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Quantifying cervical and axioscapular muscle stiffness using shear wave elastography

Yanfei Xie[a,*], Lucy Thomas[a], François Hug[b,c,d], Venerina Johnston[a,e], Brooke K. Coombes[a,f]

[a] *School of Health and Rehabilitation Science, The University of Queensland, Australia*
[b] *Laboratory "Movement, Interactions, Performance" (EA 4334), UFR STAPS, University of Nantes, France*
[c] *Institut Universitaire de France (IUF), Paris, France*
[d] *School of Biomedical Sciences, The University of Queensland, Australia*
[e] *RECOVER Injury Research Centre, The University of Queensland, Australia*
[f] *School of Allied Health Sciences, Griffith University, Australia*

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ABSTRACT

This study aimed to assess intra-rater (intra-session and inter-day) reliability and influence of side dominance and the scapular resting position on the shear modulus (an index of stiffness) of resting cervical and axioscapular muscles. Sixteen healthy participants were recruited. On day one, ultrasound shear wave elastography was used to measure the shear modulus of superficial and deep cervical extensor and axioscapular muscles bilaterally. Clinical assessments of scapular resting position were performed bilaterally. On day two, testing was repeated on the dominant side. Both intra-session and inter-day reliability were good to excellent for shear modulus of superficial muscles, and poor to excellent for deep muscles. Side differences of shear modulus for posterior upper trapezius were statistically significant but clinically irrelevant. The shear modulus of posterior upper trapezius and middle trapezius were significantly correlated with scapular depression. Ultrasound shear wave elastography is a reliable tool for quantitatively assessing stiffness of superficial cervical and axioscapular muscles. The influence of scapular position should be considered in future comparative studies of healthy controls and patients with neck/shoulder pain. This study provides the necessary first step for future studies on assessing and interpreting the stiffness of cervical and axioscapular muscles for neck and shoulder musculoskeletal disorders.

1. Introduction

Up to one in two people experience neck or shoulder pain each year (Hogg-Johnson et al., 2009), contributing to substantial functional disability and economic burden (Hoy et al., 2014; Pereira et al., 2017). Among patients with neck and shoulder pain, 50% to 82% of patients have increased palpable stiffness in muscles such as the cervical extensors, trapezius and levator scapulae (Andersen et al., 2011; Brandt et al., 2014). Furthermore, among pain-free individuals, self-reported high perceived stiffness of these muscles has been shown to increase the likelihood of future neck-shoulder pain by up to four times (adjusted relative risk ratio = 1.9–4.4) (Huysmans et al., 2012; Wahlström et al., 2004). Thus, quantifying local muscle stiffness might provide clinically useful information in the diagnosis of musculoskeletal disorders including idiopathic neck pain, whiplash associated disorders and shoulder problems, or assessing the effect of various treatments.

Shear wave elastography (SWE) provides noninvasive, quantitative, and real-time imaging of stiffness of various soft tissues including skeletal muscles. This technique involves generation of shear waves induced by focused acoustic radiation force, and measurement of shear wave propagation speed (Bercoff et al., 2004). Shear wave velocity is proportional to the shear modulus (considered an index of stiffness) of tissues, with greater speeds being recorded in tissues with higher stiffness. The validity of SWE in assessing passive muscle shear modulus has been demonstrated in specimens (Koo et al., 2013) and phantoms (Miyamoto et al., 2015). It has been shown that SWE is reliable to assess limb muscles (Lacourpaille et al., 2012). However, there are some doubts whether it is possible to obtain highly reliable measurements of shear modulus of cervical and axioscapular muscles, particularly the deep muscles, as they have complex fibre orientation arrangement and are covered by superficial muscles and subcutaneous fat. Recent studies have attempted to use SWE to assess shear modulus or velocity in cervical extensor muscles and some axioscapular muscles such as upper trapezius and levator scapulae in both healthy individuals (Dieterich

* Corresponding author at: School of Health and Rehabilitation Sciences, Therapies Building 84A, level 7, The University of Queensland, St Lucia, QLD 4072, Australia.

E-mail address: yanfei.xie@uqconnect.edu.au (Y. Xie).

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et al., 2017; Ewertsen et al., 2018; Heizelmann et al., 2017) and individuals with neck pain (Tas et al., 2018). However, these studies did not examine the reliability of SWE in measuring stiffness of cervical and axioscapular muscles. It is difficult to accurately interpret findings of the studies without knowing the reliability and errors of the measurements. To consider SWE for routine clinical application on cervical and axioscapular muscles and to facilitate accurate interpretation of changes in muscle stiffness, further investigations are needed to establish the test-retest reliability, standard measurements of error and minimum detection differences of SWE in assessing shear modulus of cervical and axioscapular muscles.

Measurement of axioscapular muscle stiffness requires specific considerations, including the effect of side dominance and posture, to help the interpretation of changes in muscle stiffness. Long-term preferential utilization of muscles on one body side, related to side dominance, may lead to changes in thickness of scapular muscles (Uthaikhup et al., 2015; Wannaprom et al., 2017), neuromuscular control characteristics (Farina et al., 2003; Shih and Kao, 2011), and muscle fiber composition (Fugl-Meyer et al., 1982). As these factors could potentially alter muscle stiffness, it is necessary to investigate whether there is variation in the shear modulus of cervical and axioscapular muscles between sides. In addition, scapular position may affect stiffness of axioscapular muscles due to changes in their length (Lee et al., 2015; Leong et al., 2016; Martinez-Merinero et al., 2017). Higher muscle shear modulus is consistently reported during passive lengthening (Koo et al., 2014), although synergistic muscles may show different patterns of increase in shear modulus (Coombes et al., 2018). Increased length of the trapezius by scapular depression, downward rotation or protraction may result in increased shear modulus within part of the muscle. Leong et al. (2016) found increased shear modulus of the upper trapezius in overhead athletes with rotator cuff tendinopathy and postulated that the increased stiffness may be associated with their forward shoulder postures. However, no studies have examined the association between resting scapular position and shear modulus of axioscapular muscles.

The aims of this study are threefold: (1) to evaluate intra-session and inter-day reliability of the resting shear modulus of cervical and axioscapular muscles measured by SWE in healthy people; (2) to compare the muscle shear modulus between dominant and non-dominant sides; and (3) to explore the association between shear modulus of axioscapular muscles and resting scapular position.

2. Material and methods

2.1. Participants

Sixteen pain-free participants (50% females, age: 29.3 ± 9.8 years and body mass index: 22.1 ± 3.1) with full active pain-free range of motion of the neck and shoulders, were recruited through advertising in the local university. Participants were excluded if they took muscle relaxant medication, had significant trauma or surgery to the upper body in the past 5 years, scoliosis, ankylosing spondylitis, and were pregnant or unable to sit still for a 10-min period. Purposes and procedures of this study were explained to participants prior to obtaining written consent. Ethical approval was obtained from the University of Queensland Human Research Ethics Committee (approval number: 2017001513).

