonance imaging (MRI) through the assessment of local tissue deformation that occurs after the application of kinesio-tape. Overall, it provides a biomechanical explanation for the effect of tape, observed in clinical practice (reduce pain, restore function and aid recovery). Even if the clinical outcome such as pain relief is the most relevant indicator of tape effectiveness, the ability to assess the effect of tape on tissue stiffness opens interesting perspectives to test the mechanical efficacy of different tape configurations. Massage is another controversial technique that may be used to reduce muscle stiffness. Using SSI, Eriksson-Crommert et al. provided direct evidence that 7 minutes of massage (a standardised combination of effleurage, petrissage and deep circular frictions) was effective in decreasing muscle stiffness. However, this decrease in stiffness did not persist after a short period of rest (3 minutes). This study was performed on asymptomatic participants and therefore further work is needed to assess the effectiveness of massage in a clinical population. The effect of dry needling on palpable myofascial trigger points was also quantified using elastography. A decrease in stiffness of about 30% was observed after the dry needling intervention. This result offers interesting perspectives for objective assessment of trigger points, in particular for deep muscles and for quantifying the effect of an intervention.

**Figure 2:** Typical example of Magnetic Resonance Imaging (a) and elastography (b) measurements for the biceps brachii before (PRE) and 1 hour (1H), 48 hours (48H) and 21 days (21D) post-eccentric exercise. The white signal observable at 48 hours on the T2-weighted image (a) indicates the presence of fluid accumulation (oedema). The map of shear modulus superposed onto the B-mode ultrasound image shows an increased stiffness at 1 hour and 48 hours (b, colour scale depicting graduation of shear modulus).

Elastography may help identify stiffer muscle such that stretching interventions may target this muscle using an optimal joint configuration.
Feedback on change in muscle tension during motor control interventions is another area where elastography might be a useful tool for the clinician. Trunk rehabilitation exercises that differentially target trunk muscle activation are commonly prescribed for patients with low back pain. As these exercises involve fine motor skills, the efficacy of the rehabilitation protocol may depend on the ability of the patient to accurately perform the task. To this end, a real-time, non-invasive measure to quantify individual muscle tension may benefit clinical practice. Techniques such as electromyography and B-mode ultrasound can indirectly provide this information. However, surface electromyography recordings cannot be used to isolate the activity of small or deep muscles. In addition, the relationship between muscle tension and muscle architecture (thickness or length) is not linear, which makes it difficult to accurately infer a change in muscle tension from a change in muscle architecture measured with B-mode ultrasound. The reliability of SSI to assess change in abdominal muscle stiffness during rehabilitation tasks has been assessed in asymptomatic participants (MacDonald et al, in revision). Reliability was excellent for superficial muscles (obliquus externus abdominis and rectus abdominis). The deeper muscles (obliquus internus abdominis and transversus abdominis) provided greater methodological challenges with poor quality elasticity maps, often observed in people with higher body mass index. Increased fat between the probe and the targeted tissue interferes with the generation of the shear waves within the target tissue and hence may lead to the inability of the technique to measure the stiffness. This limitation needs to be considered when assessing people with a high body fat percentage.

ELASTOGRAPHY AND TENDINOPATHY

First-line imaging examination for people with suspected tendinopathy classically involves morphology (thickness, echogenicity) and vascular response assessments using B-mode and power Doppler ultrasound, respectively. The accuracy of these measures for diagnosis of tendon pain remains controversial. In addition, it does not provide information about the mechanical properties of the tendon, which may be altered in people with tendinopathy. Elastography has been used to show regional changes in tendon stiffness caused by partial tears in a porcine model. Preliminary research using SSI reported decreased tendon stiffness in patients with Achilles tendinopathy and increased stiffness in athletes with patellar tendinopathy. The reason for this differential effect of tendinopathy on the patellar and Achilles tendon remains unclear. Study of tendon mechanical properties using shear wave elastography is a relatively recent approach, with more work needed to exclude the possibility of a methodological explanation, e.g. regional differences, inclusion criterion of the participants, length at which the tendon is measured and change in tendon thickness. For example, because tendons are both very stiff and thin, shear wavelengths are greater than tendon thickness, leading to guide wave propagation. Consequently, measurements are biased if no correction
for tendon thickness is applied. For instance, two tendons with the same stiffness but with different thickness will exhibit different shear modulus values. This problem can be resolved by using shear wave spectroscopy, which involves an additional dispersion analysis (i.e. spectral analysis) of the shear wave propagation. However, to the best of our knowledge, this technique has not yet been tested on pathological tendons.

ELASTOGRAPHY AND NEURODYNAMICS

Altered nerve excursion and strain in people with peripheral neuropathies may be associated with compromised nerve function. Conversely, techniques that aim to mobilise peripheral nerves, such as the tensioner or slider techniques, have been proven useful for the management of various nerve entrapment syndromes (e.g. carpal tunnel syndrome, radiculopathy). Within this context, assessment of nerve tension may assist in both diagnosis and management of clinical populations. For example, median nerve stiffness measured using elastography at the carpal tunnel inlet is significantly higher in patients with carpal tunnel syndrome. Although classic ultrasound can be used to measure the nerve excursion during mobilisation techniques, it does not provide direct information on nerve tension, which is crucial information from a clinical perspective. A recent study showed the feasibility of quantifying sciatic nerve stiffness using elastography during lower limb passive movements (Andrade et al, in revision). Specifically, these results showed that sciatic nerve stiffness increased during passive dorsiflexion when the knee was fully extended; but no changes were observed when the knee was flexed. Future work is needed to compare the efficacy of various mobilisation techniques.

CONCLUSION

There is growing evidence that elastography may be a useful tool in detecting subtle changes in muscle, tendon or nerve mechanical properties that occur early in the course of an injury or disorder. This is particularly important as earlier detection could improve sports training and rehabilitation strategies. The quantification of muscle, tendon or nerve stiffness also provides insight into the mechanisms that may underpin treatments and rehabilitation programmes and could ultimately assess their efficacy. Despite these promising applications of elastography for musculoskeletal rehabilitation, important methodological limitations need to be considered, e.g. decreased quality of the measurement in overweight persons and the inability to accurately infer tendon stiffness from classical measurements of shear wave speed. Future improvements in elastography techniques are likely to overcome these limitations. For more information on the use of elastography for musculoskeletal rehabilitation, please visit the website of a recently funded project from the ‘Region Pays de la Loire’ (France): www.quete.univ-nantes.fr
Elastography may be a useful tool in detecting subtle changes in muscle, tendon or nerve mechanical properties that occur early in the course of an injury or disorder.

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