ASSOCIATION BETWEEN THE MECHANICAL PROPERTIES OF PARASPINAL MUSCLES AND CHRONIC NON-SPECIFIC LOW BACK PAIN IN ATHLETES

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Association Between the Mechanical Properties of Paraspinal Muscles and Chronic Non-Specific Low Back Pain in Athletes

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CERTIFICATE OF ORIGINALITY

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ABSTRACT

Although alterations in lumbar muscle mechanics have been proposed as a cause of low back pain (LBP) in athletes, there is limited research on the diaphragm and psoas major (PM) muscles and their association with chronic LBP. Therefore, this thesis aimed to deepen our understanding of lumbar muscle mechanical dysfunctions in athletes with chronic LBP.

Previous studies have identified a connection between the mechanical properties of the diaphragm, PM, lumbar multifidus (LM), and LBP. However, several knowledge gaps indicate the need for further exploration. First, it is unclear whether athletes with LBP exhibit inferior diaphragm mechanical properties. More essentially, how diaphragm mechanical properties are associated with sports performance and the severity of LBP are largely unknown. Second, a reliable method for quantifying PM muscle stiffness is needed, along with a comparison of stiffness between athletes with and without LBP. Finally, research is lacking on muscle stiffness, particularly the differential modulation of the deep (DLM) and superficial (SLM) layers of the LM muscle by LBP or specific sports activities, necessitating further investigation.

The review **(Study 1)** aimed to identify a feasible and reliable method for quantifying diaphragm thickness and excursion at a sports centre, while the cross-sectional study **(Study 2)** assessed the test-retest reliability of using ultrasound shear wave elastography (SWE) to measure the stiffness of the PM. The findings from these studies indicated that ultrasonography provides sufficient reliability (ICC > 0.7) for assessing diaphragm thickness and excursion. The test-retest reliability of Young's modulus measurements was found to be

good to excellent for the PM muscle (ICC: 0.79–0.92). These results supported the use of B-mode ultrasound for measuring diaphragm thickness, M-mode ultrasound for measuring diaphragm excursion, and SWE for quantifying the PM stiffness.

Following confirming the measurement methods, three cross-sectional studies were conducted aiming to explore dysfunctions in the muscle mechanical properties of the diaphragm, PM, and LM in athletes with chronic LBP. We discovered that (1) weightlifters with chronic LBP exhibited significantly reduced diaphragmatic contractility, as evidenced by lower diaphragm thickening fractions and excursion. Also, greater inspiratory muscle strength (primary diaphragm) may enhance lifting performance **(Study 3)**; (2) PM stiffness was significantly elevated in gymnastic and wushu athletes with chronic LBP; increased PM stiffness was associated with greater LBP severity **(Study 4)**; and (3) athletes with LBP exhibited significantly greater stiffness in the DLM compared to their pain-free counterparts, while SLM stiffness was affected by type of sports **(Study 5)**.

In summary, this project has developed a reliable method for quantifying the stiffness of deep-seated lumbar stabilizing muscles. More importantly, it has provided evidence of dysfunction in muscle mechanical properties among athletes with chronic LBP, highlighting their association with pain severity and sports participation. These findings suggest that chronic LBP may be linked to multi-muscle dysfunctions in mechanical properties, with each muscle exhibiting distinct types of mechanical property impairments. This underscores the need for precise assessment and management strategies. Further longitudinal or interventional

studies are recommended to evaluate the cause-effect relationship between muscle mechanical properties and the incidence of LBP.

RESEARCH OUTPUT ARISING FROM THE THESIS

Journal papers:

1. **Zhou EFM**, Fu SN, Huang C, Huang XP, Wong AYL. Reliability and validity of ultrasonography in evaluating the thickness, excursion, stiffness, and strain rate of respiratory muscles in non-hospitalized individuals: a systematic review. *BMC Oral Health* 2023; 23: 959. 20231202. DOI: 10.1186/s12903-023-03558-y.
2. **Zhou EFM**, Wong AYL, Zheng YP, Lam KHS, Fu SN. Reliability of Ultrasound Shear Wave Elastography for Evaluating Psoas Major and Quadratus Lumborum Stiffness: Gender and Physical Activity Effects. *Ultrasound Med Biol* 2024; 50: 564-570. 20240124. DOI: 10.1016/j.ultrasmedbio.2023.12.021.
3. **Zhou EFM**, Wong AYL, Lin GH, Peng JH, Fang JH, Wen T, Zhou CF, Fu SN. Diaphragm function in elite weightlifters with and without chronic low back pain and its impacts on sports performance. ***(accepted by the Journal of Strength and Conditioning Research)***
4. **Zhou EFM**, Wong AYL, Lin GH, Liang WT, Cai MX, Fang JH, Fu SN. Beyond Muscle Strength and Flexibility: Exploring Psoas Major Stiffness as a Key Factor in Athletes' Lower Back Pain. ***(submitted)***
5. **Zhou EFM**, Wong AYL, Lin GH, Peng JH, Fang JH, Wen T, Fu SN. Increased stiffness is evidenced in the deep but not superficial lumbar multifidus muscle in professional athletes with chronic low back pain. ***(under review)***

Conference presentations:

1. **Zhou EFM**, Leung KL, Fu SN. Diaphragm function in weightlifters with and without chronic low back pain and its association with sports performance. *World Physiotherapy Asia Western Pacific Regional Congress with HKPA Conference 2022, Hong Kong, 18-20 June 2022*

2. **Zhou EFM**, Wong AYL, Fu SN. Increase in muscle stiffness is evidenced at the deep but not superficial multifidus muscle in athletes with low back pain. *The Hong Kong Physiotherapy Association 60th Anniversary Conference 2023, Hong Kong, 24 June 2023*
3. **Zhou EFM**, Wong AYL, Lam KHS, Fu SN. Feasibility and Reliability in Using Ultrasound Shear Wave Elastography on Measuring Stiffness of the Psoas Major and Quadratus Lumborum Muscles. *11th Interdisciplinary World Congress on Low Back and Pelvic Girdle Pain, Melbourne, Australia, 1-4 November, 2023*
4. **Zhou EFM**, Wong AYL, Fu SN. Diaphragm function in weightlifters with and without chronic low back pain and its association with sports performance. *11th Interdisciplinary World Congress on Low Back and Pelvic Girdle Pain, Melbourne, Australia, 1-4 November, 2023*
5. **Zhou EFM**, Wong AYL, Lin GH, Fu SN. Psoas major stiffness quantified with ultrasound shear wave elastography in athletes with and without chronic low back pain. *2024 World Congress of Sports Physical Therapy, Oslo, Norway, 14-15 June, 2024*

Book:

Contributed to writing a popular science book: Fu SN & Ng G (2023).*日常全方位運動指南.* The Hong Kong Polytechnic University.