2.2. Procedures

Participants attended two days of testing, approximately 48 h apart. On the first day, clinical assessments of scapular resting position were firstly performed. Then resting shear modulus of superficial and deep cervical and axioscapular muscles were measured bilaterally, including cervical, anterior and posterior portions of the upper trapezius, spinalis capitis, semispinalis capitis and cervicis, multifidus, middle and lower trapezius, levator scapular, and serratus anterior. The anterior and posterior portions of upper trapezius were measured as studies (Johnson et al., 1994; Mercer, 2002) suggest that there are two parts of upper trapezius attached to the shoulder girdle. Three trials of a 10-s elastography video clip were recorded for each muscle, with a 5-min interval between each trial, during which participants were allowed to stand up and move. The order of muscles measured and sides were randomized. All testing was performed by one investigator who had 6 months experience in the use of SWE. Muscle activity of the upper and lower trapezius was recorded using surface electromyography (EMG) during the elastrography measurement. On completion of imaging, the handedness of participants was assessed using a modified Annett Hand Preference Questionnaire (Annett, 1970). The assessor was blind to the participant's side dominance at the time of testing. On the second day, the same testing was repeated only on the dominant side by the same investigator.

2.3. Measurement of scapular resting position

The bony landmarks used for measurements of scapular resting position were identified through palpation and confirmed using B-mode ultrasound. The scapular resting position was evaluated through the following four measurements using a measuring tape and an inclinometer: the upper and lower horizontal scapular distance as indicators of scapular protraction (da Costa et al., 2010) (Fig. 1**a**), vertical distance between the 7th cervical spinous and acromion as indicator of scapular depression (Struyf et al., 2009) (Fig. 1**a**), and the acromion distance as indicator of forward shoulder posture (Struyf et al., 2009) (Fig. 1**b**). These clinical measurements have demonstrated generally good intra-rater (ICC = 0.72–0.99) and inter-rater reliability (ICC = 0.72–0.87) (da Costa et al., 2010; McKenna et al, 2004; Struyf et al., 2009). Participants sat with their back against the wall when assessing the forward shoulder posture, while they adopted the same sitting position as during imaging (described below) for other measurements.

2.4. Measurement of muscle shear modulus

For all muscles except serratus anterior, participants were seated in a height-adjustable chair, with lower back support, knees and hips bent

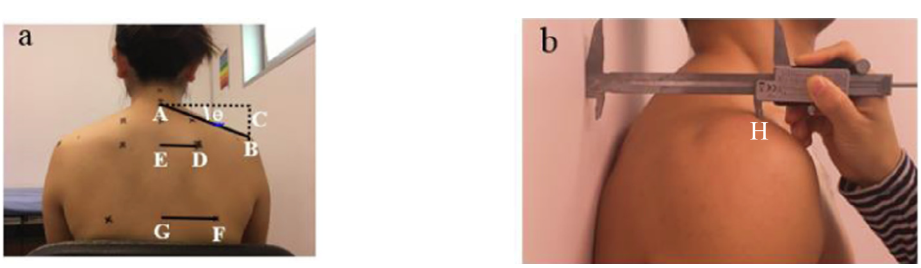
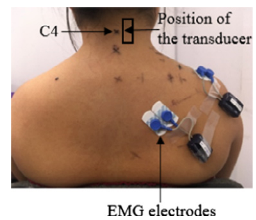
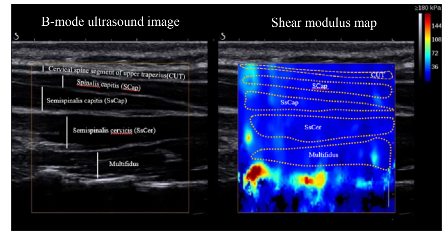
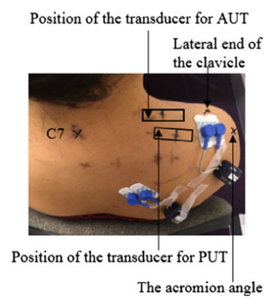
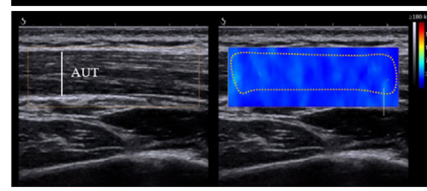
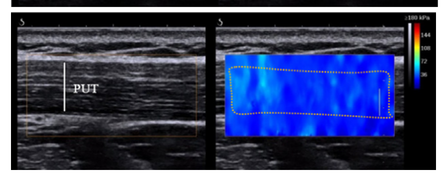
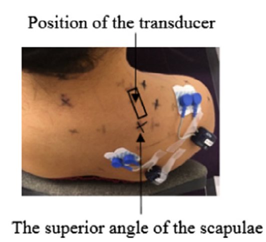
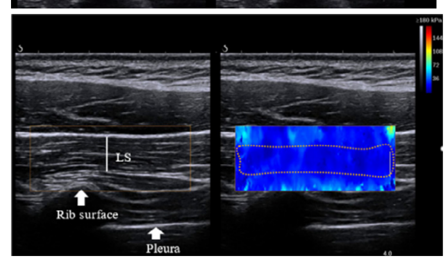
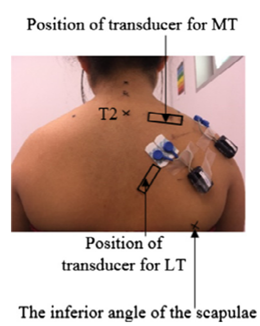
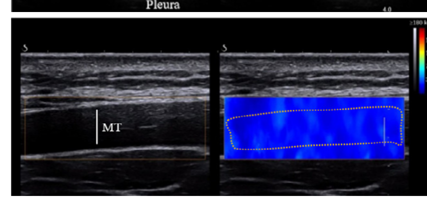
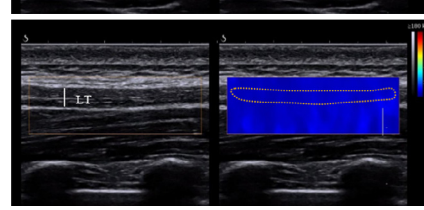
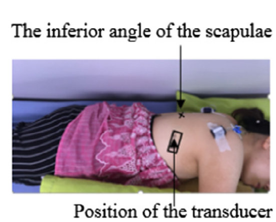
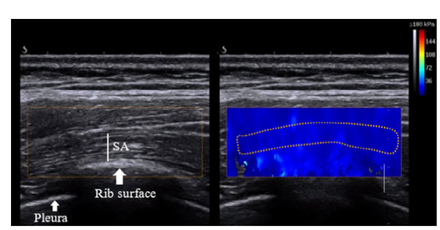


Fig. 1. Anatomical landmarks and measurements of the scapular resting position. (1a) Scapular depression (C) was estimated as the distance between the 7th cervical spinous process (A) and acromion (B) * sin ɵ; an inclinometer was used to measure ɵ. Scapular protraction was estimated as the upper horizontal scapular distance = distance between the root of the scapulae (D) and the matched thoracic spinous process (E), and the lower horizontal scapular distance = distance between inferior angle of the scapulae (F) and the matched thoracic spinous process (G). (1b) Forward shoulder posture was estimated as the distance between the anterior tip of the acromion (H) and the wall with the participant in a sitting position.

Table 1
Methods for identifying cervical and axioscapular muscles, transducer positions and regions of interest.

	Methods for identifying muscles and positions of the transducer	Positions of the ultrasound transducer	B-mode and shear modulus maps, and selected regions of interest of measured muscles for one participant
Cervical extensor muscles	The transducer was positioned in a transverse orientation at the level of 4th cervical vertebra (C4). Once the C4 level was identified, the transducer was rotated longitudinally to grossly align with muscle fibres below		
Anterior upper trapezius (AUT)	The transducer was placed mid-way between C6 and the lateral end of the clavicle, over fibers of the upper trapezius that attach to the clavicle		
Posterior upper trapezius (PUT)	The transducer was placed mid-way between the acromion angle and C7, over fibers of the upper trapezius that attach to the lateral acromion		
Levator scapulae (LS)	The transducer was placed between the superior angle of the scapulae and the midpoint between the C1 and C4 transverse processes at region of greatest muscle thickness		
Middle trapezius (MT)	The transducer was placed mid-way between the 2nd thoracic vertebra and the medial third of the scapular spine		
Lower trapezius (LT)	The transducer was first placed transversely over the spinous process at a level mid-way between the root of the spine of the scapulae and the inferior angle of the scapulae. The transducer was then moved laterally towards the deltoid tubercle of spine of the scapulae until the transducer aligned with the muscle fibers		
Serratus anterior (SA)	The transducer was positioned just below a horizontal line from the inferior angle of the scapulae to the mid-axillary line of the trunk and aligned with direction of the inferior portion of SA fibers		

Note: The dot shapes are the region of interest outlined for one participant.

at 90°, and feet resting on a foot rest. Participants were instructed with the following cues: to adopt a self-selected comfortable sitting posture; to keep the jaw relaxed without clenching; to sustain eye contact with a target placed in front at the eye level; to rest hands on thighs with palms facing down, and to maintain shoulders and scapulae in a naturally comfortable position. For serratus anterior, participants lay on the contralateral side, with their trunk in a neutral position and the upper arm and elbow supported in 90° of flexion (Talbott and Witt, 2014). Participants were asked to maintain the same position, while being as relaxed as possible during imaging. Photos of the participant's position were taken to guide return to the same position for each trial.

Supersonic shear imaging (Aixplorer version 9, Aix-en-Provence, France) and a linear transducer (2–10 MHz, SuperLinear™ SL 10–2, Aix-en-Provence, France) were used to record shear modulus. The elastography machine was set to the musculoskeletal preset, high penetration, 100% opacity, smoothing 4, and an upper limit of shear modulus of 180 kPa. The methods (Table 1) for identifying the muscles and positions for imaging were informed by previous ultrasound studies (Dieterich et al., 2017; Ishikawa et al., 2015; Krzesniak-Swinarska et al., 2017; Leong et al., 2013), and confirmed by observation of typical muscle fibre directions in 6 embalmed cadavers. The transducer was placed parallel to the muscle fibers (Gennisson et al., 2010), applying very light transducer pressure on the skin (Kot et al., 2012). Positions of the transducer were marked on the skin to facilitate consistency between testing trials.

Mean Young's modulus values were extracted using the in-built software called "Q-Box", by selecting the largest region of interest avoiding fascia planes and bony prominences (Ates et al., 2015) (Table 1). Young's modulus was converted to shear modulus by dividing by three as skeletal muscles are not isotropic materials (Leong et al., 2013). In our preliminary data analysis, no differences were identified in shear modulus values between the analysis of three representative images and analysis of all images sequenced from the 10-second video clip using Matlab software. Therefore, three images at around the 2nd, 5th, and 8th second of the 10-second video clip were extracted for calculation of shear modulus for each trial. Artifacts presenting as void occur when SWE fails to determine the shear wave propagation speed travelling through the tissue. If visually the void approached 50% of the region of interest, it was deemed as absence of shear wave estimation.

2.5. Surface EMG recording

Surface EMG was recorded using a wireless EMG system (ZeroWire EMG, Aurion, Italy) to verify that muscles were relaxed during the elastography measurement. Before the electrode placement, the skin was shaved if necessary, cleaned with alcohol pads, gently abraded with sandpaper and cleaned again with alcohol pads. Due to limited space to position both the ultrasound transducer and electrodes, only two pairs of bipolar Ag–AgCl surface electrodes (Ambu®WhiteSensor WS, diameter of the recording zone: 15 mm) were placed over posterior upper trapezius and lower trapezius with center to center electrode distance of 2 cm. Electrodes were placed beside the ultrasound transducer (Table 1). Signals were sampled at 1 kHz and digitized (30–500 Hz bandwidth) using the "Spike2" software (version 7.09, CED, Cambridge, UK). The root mean square (RMS) of EMG signals was firstly calculated over a time window of 500-millisecond and then computed averagely over the 10-second imaging. The RMS values of the trapezius were normalized to that recorded during a reference voluntary contraction performed by participants through holding a 2-kg dumbbell in both hands with shoulders abducted to 90 degrees for 15 s. Muscles were regarded as relaxed if normalized amplitude was lower than 15% of activity during reference voluntary contraction, which is approximately equivalent to 3% of activity during maximum voluntary contraction (Hansson et al., 2000).

2.6. Statistical analysis

All statistical analyses were conducted with IBM SPSS Statistics 23.0 (IBM SPSS, Armonk, New York). Data were firstly tested for normal distribution using the Shapiro-Wilk test. Potential outliers affecting normal distribution of the data were identified as points lying beyond the plot's whiskers in the box plot. Most data was normally distributed and became normally distributed after excluding one outlier for shear modulus of some muscles (described in session 3.1), therefore parametric tests were performed.

For intra-session reliability, a model 3 (2-way mixed effects, absolute agreement) single measure ICC [ICC (3, 1)] was analyzed separately for dominant and non-dominant sides on day 1 (Koo and Li, 2016). As the number of trials of scanning might influence reliability, the ICC (3,1), ICC (3, 2) and ICC (3,3) were analyzed for inter-day reliability using data of a single, the mean of two and the mean of three trials, respectively (Koo and Li, 2016). Additionally, standard error of measurement (SEM) and the minimal detectable difference (MDD) were calculated (Weir, 2005).

To compare shear modulus between sides, repeated measures analysis of variance (ANOVA) was used to test the main effect of side and a side-by-muscle interaction effect using the averaged shear modulus of three trials on day 1. When appropriate, post-hoc analyses with Bonferroni correction were conducted for multiple comparison. Finally, Pearson correlation was performed to determine any correlation between shear modulus of axioscapular muscles and measures of scapular resting position on the dominant side, as this is more likely to represent the site of pain in clinical cases.

3. Results

3.1. Reliability of muscle shear modulus

Elastography artefacts (void was larger than 50% of region of interest in the elasticity map) precluded measurement of some deep muscles including semispinalis cervicis (n = 1, 6%), multifidus (n = 2, 13%), and levator scapulae (n = 1, 6%). Data from one participant for bilateral anterior and posterior upper trapezius, semispinalis capitis, and semispinalis cervicis were excluded from the analysis (outliers). Therefore, 15/16 participants were included for the analyses of semispinalis cervicis, anterior and posterior upper trapezius and levator scapulae, 14/16 were included for semispinalis cervicis and multifidus, while all 16 were included for other muscles.

For intra-session reliability, the mean (± SD) of ICC values for superficial cervical and axioscapular muscles was 0.82 (± 0.07), ranging from 0.68 (for lower trapezius on the non-dominant side) to 0.90 (for anterior and posterior upper trapezius on the dominant side). The lower bounds of the 95% CI of ICC values was larger than 0.50 for most of superficial muscles (Table 2). The SEM and MDD for the superficial muscles were lower than 1.09 kPa and 3.03 kPa, respectively (Table 2). Regarding deep cervical and axioscapular muscles, the mean (± SD) intra-session ICC value was 0.68 (± 0.12), ranging from 0.47 for the semispinalis capitis and 0.84 for the serratus anterior on the non-dominant side. These deep muscles showed lower bounds of 95% CI of intra-session ICC values ranging from 0.14 to 0.67, SEM values of 0.53–4.69 kPa and MDD values of 1.46–13.00 kPa (Table 2).