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LIST OF ABBREVIATIONS

Abbreviation	Full name
ADI	Athletes Disability Index Questionnaire
AIS	Adolescent idiopathic scoliosis
ANCOVAs	Two-way analyses of covariate
B-mode	Brightness-mode
BMI	Body mass index
CHAMP	CHecklist for statistical Assessment of Medical Papers
CI	Confidence interval
CIPS	Certified Interventional Pain Sonologist
CLBP	Chronic low back pain
ClinROMs	Clinician-Reported Outcome Measures
COPD	Chronic obstructive pulmonary disease
COSMIN	The Consensus-based Standards for the Selection of Health Measurement Instruments
CSA	Cross-sectional area
DLM	Deep layer of lumbar multifidus
dom	Dominant side
DTF	Diaphragm thickening fraction
ECM	Extracellular matrix
EMG	Electromyographic activity
FEV1:	Forced expiratory volume in the first second
FVC:	Forced vital capacity
HA	Hyaluronan
HHD	Handheld Dynamometer
ICC:	Intra-class correlation coefficient
IMCT	Intramuscular connective tissue
LBP:	Low back pain
LM	Lumbar multifidus
M-mode:	Motion-mode
MD	Mean difference
MDC_{95}	Minimal detectable change with 95% confidence interval
MIP	Maximal inspiratory pressure
MRI	Magnetic resonance imaging
MVC	Maximal voluntary contraction
ndom	Non-dominant side
NLBP	Non-low back pain
NPRS	Numeric Pain Rating Scale
OSTRC-H	Oslo Sports Trauma Research Center Questionnaire on Health Problems

Pdi	Transdiaphragmatic pressure
PM	Psoas major
PROMs:	Patient-Reported Outcome Measures
Q-box	Quantification box
QL	Quadratus lumborum
RMSK	Registered Musculoskeletal Sonologist
ROI	Region of interest
SD	Standard deviation
SEM	Standard error of measurement
SLM	Superficial layer of lumbar multifidus
STI:	Speckle tracking imaging
SWE:	Shear wave elastography
TDI:	Tissue doppler imaging
Tex	Diaphragm thickness at the end of tidal expiration
Tin	Diaphragm thickness at the end of maximal inspiration
USG	Ultrasonography

CHAPTER 1

Introduction and literature review

1.1 Foundation knowledge

Non-specific low back pain (LBP) is defined as the pain located between the lower rib margins and the buttock creases with or without referral to legs without a clear pathoanatomical cause [1-4]. Recognized as a significant cause of functional limitation and economic burden [5], this condition is particularly concerning among athletes [6]. A mean point prevalence, 12-month prevalence, and lifetime prevalence of LBP in athletes are 42%, 51%, and 63%, respectively [7, 8]. Athletes engaged in sports requiring repetitive extreme lower back loading, such as weightlifting, or those involving high-velocity twisting, jumping, and landing movements, like gymnastics and wushu, are at a heightened risk. In these groups, LBP prevalence can soar to 85-94% [7, 9, 10]. Alarmingly, 90% of Olympic athletes report experiencing LBP at some point in their careers [7]. As a pervasive issue, non-specific LBP not only diminishes athletic performance but can also potentially end careers and affect athletes' quality of life indefinitely [8].

1.2 The comprehensive model for sports injury causation and risk factors of low back pain in athletes

Sports injury has been defined as “tissue damage or other derangement of normal physical function due to participation in sports, resulting from rapid or repetitive transfer of kinetic energy” [11]. Non-specific LBP is often characterized by sudden or gradual onset among athletes. Based on Meeuwisse’s epidemiological model [12] and McIntosh’s biomechanical model [13], Bahr and Krosshaug have developed a well-accepted

comprehensive model for injury causation [14]. This model serves not only as a framework for understanding injury mechanisms but also guides research into the risk factors associated with sports injuries which also can be used as guidance for research on risk factors of sports injury.

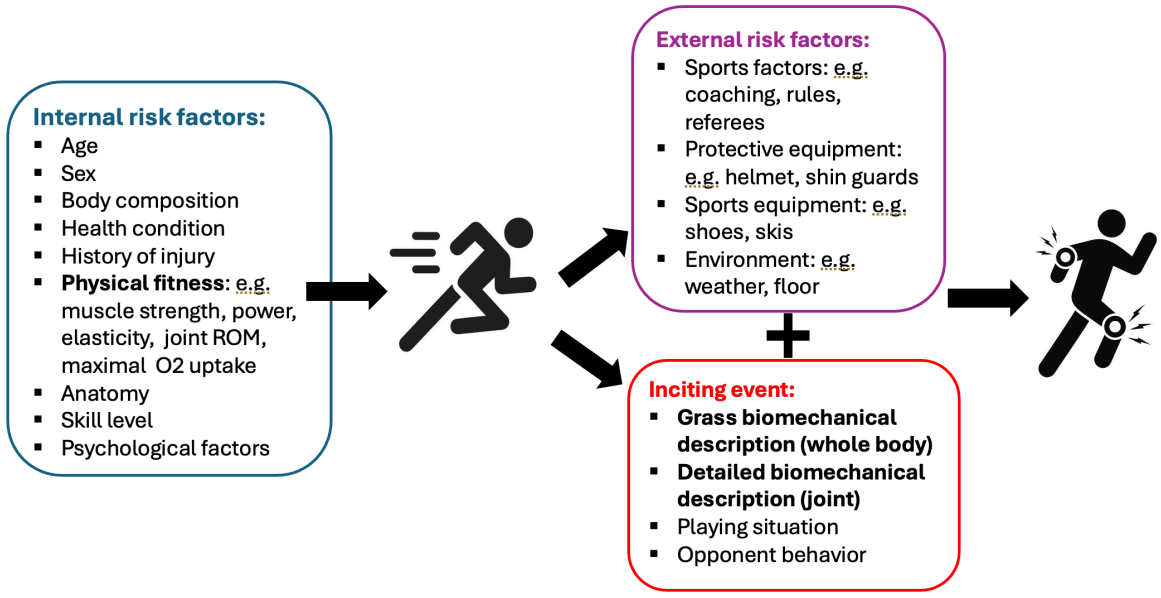

FIGURE 1. 1 Comprehensive model for injury causation. ROM = range of motion. (Adapted from Bahr & Krosshaug, 2005)

Figure 1.1 illustrates the causation mechanism of sports injuries. It shows that athletes who are subjected to personal internal risk factors (such as age, sex, and physical fitness) and exposed to external risk factors (including high training loads and sports equipment) may sustain injuries through an inciting event (such as adopting extreme joint positions or landing with high velocity) during training or competition [14].

From a biomechanical perspective, injuries occur when the load transferred to tissues exceeds their tolerance threshold, or when the tissue's load tolerance is compromised, influenced by all three elements depicted in the model [13]. It happens when loading exceeds

the tolerated limit, or the tolerance level is reduced which can be affected by all three elements in the model. Tissue mechanical properties (e.g. muscle strength, stiffness), are pivotal as they govern the body's response to load and significantly impact the load tolerance threshold, thus representing critical internal risk factors for injuries [14].

Plenty of studies researched the risk factors of non-specific LBP in athletes. External risk factors such as high training volume and periods of increased training load have been reported most frequently and consistently, following internal risk factors such as a history of LBP and training years [8]. All these factors are associated with increased mechanical loading. Consequently, the mechanical properties that modulate tissue response to such loading are considered potential underlying causes of injury.

Given the above, muscle mechanical properties are one of the modifiable factors associated with LBP in athletes, highlighting the importance of targeted research on this area.