For inter-day reliability, ICC values increased when they were analyzed using the mean of two or three trials compared to using data of a single trial. When calculated using data of a single trial, the estimated ICC of all muscles ranged from 0.62 to 0.89, with lower bounds of 95% CI of the ICC were < 0.50 for almost all muscles (Table 3). In contrast, when calculating using the mean of two trials, all superficial muscles showed ICC values of 0.87–0.95 (lower bound of 95%CI ≥ 0.62) (Table 3), SEM values ≤ 1.71 kPa and MDD values ≤ 4.73 kPa, while deep muscles demonstrated ICC values of 0.82–0.91 (lower bound of 95%CI ≥ 0.45), SEM values ≤ 1.78 kPa and MDD values ≤ 4.92 kPa (Table 3). Averaging shear modulus of three trials, compared to two trials, resulted in no further to little increase in ICC values or decrease in SEM (Table 3).

3.2. EMG results

Due to technical issues, EMG recordings were synchronized with the elastography measurement for only 10 participants. Amongst these 10 participants, normalized EMG amplitudes remained less than 15% of reference voluntary contraction during all trials of imaging of all trapezius muscles (Table 4), indicating the trapezius muscles were in a resting state.

Table 2
Reliability results of intra-session measurement, mean shear modulus and standard deviation (SD) of three trials on the first day of measurement for cervical extensor and axioscapular muscles.

Muscles		Non-dominant side				Dominant side			
		ICC (95% CI)	SEM (KPa)	MDD (kPa)	Shear modulus (kPa)	ICC (95% CI)	SEM (kPa)	MDD (kPa)	Shear modulus (kPa)
Superficial cervical extensor muscles	CUT (n = 16)	0.85 (0.70, 0.94)	0.71	1.96	6.45 ± 1.73	0.75 (0.53, 0.89)	1.07	2.95	6.36 ± 1.94
	SCap (n = 16)	0.80 (0.60, 0.92)	0.95	2.63	7.32 ± 1.95	0.76 (0.55, 0.90)	1.09	3.03	6.93 ± 2.06
Deep cervical extensor muscles	SsCap (n = 15)	0.78 (0.57, 0.91)	1.70	4.71	9.04 ± 3.36	0.64 (0.37, 0.85)	1.44	3.99	7.71 ± 2.09
	SsCer (n = 14)	0.47 (0.14, 0.76)	2.23	6.71	8.40 ± 2.47	0.62 (0.32, 0.84)	1.75	4.85	7.82 ± 2.41
	Multifidus (n = 14)	0.65 (0.37, 0.86)	3.67	10.17	13.48 ± 5.48	0.51 (0.21, 0.79)	4.69	13.00	11.62 ± 5.53
Superficial axioscapular muscles	AUT (n = 15)	0.84 (0.67, 0.94)	0.94	2.61	12.91 ± 2.22	0.90 (0.78, 0.96)	1.01	2.80	13.56 ± 3.02
	PUT (n = 15)	0.83 (0.66, 0.93)	0.90	2.50	12.18 ± 2.09	0.90 (0.78, 0.96)	0.97	2.70	13.43 ± 2.98
	MT (n = 16)	0.81 (0.63, 0.92)	0.90	2.49	8.38 ± 1.93	0.88 (0.74, 0.95)	0.82	2.28	8.93 ± 2.23
	LT (n = 16)	0.68 (0.42, 0.86)	0.57	1.59	4.65 ± 0.89	0.80 (0.59, 0.91)	0.49	1.37	4.46 ± 1.01
Deep axioscapular muscles	LS (n = 15)	0.84 (0.67, 0.94)	1.05	2.92	8.37 ± 2.47	0.76 (0.53, 0.90)	0.97	2.69	7.66 ± 1.82
	SA (n = 16)	0.75 (0.54, 0.90)	0.70	1.95	5.36 ± 1.30	0.80 (0.60, 0.92)	0.53	1.46	5.26 ± 1.09

Note: A series of 10-s elastography videos were recorded on alternate sides for each of 11 muscle regions in a randomized order. This protocol was repeated three times (3 trials) with a 5-min interval between each trial, during which period the participant was able to stand up and move. The intraclass correlation coefficient (ICC) and 95% confidence interval (CI), standard error of measurement (SEM) and minimal detectable difference (MDD) were calculated from the three trials for each muscle region.
CUT = Cervical spine segment of upper trapezius; SCap = Splenius capitis; SsCap = Semispinalis capitis; SsCer = Semispinalis cervicis; AUT = Anterior upper trapezius; PUT = Posterior upper trapezius; MT = Middle trapezius; LT = Lower trapezius; LS = Levator scapulae; SA = Serratus anterior.

3.3. Side difference in muscle shear modulus

For shear modulus measurements, there was significant side-by-muscle interaction ($p = 0.012$). Post-hoc analyses showed that significant side differences were only found for posterior upper trapezius [mean difference = 1.25 kPa, 95%CI = (0.27, 2.23), $p = 0.016$], with higher shear modulus on the dominant side than the non-dominant side (Table 2).

3.4. Correlation between scapular resting position and shear modulus

Scapular depression was significantly and positively correlated with shear modulus of posterior upper trapezius (day 1: r = 0.45, $p = 0.044$; day 2: r = 0.48, $p = 0.030$) and with middle trapezius (day 1: r = 0.57, $p = 0.010$; day 2: r = 0.60, $p = 0.007$) on the dominant side (Fig. 2).

4. Discussion

In this study, the point intra-session and inter-day (calculated using the mean of two or three trials) ICC estimates of most of the superficial cervical and axioscapular muscles were larger than 0.75, demonstrating good to excellent reliability (Koo and Li, 2016). Furthermore, these muscles presented lower bounds of 95% CI ≥ 0.50 for the ICC estimates, indicating 95% confidence of being at least moderately reliable in a worst case scenario (Koo and Li, 2016). Additionally, the intra-session and inter-day SEMs were less than 18% of the mean shear modulus for all superficial muscles. Thus, this study showed that SWE can reliably assess and monitor stiffness of the superficial cervical and axioscapular muscles.

In contrast, it was more challenging and less reliable to measure shear modulus of deep muscles, particularly the deep cervical muscles. Shear modulus of the deep muscles could not be calculated for a small proportion of participants (6–12.5% depending on the muscles) because of the absence of shear wave estimation. A similar phenomenon was observed by MacDonald et al. (2016) using the same elastography technique to measure shear modulus of deep abdominal muscles. The absence of shear wave estimation could be due to increased scanning depth associated with thick superficial fat and/or tissue layers (Ewertsen et al., 2016; Rominger et al., 2018). Rominger et al. (2018) found measurement of shear modulus is incomplete at the depth of 4 cm and not feasible at a depth ≥ 5 cm when measuring fresh porcine muscles using SWE. This technique therefore may have limited application in cases of large or obese individuals. Of the successfully imaged participants, the measured deep muscles demonstrated poor to excellent intra-session and inter-day reliability with wide ranges of 95% CI. Furthermore, the SEM could be as high as 40% of the mean shear modulus of the muscle. Therefore, caution is needed when interpreting changes of stiffness of the deep cervical and axioscapular muscles in future studies. Averaging the shear modulus of multiple measurements for one sample may help improve the reliability. This study showed that, regardless of the muscle imaged, the ICC and SEM values substantially improved when averaging two or three trials of measurements compared to a single trial of measurement. But there was not much improvement when averaging two trials of measurements compared to three trials. Therefore, reliable measurements can be equally achieved when performing two or three nonconsecutive scans.

Shear modulus was comparable between dominant and non-dominant sides for the majority of muscles, except posterior upper trapezius. Significantly greater shear modulus was observed for posterior upper trapezius on the dominant side than the non-dominant side. Such difference may be explained by muscle adaptation secondary to higher mechanical loading resulting from long-term and frequent use of the dominant arm. However, the side-to-side difference was less than the MDD for posterior upper trapezius, indicating this was clinically irrelevant. Recent studies reported mixed results regarding the influence of hand dominance on the posterior upper trapezius. A study with 5

Table 3
Reliability results of inter-day measurements calculated using data of a single trial, means of first and second trials and means of three trials from day 1 and day 2, and averages of shear modulus of three trials on day 2 for cervical extensor muscles and axioscapular muscles on the dominant side.

Muscles	Number of measurements	ICC (95% CI)	SEM (kPa)	MDD (kPa)	Mean shear modulus of three trials (kPa) (mean ± SD)
Superficial cervical extensor muscles					
CUT (n = 16)	Single trial	0.69 (0.32, 0.88)	1.10	3.04	6.15 ± 1.90
	Mean of two trials	0.87 (0.62, 0.95)	0.91	2.53	
	Mean of three trials	0.91 (0.74, 0.97)	0.78	2.17	
SCap (n = 16)	Single trial	0.78 (0.49, 0.92)	1.07	2.98	6.82 ± 2.20
	Mean of two trials	0.90 (0.72, 0.97)	0.87	2.40	
	Mean of three trials	0.92 (0.78, 0.97)	0.80	2.21	
Deep cervical extensor muscles					
SsCap (n = 15)	Single trial	0.77 (0.43, 0.92)	1.29	3.56	7.78 ± 2.88
	Mean of two trials	0.82 (0.46, 0.94)	1.32	3.66	
	Mean of three trials	0.85 (0.55, 0.95)	1.27	3.52	
SsCer (n = 14)	Single trial	0.78 (0.44, 0.92)	1.28	3.55	7.65 ± 2.72
	Mean of two trials	0.83 (0.47, 0.95)	1.21	3.37	
	Mean of three trials	0.80 (0.36, 0.94)	1.46	4.06	
Multifidus (n = 14)	Single trial	0.72 (0.33, 0.90)	2.03	5.63	10.10 ± 3.42
	Mean of two trials	0.88 (0.63, 0.96)	1.78	4.92	
	Mean of three trials	0.71 (0.15, 0.91)	3.12	8.64	
Superficial axioscapular muscles					
AUT (n = 15)	Single trial	0.85 (0.47, 0.95)	1.40	3.88	12.91 ± 3.30
	Mean of two trials	0.95 (0.84, 0.99)	1.71	4.73	
	Mean of three trials	0.96 (0.85, 0.99)	0.93	2.57	
PUT (n = 15)	Single trial	0.80 (0.31, 0.94)	1.44	3.99	12.26 ± 2.99
	Mean of two trials	0.95 (0.72, 0.99)	1.23	3.41	
	Mean of three trials	0.90 (0.54, 0.97)	1.34	3.71	
MT (n = 16)	Single trial	0.89 (0.64, 0.96)	0.78	2.17	8.38 ± 2.17
	Mean of two trials	0.94 (0.80, 0.98)	0.78	2.17	
	Mean of three trials	0.94 (0.78, 0.98)	0.77	2.15	
LT (n = 16)	Single trial	0.74 (0.40, 0.90)	0.60	1.66	4.39 ± 1.09
	Mean of two trials	0.92 (0.78, 0.97)	0.40	1.10	
	Mean of three trials	0.92 (0.78, 0.97)	0.40	1.12	
Deep axioscapular muscles					
LS (n = 15)	Single trial	0.71 (0.33, 0.89)	1.18	3.26	7.57 ± 2.01
	Mean of two trials	0.91 (0.74, 0.97)	0.80	2.21	
	Mean of three trials	0.94 (0.81, 0.98)	0.67	1.58	
SA (n = 16)	Single trial	0.62 (0.19, 0.85)	0.75	2.08	5.21 ± 1.00
	Mean of two trials	0.81 (0.45, 0.93)	0.63	1.76	
	Mean of three trials	0.90 (0.74, 0.97)	0.43	1.18	

Note: ICC = Intraclass correlation coefficient; SEM = Standard error of measurement; MDD = Minimal detectable difference; CUT = Cervical spine segment of upper trapezius; SCap = Spinalis capitis; SsCap = Semispinalis capitis; SsCer = Semispinalis cervicis; AUT = Anterior upper trapezius; PUT = Posterior upper trapezius; MT = Middle trapezius; LT = Lower trapezius; LS = Levator scapulae; SA = Serratus anterior.

female and 5 male participants found no side differences in shear velocity of the posterior upper trapezius (Ewertsen et al., 2018), while the other study with 20 male participants reported significantly higher Young's modulus of the posterior upper trapezius on the dominant side than the non-dominant side (mean difference = 5.22 kPa) (Zhang et al., 2019). Different results might be associated with factors related to the samples used in the studies, such as gender and levels of physical activity (Heizelmann et al., 2017). Alternatively, the small side-to-side difference may be related to the small sample size. Although this study indicates that hand dominance does not have a clinically important effect on the SWE results, to accurately interpret pathological changes, clinical application of SWE may need to account for arm dominance-related differences when comparing stiffness of the posterior upper trapezius between a healthy and pathological side among athletes who frequently use the dominant hand to play sports such as badmintons and tennis.

Table 4
Means and standard deviations of normalized surface electromyography amplitude [percentages of reference voluntary contraction (%RVC)] during imaging of anterior upper trapezius (AUT), posterior upper trapezius (PUT), middle trapezius (MT), and lower trapezius (LT) on day 1 and day 2.

Imaged muscles	Day 1 (%RVC)			Day 2 (%RVC)		
	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3
ND_AUT	2.8 ± 1.8	2.7 ± 1.8	2.8 ± 1.8	NA	NA	NA
D_AUT	3.2 ± 1.8	3.1 ± 1.8	2.7 ± 1.4	2.9 ± 2.0	2.8 ± 1.8	3.0 ± 2.1
ND_PUT	3.0 ± 1.8	3.0 ± 2.3	2.7 ± 1.8	NA	NA	NA
D_PUT	3.4 ± 2.3	3.0 ± 1.8	3.1 ± 1.8	2.9 ± 1.9	2.7 ± 1.5	2.8 ± 1.7
ND_MT	5.5 ± 3.3	5.1 ± 2.8	4.9 ± 2.5	NA	NA	NA
D_MT	6.1 ± 2.3	5.4 ± 2.3	5.4 ± 2.5	5.5 ± 3.4	5.2 ± 3.1	5.4 ± 3.0
ND_LT	5.2 ± 2.7	4.8 ± 2.8	4.8 ± 2.7	NA	NA	NA
D_LT	5.3 ± 2.3	5.2 ± 2.5	5.7 ± 2.9	5.8 ± 2.9	5.2 ± 3.2	5.5 ± 3.0

Note: ND = Non-dominant side; D = Dominant side; NA = Not applicable.