1.3 Paraspinal muscles and low back pain

The muscular system is recognized as an essential component for spinal stabilization, as proposed in Panjabi [15]'s theory. Stability of the spine is critical not only for effective force generation and transfer but also for preventing biomechanical injuries[16]. Lumbar spine instability, in particular, is a frequent and significant cause of LBP [16, 17]. Paraspinal muscles such as erector spinae, multifidus, psoas major (PM), and quadratus lumborum (QL) which are directly attached to vertebras play a pivotal role in supporting the lumbar spine [18,

19]. Furthermore, the lumbopelvic muscles, commonly referred to as "core muscles," create a functional cylinder around the lumbar spine. This cylinder is topped by the diaphragm, anchored at the bottom by the pelvic floor and hip girdle muscles, with the abdominals in the front and the paraspinals and gluteals at the back [20]. These core muscles are essential for both lumbar spine stability and overall "core stability," which are vital for optimal force production, transfer, and control within the integrated kinetic chain, particularly in sports [21].

Extensive research has explored the link between paraspinal stabilizers and LBP. The role of the lumbar multifidus (LM) in LBP is well-established [22-24]; however, recent investigations into its stiffness and the distinctions between its deep and superficial layers have highlighted ongoing complexities. Notably, despite the significant focus on the LM, the diaphragm positioned anterior-superiorly and the PM located anteriorly have received considerably less attention in LBP research. This project aims to bridge these gaps by conducting a comprehensive analysis of these three pivotal muscles—the diaphragm, PM, and LM —to further elucidate their roles and contributions in the context of LBP.

1.3.1 Diaphragm and low back pain

1.3.1.1 Anatomy and function of diaphragm

The diaphragm, a crucial dome-shaped muscle partitioning the thoracic and abdominal cavities, serves dual critical functions: respiratory and spine stability [25]. As the primary muscle responsible for inspiration, it accounts for a significant 70-90% of tidal volume variation across different postures, underscoring its respiratory importance [26].

Notably, anatomically rooted in the lumbar vertebrae, sternal, and lower ribs, the diaphragm's descending crura attach directly to the lumbar spine, thereby fortifying spinal stability (FIGURE 1.2) [27-30]. This structural anchoring enables the diaphragm to enhance the lumbar spine's stiffness during contraction, contributing to a harmonized regulation of both inspiration and postural stability [31-33]. In addition, the diaphragm is also recognized as the top of the core cylinder contributing to the core stability [34].

Pioneering studies by Hodges and colleagues have detailed the pre-activation of the diaphragm prior to limb movements, akin to other lumbar stabilizers, thus reinforcing its role in maintaining lumbar stiffness and overall posture [28, 30, 35, 36]. Magnetic resonance imaging (MRI) studies further support its dual functionality, demonstrating its integral involvement in maintaining spinal alignment and stability alongside its respiratory duties [29, 37, 38].

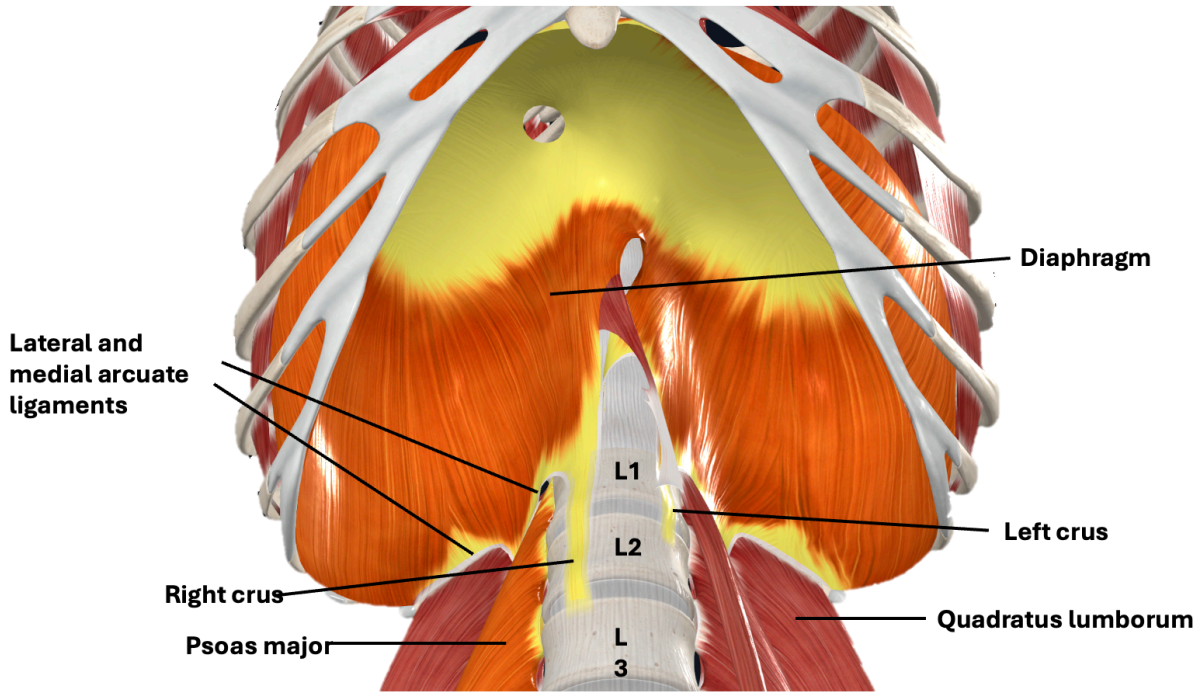

FIGURE 1. 2 Diaphragm arcuate ligaments, left and right crura.

1.3.1.2 Diaphragm dysfunction and low back pain

Despite its established role as a spine stabilizer and core muscle [34], research into diaphragm dysfunction as it relates to LBP is relatively underexplored. Research has been starting to delve into the link between diaphragm dysfunction and LBP, building upon revelations of the diaphragm's role in spinal stabilization. Ultrasonographic assessments have yielded divergent findings, with two studies indicating reduced diaphragmatic thickening during contraction among LBP patients in contrast to healthy individuals, though these studies did not find differences in diaphragmatic excursion (distance of motion) [39, 40]. Conversely, decreased diaphragmatic excursion was noted in another cohort with LBP [41].

Current research into the impact of diaphragmatic function on LBP, particularly among athletes, is still in its infancy. Only one study has been conducted on semi-

professional athletes participating in ball games, which has reported decreased diaphragmatic thickening but not excursion in LBP cohort [40]. Notably, diaphragm fatigue, potentially undermining postural stability, has been more prevalent in the LBP population [42, 43]. This fatigue may also precipitate reduced limb muscle perfusion due to metabolic reflex mechanisms, potentially triggering earlier fatigue in locomotor muscles, which has implications for athletic performance and injury risk [44-47].

Furthermore, MRI studies have illuminated the harmonious coordination of inspiration and postural control in healthy subjects, a synchronization that is disrupted in LBP sufferers, manifesting in altered diaphragm positioning and recruitment patterns. LBP individuals exhibited higher diaphragm position, steeper slope, and irregular activation patterns compared to those without LBP [38, 48].

In summary, there is a potential correlation between dysfunction in diaphragm performance and LBP, which warrants further investigation, especially among athletes. This need is underscored by the critical role of spinal stability and the distinct challenges posed by the combined demands of spinal and respiratory functions during athletic activities. A review was necessary to search for a valid and reliable method for athletes.