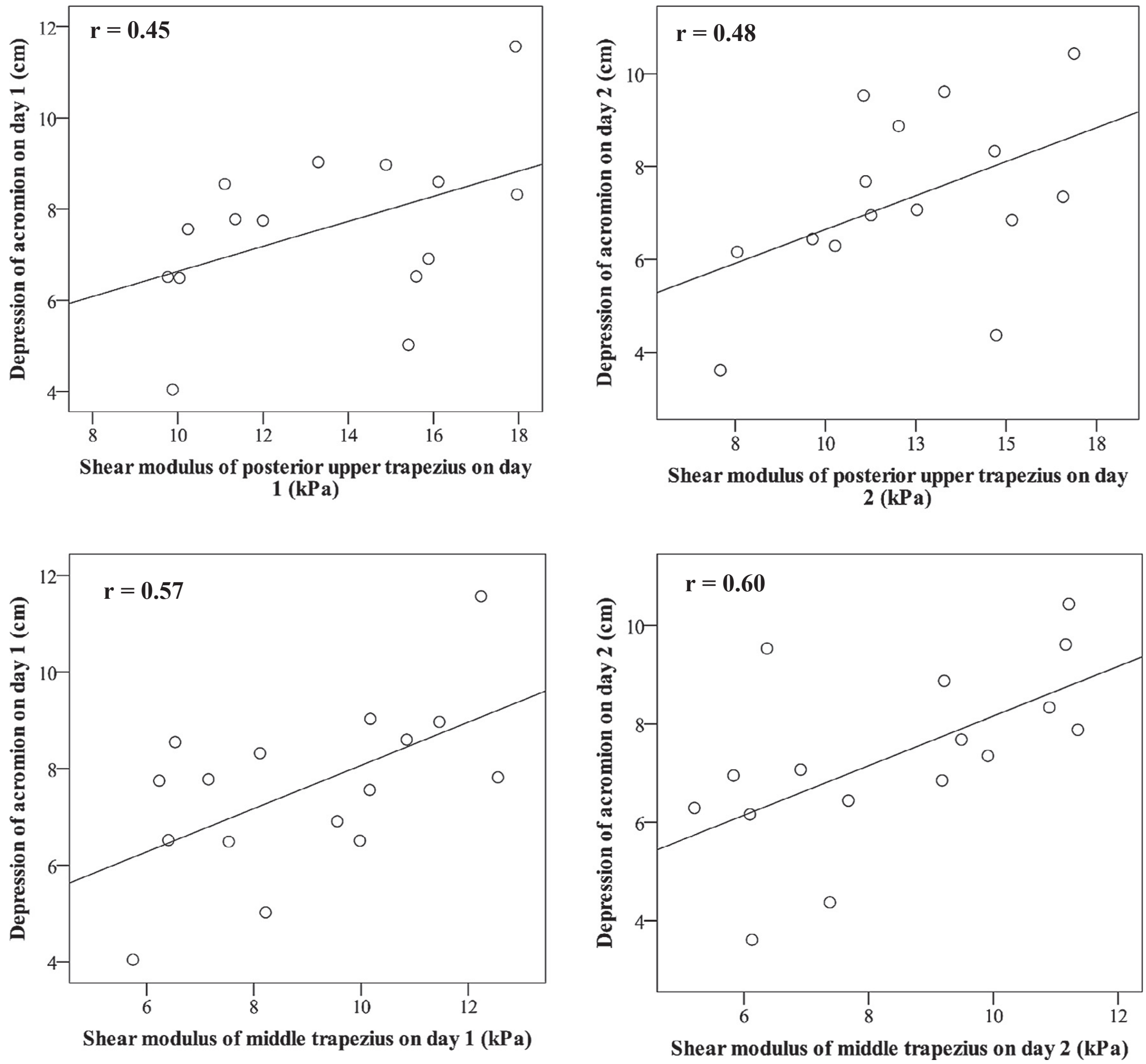


Fig. 2. Correlation of scapular depression with shear modulus of the posterior upper trapezius and middle trapezius on the dominant side.

This study identified moderate to large positive correlations between the extent of scapular depression and shear modulus of posterior upper trapezius and middle trapezius respectively. It has been well documented that shear modulus of muscles increases as muscle length increases (Koo et al., 2014; Maisetti et al., 2012). Our findings verify the hypothesis proposed by previous studies (Lee et al., 2015; Martinez-Merinero et al., 2017) that a depressed scapular position would place the upper and middle trapezius in a lengthened position, increasing the tension on these muscles. The correlations between the scapular depression and shear modulus of the trapezius muscles may help partly interpret the association between altered scapular alignment and neck/shoulder pain described in the literature (Ha et al., 2011; Swift and Nichols, 1984; Van Dillen et al., 2007). Although preliminary, these findings provide justification for a larger scale exploration of the biomechanical mechanisms involved in conditions such as chronic neck pain, whiplash injuries, headaches and shoulder problems, by combining shear wave elastography, scapular kinematics and EMG measurements.

Increased muscle stiffness is a common clinical symptom and has been previously associated with increased risk of musculoskeletal pain (Huysmans et al., 2012; Wahlström et al., 2004) and sport-related injuries (Watsford et al., 2010). Therefore, quantitative estimates of local muscle stiffness may present a clinical application in predicting the development and progression of musculoskeletal pain and in tracking responses of muscles to rehabilitation interventions. The good to excellent repeatability of assessing superficial cervical and axioscapular muscles highlights that SWE could be useful in identifying early changes of muscle mechanical properties involved in neck/shoulder and other neuromuscular disorders (Harmon et al., 2019). Minimal detectable differences established in this study provided important information to guide clinicians and researchers in interpretation of true changes in shear modulus of cervical and axioscapular muscles. The following limitations for this study are acknowledged. First, inter-operator reliability which is also a key element to determine the reliability of a tool was not established. Second, due to the limited space in the neck and scapulae, EMG activity recorded in some superficial muscles was used to represent the activity for all muscles. Last, the simple and clinical characterization of the scapular position may limit our findings on its relationship with the shear modulus of axioscapular muscles. It might be more accurate using a radiological assessment of the scapular position.

In summary, SWE can reliably and quantitatively assess the stiffness of superficial cervical and axioscapular muscles but it is less reliable for deep muscles. Two and three separate scans were equally able to achieve acceptable inter-day reliability. Future study is warranted to characterize stiffness of these muscles among symptomatic and asymptomatic individuals to better understand the etiology and progression of neck and shoulder musculoskeletal conditions which may help guide treatment. The influence of scapular position should be considered when interpreting differences in shear modulus between symptomatic and asymptomatic individuals.

Declaration of Competing Interest

The authors declared that there is no conflict of interest.

References

Andersen, L.L., Hansen, K., Mortensen, O.S., Zebis, M.K., 2011. Prevalence and anatomical location of muscle tenderness in adults with nonspecific neck/shoulder pain. BMC Musculoskelet. Disord. 12, 169.

Annett, M., 1970. A classification of hand preference by association analysis. Br. J. Psychol. 61 (3), 303–321.