1.3.2 The psoas major and low back pain

1.3.2.1 Anatomy and function of psoas major

The PM muscle, originating from the T12 to L5 vertebrae and inserting into the lesser trochanter of the femur, is traditionally characterized as a hip flexor that also functions in trunk flexion when origin and insertion are reversed [49, 50]. However, PM is not just a hip

flexor but notably acts dynamically to stabilize the spine [51-53]. PM consists of a blend of muscle fiber types: approximately 40-50% type I fibers that facilitate its postural role, and 50-60% type II fibers that contribute to joint motion dynamics [54, 55]. These fiber compositions vary along its length, with a higher proportion of type I fibers in the upper segments and an increasing proportion of type II fibers in the lower segments, potentially reflecting segment-specific functional emphasis [55]. Furthermore, the force generated by PM likely varies between its lumbar origin and hip insertion due to the converging distal tendon with the iliacus muscle, suggesting different force applications on the lumbar spine compared to the hip joint [51].

1.3.2.2 Psoas major dysfunction and low back pain

Despite the critical role in spinal stabilization, the specific impact of PM muscle dysfunction on LBP has not been conclusively established. Morphological studies of the PM muscle have yielded inconsistent results. While some have shown a reduced CSA of the PM in individuals with LBP compared to controls [56-58], these findings have not been universally replicated [18, 59-61]. Similarly, the evaluation of PM muscle strength (often assessed in conjunction with the iliacus as part of hip flexor strength) has produced conflicting outcomes, with reports of both increased and decreased strength in those with LBP [62, 63].

Critically, excessive PM tension has been implicated in vitro and in simulated models to contribute to heightened compressive and shear forces on the lumbar spine, particularly at the L5-S1 segment, potentially increasing the risk of LBP [52, 53, 64, 65]. The Modified

Thomas test, which assesses hip flexor flexibility, has been employed to estimate PM muscle tension, but has produced inconclusive results regarding hip extension range between LBP and non-LBP populations [66-68]. It is noteworthy that the range of hip extension may also be influenced by other factors, including the extensibility of the surrounding soft tissues at the hip joint.

Recent advancement in direct PM stiffness measurement was conducted by Kitamura et al [69], who employed SWE to quantify PM stiffness and found increased stiffness in swimmers with LBP [69]. Notably, the measurement focused on the distal portion of the PM at the groin level, where a tendinous architecture has formed [50, 69]. Given the variable distribution of fiber types from the upper to lower segments of the PM, which likely tailor to specific functional needs from postural support to joint motion [55, 70], and known variations in muscle stiffness due to sports-specific loading in other muscle groups [71, 72], it becomes crucial to measure PM stiffness at the lumbar region to uncover potential changes linked with LBP.

Despite the link between excessive tension of PM and LBP has been reported in vitro studies, how the stiffness of PM would relate to LBP have not been established. A reliable method in measuring the stiffness of this deep-seated muscle is essential to fulfill the goal.

1.3.3 Lumbar multifidus and low back pain

1.3.3.1 Anatomy and function of deep and superficial layers of lumbar multifidus

The LM muscle originates from the sacrum and the transverse processes of the lumbar vertebrates, inserting on the spinal processes of the vertebrae superior to the origins [50]. It plays a critical role in the stabilization of the lumbar spine [50]. Structurally, the LM is divided into the deep (DLM) and superficial (SLM) layers, each characterized by distinct features and functions [23, 73, 74]. The DLM primarily acts as a segmental stabilizer, characterized by shorter, smaller, more oblique fibers that span across two vertebral levels and increase in size from the L1 to L5 segments. In contrast, the SLM facilitates spinal extension and rotation, featuring longer, larger, and more vertically oriented fibers that extend over five vertebral levels and decrease in size from L1 to L5 [73]. Notably, the SLM includes extramuscular tendons that attach to bones, unlike the DLM's fully muscular composition [73], highlighting different mechanical properties between the layers.

1.3.3.2 Lumbar multifidus dysfunction and low back pain

The LM's function in lumbar spine stabilization and its implication in LBP are well-documented [17, 75, 76]. Research has consistently shown that features such as fat infiltration, reduced cross-sectional area (CSA), and a decreased lean muscle index are prevalent in individuals with LBP [23, 24, 77, 78]. However, there is an increasing focus on measuring muscle stiffness using ultrasound shear wave elastography (SWE), with studies reporting increased stiffness in the LM of both athletes and the general population suffering from LBP [79-81].

Importantly, DLM and SLM are uniquely related to lumbar stability and movement. The DLM is primarily associated with segmental stabilization during lumbar activities and is thought to be closely linked to LBP [23, 73]. Observations suggest that LBP patients often have delayed or reduced activation of the DLM, contrasting with the functionality of the SLM [23, 35, 82]. Thus, LBP-related changes in LM stiffness might be more pronounced in the DLM, which could inform more targeted assessments and interventions.

Conversely, the SLM is engaged in executing spinal movements, specifically extension and rotation [73]. Its stiffness may be influenced by various physical activities that impose mechanical loads, reflecting adaptations to specific demands of different sports or physical tasks [72, 83-86]. This adaptive stiffness in the SLM could potentially increase under conditions of intense mechanical loading that align with its primary functions.

In summary, although morphological assessments of the LM provide substantial information, evaluating muscle stiffness offers additional, clinically relevant insights [87]. There is no study conducting differential measurements on the mechanical properties of the DLM and SLM in athletes. Such investigation is essential for precisely assessing and managing LBP.

1.4 Measurements of muscle mechanical properties

1.4.1 Ultrasound shear wave elastography

Since its introduction in 1991, ultrasound elastography has been a valuable imaging technique for measuring tissue elasticity, particularly sensitive to changes in tissue stiffness

due to various pathological or physiological processes [87, 88]. This technique has evolved into a reliable and objective method for quantifying the mechanical properties of soft tissues and has been widely used in diagnosing and treating disorders in organs such as the breast, liver, thyroid, and prostate [88, 89]. Its application to the musculoskeletal system began in 2009, steadily gaining attention for its utility in this field [90].

SWE is a prominent ultrasound elastography technique. Firstly, shear wave is generated by focused acoustic radiation force from transducer and propagate in the transverse plane which is perpendicular to the original producing direction and causing shear displacement in tissue. Secondly, using fast plane wave excitation to track the tissue displacement as well as shear wave velocity. Thirdly, using tissue displacement maps to calculate the shear wave velocity [91]. The stiffer the tissue, the higher the shear wave propagation velocity, which can be converted into the Young's modulus of tissue (a definitive measure of the tissue's elastic property) [91, 92].

Recognized for its non-invasive, convenient, and cost-effective nature, ultrasound SWE has become a leading method for evaluating muscle stiffness in vivo, providing crucial insights for musculoskeletal disorders [87, 91, 93, 94]. It has been used in various muscle groups, such as the rotator cuff, multifidus, quadriceps, calf muscles, and masticatory muscles [91, 95-98].