Ates, F., Hug, F., Bouillard, K., Jubeau, M., Frappart, T., Couade, M., Bercoff, J., Nordez, A., 2015. Muscle shear elastic modulus is linearly related to muscle torque over the entire range of isometric contraction intensity. J. Electromyogr. Kinesiol. 25 (4), 703–708.

Bercoff, J., Tanter, M., Fink, M., 2004. Supersonic shear imaging: a new technique for soft tissue elasticity mapping. IEEE Trans. Ultrason. Ferroelectr. Freq. Control 51 (4), 396–409.

Brandt, M., Sundstrup, E., Jakobsen, M.D., Jay, K., Colado, J.C., Wang, Y., Zebis, M.K., Andersen, L.L., 2014. Association between neck/shoulder pain and trapezius muscle tenderness in office workers. Pain Res. Treat. 2014, 352735.

Coombes, B.K., Ziegenfuss, B., David, M., Badya, R., van den Hoorn, W., Hug, F., Tucker, K., 2018. Heterogeneity of passive elastic properties within the quadriceps femoris muscle-tendon unit. Eur. J. Appl. Physiol. 118 (1), 213–221.

da Costa, B.R., Armijo-Olivo, S., Gadotti, L., Warren, S., Reid, D.C., Magee, D.J., 2010. Reliability of scapular positioning measurement procedure using the Palpation Meter (PALM). Physiotherapy 96 (1), 59–67.

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. Eur. J. Appl. Physiol. 117 (1), 171–178.

Ewertsen, C., Carlsen, J.F., Christiansen, I.R., Jensen, J.A., Nielsen, M.B., 2016. Evaluation of healthy muscle tissue by strain and shear wave elastography - dependency on depth and ROI position in relation to underlying bone. Ultrasonics 71, 127–133.

Ewertsen, C., Carlsen, J., Perveez, M.A., Schytz, H., 2018. Reference values for shear wave elastography of neck and shoulder muscles in healthy individuals. Ultras. Int. Open. 4 (1), E23–E29.

Farina, D., Kallenberg, L.A., Merletti, R., Hermens, H.J., 2003. Effect of side dominance on myoelectric manifestations of muscle fatigue in the human upper trapezius muscle. Eur. J. Appl. Physiol. 90 (5–6), 480–488.

Fugl-Meyer, A.R., Eriksson, A., Sjöström, M., Söderström, G., 1982. Is muscle structure influenced by genetical or functional factors? A study of three forearm muscles. Acta Physiol. Scand. 114 (2), 277–281.

Gennisson, J.L., Deffieux, T., Mace, E., Montaldo, G., Fink, M., Tanter, M., 2010. Viscoelastic and anisotropic mechanical properties of in vivo muscle tissue assessed by supersonic shear imaging. Ultras. Med. Biol. 36 (5), 789–801.

Ha, S.M., Kwon, O.Y., Yi, C.H., Jeon, H.S., Lee, W.H., 2011. Effects of passive correction of scapular position on pain, proprioception, and range of motion in neck-pain patients with bilateral scapular downward-rotation syndrome. Man. Ther. 16 (6), 585–589.

Hansson, G.A., Nordander, C., Asterland, P., Ohlsson, K., Stromberg, U., Skerfving, S., Rempel, D., 2000. Sensitivity of trapezius electromyography to differences between work tasks - influence of gap definition and normalisation methods. J. Electromyogr. Kinesiol. 10 (2), 103–115.

Harmon, B., Wells, M., Park, D., Gao, J., 2019. Ultrasound elastography in neuromuscular and movement disorders. Clin. Imag. 53, 35–42.

Heizelmann, A., Tasdemir, S., Schmidberger, J., Gräter, T., Kratzer, W., Grüner, B., 2017. Measurements of the trapezius and erector spinae muscles using virtual touch imaging quantification ultrasound-Elastography: a cross section study. BMC Musculoskelet. Disord. 18 (1), 370.

Hogg-Johnson, S., van der Velde, G., Carroll, L.J., Holm, L.W., Cassidy, J.D., Guzman, J., Côté, P., Haldeman, S., Ammendolia, C., Carragee, E., Hurwitz, E., Nordin, M., Peloso, P., 2009. The burden and determinants of neck pain in the general population: results of the Bone and Joint Decade 2000–2010 Task Force on Neck Pain and Its Associated Disorders. J. Manipul. Physiol. Ther. 32 (2 Suppl), S46–S60.

Hoy, D., March, L., Woolf, A., Blyth, F., Brooks, P., Smith, E., Vos, T., Barendregt, J., Blore, J., Murray, C., Burstein, R., Buchbinder, R., 2014. The global burden of neck pain: estimates from the global burden of disease 2010 study. Ann. Rheum. Dis. 73 (7), 1309–1315.

Huysmans, M.A., Blatter, B.M., van der Beek, A.J., 2012. Perceived muscular tension predicts future neck-shoulder and arm-wrist-hand symptoms. Occup. Environ. Med. 69 (4), 261–267.

Ishikawa, H., Muraki, T., Sekiguchi, Y., Ishijima, T., Morise, S., Yamamoto, N., Itoi, E., Izumi, S., 2015. Noninvasive assessment of the activity of the shoulder girdle muscles using ultrasound real-time tissue elastography. J. Electromyogr. Kinesiol. 25 (5), 723–730.

Johnson, G., Bogduk, N., Nowitzke, A., House, D., 1994. Anatomy and actions of the trapezius muscle. Clin. Biomech. (Bristol, Avon) 9 (1), 44–50.

Koo, T.K., Guo, J.Y., Cohen, J.H., Parker, K.J., 2013. Relationship between shear elastic modulus and passive muscle force: an ex-vivo study. J. Biomech. 46 (12), 2053–2059.

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. Clin. Biomech. (Bristol, Avon) 29 (1), 33–39.

Koo, T.K., Li, M.Y., 2016. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. J. Chiropr. Med. 15 (2), 155–163.

Kot, B.C., Zhang, Z.J., Lee, A.W., Leung, V.Y., 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.

Krzesniak-Swinarska, M., Caress, J.B., Cartwright, M.S., 2017. Neuromuscular ultrasound for evaluation of scapular winging. Muscle Nerve 56 (1), 7–14.

Lacourpaille, L., Hug, F., Bouillard, K., Hogrel, J.Y., Nordez, A., 2012. Supersonic shear imaging provides a reliable measurement of resting muscle shear elastic modulus. Physiol. Meas. 33 (3), N19–N28.

Lee, K.T., Chuang, C.C., Lai, C.H., Ye, J.J., Wu, C.L., 2015. Study of the trapezius muscle region pressure pain threshold and latency time in young people with and without depressed scapula. Man. Ther. 20 (1), 124–129.

Leong, H.T., Hug, F., Fu, S.N., 2016. Increased upper trapezius muscle stiffness in overhead athletes with rotator cuff tendinopathy. PLoS ONE 11 (5), e0155187.

Leong, H.T., Ng, G.Y., Leung, V.Y., Fu, S.N., 2013. Quantitative estimation of muscle shear elastic modulus of the upper trapezius with supersonic shear imaging during arm positioning. PLoS ONE 8 (6), e67199.

MacDonald, D., Wan, A., McPhee, M., Tucker, K., Hug, F., 2016. Reliability of abdominal muscle stiffness measured using elastography during trunk rehabilitation exercises. Ultras. Med. Biol. 42 (4), 1018–1025.