1.4.2 Shear wave elastography measurements on psoas major

Although SWE has been used in a prior study to quantify the stiffness of distal PM at the groin level where part of PM has formed a tendinous architecture [50, 69], it remains

unclear whether SWE can be used to measure the stiffness of PM muscle belly, where it attaches to the lumbar spine and potentially closer linked with LBP. This deeper region of the PM poses significant challenges for stiffness assessment due to its location. Given the promising results from using a curvilinear transducer (1-4 MHz) to assess liver stiffness with minimal variability at depths of 4-5 cm below the skin surface [92], there is potential for applying SWE similarly for the PM. This method could potentially provide reliable measurements of PM stiffness at depths comparable to those in liver assessments, offering a valuable tool for better understanding the muscle's role in LBP.

Although SWE has been used for various superficial muscle groups, its reliability in assessing the stiffness of the deep-seated PM muscle belly still needs to be established.

1.4.3 Diaphragm measurements

Historically, diaphragm function has been evaluated using transdiaphragmatic pressure (Pdi) measured via esophageal and gastric balloons: considered the gold standard [99, 100]. Additional methods have included electromyography (EMG) using various invasive techniques recording from the costal diaphragm with intramuscular electrodes, and the crural diaphragm with gastro-oesophageal catheters inserted through the nasal cavity [101, 102], and costly MRI to visualize diaphragm motion [31, 103].

More recently, ultrasound has become a preferred tool for non-invasive diaphragm assessment, particularly for measuring diaphragmatic thickness and excursion in various patient populations [104, 105]. Diaphragm thickness fraction, calculated from thickness, is used as a predictor for successful weaning in ventilated patients [106-108]. Ultrasound's

reliability in measuring diaphragmatic thickness and excursion has been affirmed in healthy and LBP populations [109-114].

Ultrasound SWE has also been explored for measuring diaphragm stiffness, with some studies indicating excellent reliability [115, 116]. However, shear wave velocity is faster in stiffer tissues, but decreases significantly with the thickness in thin tissues, especially when the thickness is less than 1.5 cm [117, 118]. Considering the normal diaphragm thickness ranges from 0.13 to 0.76 cm, the accuracy of SWE in assessing inspiratory muscle stiffness has been challenged [119, 120].

Therefore, employing brightness-mode (B-mode) and motion-m (M-mode) ultrasound for assessing diaphragm thickness change (thickening) and excursion (shortening), respectively, presents a better method for evaluating diaphragmatic contractility property.

There appear to be different approaches to measuring the mechanical properties of the diaphragm muscle. A more detailed review is needed to identify the most feasible and reliable method for assessing the diaphragm's mechanical properties in elite athletes at their training ground.

1.5 Rational and objectives of the project

1.5.1 The existing gaps

A comprehensive review of the literature has identified several critical knowledge gaps:

1) The diaphragm muscle and lumbar spine are anatomically linked. Some evidence suggests that individuals with LBP may experience reduced diaphragm thickening. There is a need to further investigate whether athletes with LBP have inferior diaphragm mechanical properties. More essentially, how diaphragm mechanical properties would be associated with their sports performance and the severity of LBP remains largely unknown.
2) Although in vitro studies have reported a link between excessive PM tension and LBP, no research has measured PM stiffness in its muscular portion. There is a need to identify a reliable method for quantifying PM muscle stiffness and to compare this stiffness between athletes with and without LBP.
3) While extensive research on the morphology of the LM exists, studies exploring muscle stiffness, particularly the differential modulation of DLM and SLM layers by LBP or specific sports activities, are lacking and require further investigation.

1.5.2 Project aims, project structure, and hypotheses

The overall aim of this project was to deepen our understanding of lumbar muscle mechanical dysfunctions in athletes with chronic LBP.

Before the main studies, a literature review was conducted to identify a reliable method for measuring diaphragm thickness and excursion **(Study 1)**. Additionally, a cross-sectional study was performed to establish a dependable approach for quantifying PM stiffness **(Study 2)**. Following this, three cross-sectional studies were conducted to investigate dysfunction in the mechanical properties in the diaphragm **(Study 3)**, PM **(Study 4)**, and LM **(Study 5)**.

Study 1 (Chapter 2): The systematic review of diaphragm muscle measurements

Aim: To review the reliability of measuring diaphragm thickness and excursion.

The specific objective:

To review and establish the reliability of using ultrasonography to measure diaphragm thickness and excursion.

The hypothesis was as follows:

Ultrasonography would be reliable for measuring diaphragm thickness and excursion.

Study 2 (Chapter 3): The reliability study of PM muscle stiffness measurement

Aim: To establish the reliability of measuring PM muscle stiffness.

The specific objective:

To explore the feasibility and reliability of using SWE in quantifying PM muscle stiffness.

The hypothesis was as follows:

SWE would be feasible and reliable in quantifying muscle stiffness for the PM muscle.

<u>Study 3 (Chapter 4):</u> Diaphragm function and LBP in weightlifters

Aims: To compare the diaphragm function between elite weightlifters with and without chronic LBP and to assess associations between diaphragm function and sports performance amongst elite weightlifters.

The rationale of population:

Weightlifting is an Olympic sport that aims to lift the maximum weight above the head either in a single-stage movement/breath, as in the snatch, or in a two-stage movement/two-breathes, as in the clean and jerk [121]. This sport subjects the lower back to considerable stress, typically exposing it to an average compressive load exceeding 17,192N [9, 122]. Such intense loading demands robust lumbar stabilization to mitigate the risk of LBP.

During the weightlifting process, effective force transmission from the lower to the upper limbs requires the trunk, including the thoracic and abdominal cavities, to maintain significant rigidity and stability [34]. This biomechanical strategy not only helps to reduce the incidence of LBP and shear forces on the lumbar spine but also contributes to enhanced performance in weightlifting.

In this context, the diaphragm plays a pivotal role. Functioning similarly to a piston, it acts as a stabilizer for both the lumbar and thoracic spines as well as the chest during inspiration. Its ability to regulate lumbar spine segmental stability, and intra-abdominal and intrathoracic pressures is crucial for maintaining spinal alignment and overall postural balance during the intense phases of weightlifting movements. Therefore, assessing the

function of the diaphragm could provide key insights into its dual role in preventing LBP and enhancing performance among weightlifters, making this group a critical target for detailed study [123-125].

The specific objectives:

1) To compare the diaphragm function in weightlifters with and without chronic LBP.
2) To explore the associations between diaphragm function, pain severity, and sports performance in weightlifters.

The hypotheses were as follows:

1) Weightlifters with LBP have inferior diaphragm function.
2) Greater diaphragm function would relate to better weightlifting performance.

<u>Study 4 (Chapter 5):</u> Psoas major and low back pain in gymnastic and wushu athletes

Aim: To delve into the link between PM stiffness and chronic LBP in gymnastic and wushu athletes.

The rationale of population:

This study focuses on athletes from gymnastics and wushu due to their similar physical demands on the PM muscle. These sports require frequent high-velocity bending, extensive hip flexion (exceeding 90 degrees), stretch-shortening cycles, and dynamic jumping and landing movements [126]. Such activities place significant stress on the lumbar spine and associated musculature, necessitating robust lumbopelvic stability.

Moreover, gymnasts and wushu practitioners typically begin their intensive training at a young age (between 4 and 6 years old), which involves prolonged exposure to extreme back

positions, high-velocity twisting, and repetitive impact actions. This early and intense training regimen may predispose these athletes to higher risks of developing LBP, a common ailment reported within these communities [126, 127].

Given the demanding nature of these sports and their associated risk for LBP, studying these athletes provides valuable insights into the role of PM stiffness in spinal health and athletic performance. This population's unique physical challenges and the prevalence of LBP make them ideal candidates for investigating potential correlations between muscle mechanics and musculoskeletal health.

The specific objectives:

1) To compare PM muscle stiffness in athletes with and without chronic LBP in gymnastic and wushu athletes.
2) To explore the correlation between PM muscle stiffness and LBP severity.

The hypotheses were as follows:

1) Higher stiffness of PM muscles would be detected in athletes with LBP compared to non-LBP cohort.
2) Higher PM stiffness would relate to more pain and lower disability level in athletes with LBP.

<u>Study 5 (Chapter 6):</u> Lumbar multifidus and low back pain in athletes across different sports

Aim: To examine how DLM and SLM stiffness varies between athletes with and without chronic LBP and across different sports.

The rationale of population:

From the literature review in section 1.3.1, DLM and SLM stiffness might be differentially modulated by LBP or specific sporting activities according to their diverse role on the lumbar spine during different sports activities. These differences are thought to arise from the varied roles these muscles play in different sporting contexts that demand distinct lumbar spine movements. Consequently, this study specifically targets athletes from sports known for high LBP prevalence and varied trunk movement dynamics.

Weightlifters, who predominantly engage in trunk extension under extreme loads; badminton players, noted for their need for repetitive trunk extension and rotation; sprinters from track and field, where the primary requirement is trunk stability rather than extensive mobility [8, 9, 128, 129]. This diversified cohort allows for a comprehensive examination of how distinct mechanical demands associated with different sports modulate LM stiffness and potentially contribute to LBP.

The specific objective:

To investigate the difference in DLM and SLM stiffness in athletes with and without chronic LBP from different sports disciplines.

The hypotheses were as follows:

1) DLM stiffness would be higher in athletes with LBP than in asymptomatic controls.
2) SLM stiffness significantly differed amongst athletes who participated in different types of sports

Based on findings from three cross-sectional studies, **Chapter 7** presented a summary and discussion of new insights into the dysfunctions of lumbar muscle mechanics in athletes with chronic LBP.

CHAPTER 2

Study 1: Reliability and validity of ultrasonography in evaluating the thickness, excursion, stiffness, and strain rate of respiratory muscles in non-hospitalized individuals: a systematic review

2.1 Abstract

Objective

To summarize the reliability and validity of ultrasonography in evaluating the morphometry, function, and/or mechanical properties of respiratory muscles in non-hospitalized individuals.

Literature Search

PubMed, Embase, SPORTDiscus, CINAHL and Cochrane Library were searched from inception to May 30, 2022.

Study Selection Criteria

Case-control, cross-sectional, and longitudinal studies were included if they investigated the reliability or validity of various ultrasonography technologies (e.g., brightness-mode, motion-mode, shear wave elastography) in measuring the morphometry, function, or mechanical properties of any respiratory muscles.

Data Synthesis

Relevant data were summarized based on healthy and different patient populations. The methodological quality by different checklist depending on study design. The quality of evidence of each psychometric property was graded by the Grading of Recommendations, Assessment, Development and Evaluations, respectively.

Results

This review included 24 studies with 787 non-hospitalized individuals, spanning healthy, lower back pain (LBP), adolescent idiopathic scoliosis (AIS), and chronic obstructive pulmonary disease (COPD) populations. Both inspiratory (diaphragm and intercostal

muscles) and expiratory muscles (abdominal muscles) were investigated. Moderate-quality evidence supported sufficient (intra-class correlation coefficient >0.7) within-day intra-rater reliability of B-mode ultrasonography in measuring right diaphragmatic thickness among people with LBP, sufficient between-day intra-rater reliability of M-mode ultrasonography in measuring right diaphragmatic excursion in non-hospitalized individuals. The quality of evidence for all other measurement properties in various populations was low or very low. High-quality evidence supported sufficient positive correlations between diaphragm excursion and forced expiratory volume in the first second or forced vital capacity (r>=0.3) in healthy individuals.

Conclusions

Despite the reported sufficient reliability and validity of using ultrasonography to assess the thickness, excursion, stiffness, and strain rate of respiratory muscles in non-hospitalized individuals, further large-scale studies are warranted to improve the quality of evidence regarding using ultrasonography for these measurements in clinical practice. Researchers should establish their own reliability before using various types of ultrasonography to evaluate respiratory muscle functions.

2.2 Introduction

The diaphragm is a dome-shaped muscle that separates the thoracic and abdominal cavities [25]. In addition to being the principal inspiratory muscle that contributes to 70-90% of tidal volume in different positions [26], the diaphragm also plays an essential role in the visceral system as well as the musculoskeletal system. It assists various internal organs functions such as aiding emesis, urination, defecation, and preventing gastroesophageal reflux [123, 130, 131]. Further, the diaphragm harmoniously controls inspiration and postural control, stabilizes the lumbar spine, and contributes to optimal performance of daily activities or sports [45, 47, 103, 132].

Because the diaphragm works synergically with parasternal and external intercostals to expand the rib cage during inspiration [133, 134], uncoordinated contraction of synergists can increase the work of breathing and increases the burden of the diaphragm [133]. Likewise, while abdominal muscles serve as the force-expiratory muscles when respiratory loading increases [133, 134], the tonic activity of abdominal muscles helps maintain the optimal length of diaphragm for better force generation during the inspiration in an upright position [135]. Therefore, it is essential to comprehensively evaluate various respiratory muscles (e.g., intercostals and abdominal muscles) by reliable objective assessments in order to better assess diaphragmatic function in individuals, and to inform clinical decision-making.

Ultrasonography (USG) is a non-invasive in vivo ultrasound imaging approach to evaluate the morphometry, function, or mechanical properties of soft tissues with different imaging modes [106, 107]. Prior research has used brightness-mode (B-mode) and motion-

mode (M-mode) USG to assess the thickness and excursion of diaphragm, respectively in critically ill patients (e.g., ventilated patients) in order to estimate the inspiratory function of diaphragm [104, 105]. Diaphragm thickness fraction as measured by B-mode USG is used as a predictor for successful weaning in ventilated patients [106-108]. Although previous systematic reviews have supported the reliability and validity of B-mode USG in assessing the morphometry of diaphragm in ventilated patients [136, 137], their findings cannot be generalized to non-hospitalized individuals given the diverse functions of diaphragm in different conditions. Additionally, although some studies have used B-mode and M-mode USG to investigate the morphometry and mobility of intercostals and abdominal muscles in different populations [138-140], no systematic review has summarized the reliability or validity of such USG in these respiration-related muscles in non-hospitalized individuals.

Ultrasound shear wave elastography (SWE) is another type of USG that has recently been used to measure respiratory muscle stiffness [99, 116, 141, 142]. SWE is an objective, and reproducible method to quantify the mechanical properties of soft tissues [87, 91], although there are some concerns regarding the validity of using SWE to measure biomechanical properties of the diaphragm [120]. Given the controversy, it is important to conduct a systematic review to summarize the reliability and validity of SWE in measuring respiratory muscle stiffness.

Against this background, the current systematic review aimed to summarize the evidence regarding the reliability and validity of various types of USG (including SWE) in

evaluating the morphometry, function, and mechanical properties of respiratory muscles in non-hospitalized patients and healthy individuals.