Maisetti, O., Hug, F., Bouillard, K., Nordez, A., 2012. Characterization of passive elastic properties of the human medial gastrocnemius muscle belly using supersonic shear imaging. J. Biomech. 45 (6), 978–984.

Martinez-Merinero, P., Lluch, E., Gallezo-Izquierdo, T., Pecos-Martin, D., Plaza-Manzano, G., Nunez-Nagy, S., Falla, D., 2017. The influence of a depressed scapular alignment on upper limb neural tissue mechanosensitivity and local pressure pain sensitivity. Musculoskelet. Sci. Pract. 29, 60–65.

McKenna, L., Cunningham, J., Straker, L., 2004. Inter-tester reliability of scapular position in junior elite swimmers. Phys. Ther. Sport. 5, 146–155.

Mercer, S.R., 2002. Surface electrode placement and upper trapezius. Adv. Physiother. 4, 50–53.

Miyamoto, N., Hirata, K., Kanehisa, H., Yoshitake, Y., 2015. Validity of measurement of shear modulus by ultrasound shear wave elastography in human pennate muscle. PLoS ONE 10 (4), e0124311.

Pereira, M.J., Johnston, V., Straker, L.M., Sjøgaard, G., Melloh, M., O'Leary, S.P., Comans, T.A., 2017. An investigation of self-reported health-related productivity losses in office workers and associations with individual and work-related factors using an employer's perspective. J. Occup. Environ. Med. 59 (7), e138–e144.

Rominger, M.B., Kalin, P., Mastalerz, M., Martini, K., Klingmuller, V., Sanabria, S., Frauenfelder, T., 2018. Influencing factors of 2D shear wave elastography of the muscle - an ex vivo animal study. Ultras. Int. Open. 4 (2), E54–E60.

Shih, Y.F., Kao, Y.H., 2011. Influence of pain location and hand dominance on scapular kinematics and EMG activities: an exploratory study. BMC Musculoskelet. Disord. 12, 267.

Swift, T.R., Nichols, F.T., 1984. The droopy shoulder syndrome. Neurology 34 (2), 212–215.

Struyf, F., Nijs, J., De Coninck, K., Giunta, M., Mottram, S., Meeusen, R., 2009. Clinical assessment of scapular positioning in musicians: an intertester reliability study. J. Athl. Train. 44 (5), 519–526.

Talbott, N.R., Witt, D.W., 2014. Ultrasound examination of the serratus anterior during scapular protraction in asymptomatic individuals: reliability and changes with contraction. PM R. 6 (3), 227–234.

Tas, S., Korkusuz, F., Erden, Z., 2018. Neck muscle stiffness in participants with and without chronic neck pain: a shear-wave elastography study. J. Manipul. Physiol. Ther. 41 (7), 580–588.

Uthaikhup, S., Wannaprom, N., Kummaung, P., 2015. Effects of gender and hand dominance on size of the lower trapezius muscle. Muscle Nerve 52 (4), 576–579.

Van Dillen, L.R., McDonnell, M.K., Susco, T.M., Sahrmann, S.A., 2007. The immediate effect of passive scapular elevation on symptoms with active neck rotation in patients with neck pain. Clin. J. Pain 23 (8), 641–647.

Watsford, M.L., Murphy, A.J., McLachlan, K.A., Bryant, A.L., Cameron, M.L., Crossley, K.M., Makdissi, M., 2010. A prospective study of the relationship between lower body stiffness and hamstring injury in professional Australian rules footballers. Am. J. Sports Med. 38 (10), 2058–2064.

Wahlström, J., Hagberg, M., Toomingas, A., Wigaeus, Tornqvist, E., 2004. Perceived muscular tension, job strain, physical exposure, and associations with neck pain among VDU users; a prospective cohort study. Occup. Environ. Med. 61 (6), 523–528.

Wannaprom, N., Khamkruang, J., Puachaikul, J., Uthaikhup, S., 2017. A comparison of thickness of the serratus anterior muscle during contraction between dominant and non-dominant hands in healthy individuals. J. Assoc. Med. Sci. 50 (3), 385.

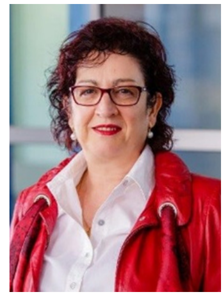
Weir, J.P., 2005. Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. J. Stren. Cond. Res. 19 (1), 231–240.

Zhang, J., Yu, J., Liu, C., Tang, C., Zhang, Z., 2019. Modulation in elastic properties of upper trapezius with varying neck angle. Appl. Bion. Biomech. 2019, 6048562.

Yanfei Xie is a PhD candidate in The University of Queensland. She received MPhil degree in rehabilitation science in The Hong Kong Polytechnic University in 2016. She received Outstanding Student Project Award from The Hong Kong Ergonomics Society recognizing her excellent work on a research project on musculoskeletal loading in using a touchscreen smartphone among young people with and without chronic neck-shoulder pain. Her current PhD project involves ultrasound elastography, quantitative sensory, physical and psychosocial tests to understand the nature of work-related neck-shoulder pain and to identify predictors of persistent pain and disability.

Dr Lucy Thomas is an academic at the University of Queensland, conjoint lecturer at the University of Newcastle and a Titled Musculoskeletal Physiotherapist. She teaches musculoskeletal physiotherapy to entry level and postgraduate students, in particular the assessment and management of cervical spine disorders. Her PhD "*Minimising Risk Factors for Cervical Spine Manipulation*" and ongoing research has investigated cervical arterial dissection, cervical arterial blood flow and screening for vascular risk in the neck. Dr Thomas chaired the working party reviewing the Australian Physiotherapy Association (2006) Guidelines for assessing Vertebrobasilar Insufficiency and lead author of the "*Clinical guide to safe manual therapy practice in the cervical spine*" (2018). Current research projects include development of a screening tool for cervical arterial dissection, anatomical and imaging studies examining stresses on the cervical artery wall. She presents regularly at both national and international conferences and workshops.

François HUG (PhD) is a Professor at Nantes University (France) and a junior fellow of the *Institut Universitaire de France* (IUF). He has a background in Human Movement Sciences (PhD in 2003 at the University of Aix-Marseille II, France). His research focuses on the control of movement in health and disease. Specifically, using a neuromechanical approach he aims to understand the origin of individual muscle coordination strategies (or signatures) and their role in the development/persistence of musculoskeletal disorders. François has published over 145 publications/book chapters. He serves on the editorial board of *Journal of Electromyography and Kinesiology*.



Venerina Johnston is an Associate Professor in RECOVER Injury Research Centre, The University of Queensland in Australia where she leads a program of research focused on optimising recovery of functional and vocational outcomes after compensable injury. Her research investigates the barriers and enablers a person may experience when attempting to return to, or remain at work after a compensable injury. This research has led to the development of strategies (individual and workplace based) to improve or maintain work ability without negatively impacting productivity. Her research lab integrates ergonomics and occupational health to deliver health interventions for neck pain in the working population.

Brooke Coombes is a Musculoskeletal Physiotherapist and academic in Physiotherapy at Griffith University. Her research focuses on understanding the mechanisms involved in the development and persistence of chronic musculoskeletal problems. She has lead randomised controlled trials to determine efficacy and cost-effectiveness of interventions to improve pain and disability for lateral elbow tendinopathy. She has developed methodology for use of ultrasound elastography to quantify the mechanical properties of muscle and tendon, gaining insight into the effects of disease, injury, ageing and exercise.