2.3 Methods

This review protocol was registered with PROSPERO (CRD42022322945) and was reported according to the guidelines of Preferred Reporting Items for Systematic Reviews and Meta-Analyses [143].

2.3.1 Literature Search

PubMed, Embase, SPORTDiscus, CINAHL and Cochrane Library were systematically searched from inception to May 30, 2022 to identify relevant studies without language restrictions. The main keywords were reliability, validity, ultrasonography, shear wave elastography, and respiratory muscles. Appropriate search strings with Boolean operators and linking terms were used (SUPPLEMENTARY FILE 2.1). Forward citation tracking of the included studies was conducted using Scopus. Backward citation tracking was also conducted. The corresponding authors were contacted by emails for additional relevant articles.

2.3.2 Eligibility Criteria

Case-control, cross-sectional, and longitudinal studies were included if they investigated the reliability or validity of USG or SWE in measuring the morphometry, function, or mechanical properties of any respiratory muscles. Animal and cadaveric studies, reviews, case reports, commentaries, and letters to the editors were excluded. Two reviewers

(FZ and XH) independently performed title and abstract screening of the identified citations according to the selection criteria. Between-reviewer disagreements were reconciled by consensus, or by the jurisdiction of a third reviewer (AW). Relevant full-text articles were retrieved. The same procedure was repeated for the full-text screening. Between-reviewer agreements were evaluated by Kappa coefficients (κ).

2.3.3 Data Extraction

Two independent reviewers (FZ and CH) extracted relevant information from the included studies: (1) authors' information (e.g., names, publication year, country); (2) study characteristics (e.g., study design, setting); (3) assessor's information; (4) participants' demographics (e.g., gender, age, types of population); (5) measurements (e.g., types of USG/SWE used and assessment locations); (6) outcomes (e.g., intra- or inter-rater reliability, which might be expressed as intra-class correlation coefficients (ICCs) or kappa coefficients and the respective 95% confidence interval (CI); and convergent/divergent validity). Any disagreements in data extraction were resolved by discussion or by the judgment of a third reviewer (AW).

2.3.4 Quality Assessment and Level of Evidence

The Consensus-based Standards for the Selection of Health Measurement Instruments (COSMIN) checklist was used to evaluate the methodological quality of the included studies. Clinician-Reported Outcome Measures (ClinROMs) checklist [144] was used to assess the quality of the included reliability studies. Patient-Reported Outcome Measures (PROMs) checklist [145] was used to evaluate the quality of validity studies (using Box 9a and 9b to

evaluate studies investigating convergent validity and discriminative/known-groups validity, respectively). The quality of the included studies was rated as “very good, adequate, doubtful, or inadequate” using the “worst-score counts” principle [144, 145].

Against the updated criteria for good measurement properties [145] (SUPPLEMENTARY FILE 2.2), the reliability and validity of various types of USG in each included study was rated as sufficient (“+”), insufficient (“-”), or indeterminate (“?)”. Likewise, the overall quality of evidence for reliability and validity of various types of USG for a given muscle assessment was first checked against the criteria for good measurement properties [145] (SUPPLEMENTARY FILE 2.2) to determine the overall consistency of each measurement property as “sufficient (+), insufficient (-), inconsistent (±), or indeterminate (?)”. Then, the quality of evidence for each measurement property in overall population and each subgroup (different populations in the included studies) was graded as “high, moderate, low, or very low” using the modified GRADE approach as suggested by COSMIN [145] (SUPPLEMENTARY FILE 2.3). These processes were conducted by two independent reviewers (FZ and CH). Any disagreements were resolved by discussion or by the judgment of a third reviewer (AW).

2.3.5 Data synthesis

Data were categorized and analyzed according to different patient populations. Although meta-analysis using random effects models in RevMan 5 was planned, it was infeasible to conduct the meta-analysis because no outcome of interest was evaluated under

the same condition (e.g., USG modes, probe locations, participants' positions, breathing phrases) in two or more studies. Therefore, a narrative review was conducted.

2.4 Results

2.4.1 Study selection

Of 1,110 identified citations from databases and other sources, 395 were included for the title and abstract screening after removing duplicates. Following the full-text screening, 24 articles were included (FIGURE 2.1). The inter-rater agreement for title and abstract screening and full text screening were good (κ = 0.88, 95%CI: 0.80 to 0.96) and adequate (κ = 0.73, 95%CI: 0.57 to 0.88), respectively [146].

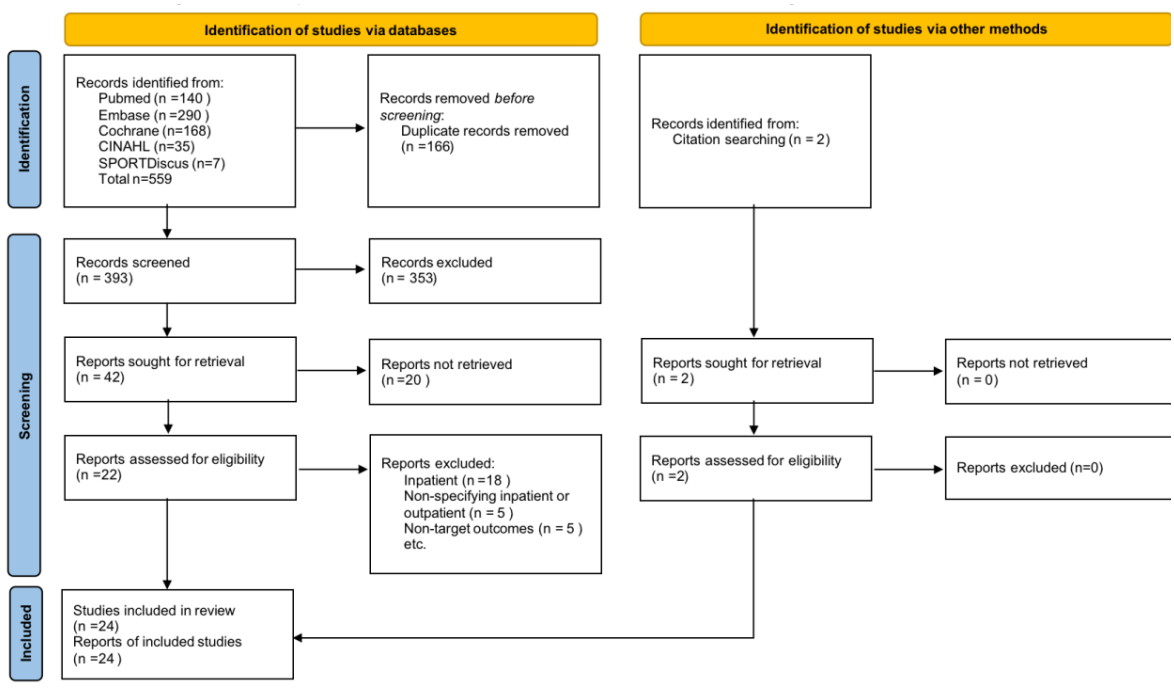

FIGURE 2. 1 Flow chart of study selection inclusion into the systematic review

2.4.2 Study characteristics

The 24 included studies were published between 1998 and 2021 involving 787 participants (aged: 12-70 years) (SUPPLEMENTARY FILE 2.4). Twenty-one included studies reported reliability (20 on intra-rater and 13 on inter-rater reliability) and eight reported validity (6 on convergent validity and 3 on discriminative/known-groups validity). Four included studies involved people with LBP (n=73, aged: 20-50 years), two involved people with chronic obstructive pulmonary disease (COPD) (n=63, aged: 57-79 years), two involved teenagers with adolescent idiopathic scoliosis (AIS) (n=48, aged: 12-17 years, Cobb angles ranging from 12°-47°), and the remaining studies involved healthy individuals (n=603, aged: 11-70 years). Three respiratory muscles were investigated. Specifically, 19 included studies examined the diaphragm (12 only on the right side, and 7 on both sides), three assessed intercostal muscles, and one evaluated abdominal muscles. Twelve included studies used brightness-mode (B-mode) USG to measure muscle thickness and nine used motion-mode (M-mode) USG to measure muscle excursions. Four included studies used SWE to measure muscle stiffness. Two included studies measured strain rate using speckle tracking imaging (STI), and one measured diaphragmatic motion velocity using Tissue Doppler Imaging (TDI)). The experiences of the examiners ranged from experienced (n=13), novice (n = 4), to unspecified (n=9).

2.4.3 Ultrasound measurement Approach

Eight included articles measured the thickness [112, 113, 147-152], nine measured excursion [112-114, 153-158], three measured stiffness [99, 115, 116], two measured strain

[100, 158], and one measured motion velocity of diaphragm [159]; one included study measured the thickness [160], and one measured stiffness of intercostal muscles [161]; one included study measured the thickness of transverse abdominals and internus obliquus with different approaches [162]. The details of each measurement approach are described in SUPPLEMENTARY FILE 2.5.

2.4.4 Reliability

FIGURES 2.2 and 2.3 illustrate the reliability of using different types of USG in measuring various respiratory muscle characteristics in different populations. SUPPLEMENTARY FILE 2.6 & 2.7 show the COSMIN scores and the rating of each study, as well as the quality of evidence regarding the reliability of each type of respiratory muscle measurement based on all included studies and separated populations, respectively. Overall, moderate-quality evidence supported sufficient within-day intra-rater reliability measuring right diaphragm thickness and sufficient between-day intra-rater reliability measuring right diaphragm excursion with B-mode and M-mode USG. The quality of evidence for the measurement properties was low or very low.

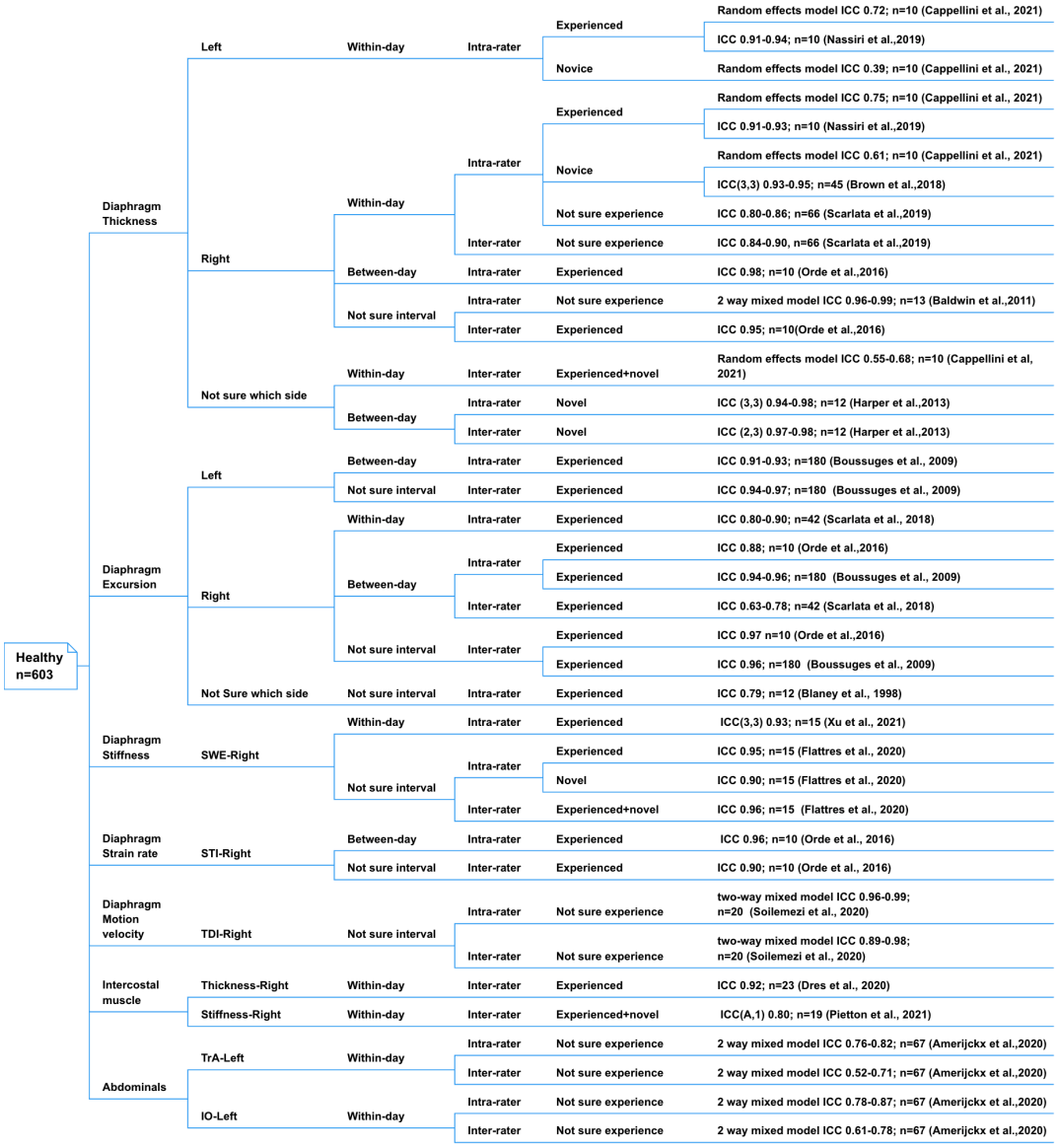

FIGURE 2. 2 Reliability of healthy population. TrA= Transverse abdominals; IO= internus obliquus; SWE=shear wave elastography; STI=speckle tracking image; TDI=tissue doppler image

Findings for different populations

Healthy individuals

Diaphragm thickness: intra-rater and inter-rater reliability

Seven included studies [109, 110, 113, 148, 149, 163, 164] examined the reliability of using B-mode USG for diaphragm thickness measurement. Two included studies reported

sufficient within-day intra-rater reliability of measuring left hemidiaphragm thickness by experienced operators (ICC=0.72-0.94) [113, 163] but insufficient within-day intra-rater reliability for novice (ICC=0.39) operators[163]. Likewise, two included studies reported sufficient within-day intra-rater reliability of measuring right hemidiaphragm thickness by experienced operators (ICC=0.75-0.93) [113, 163] or an operator of unknown experience (ICC=0.84-0.90)[110], but insufficient within-day intra-rater reliability by novice operators (ICC=0.61-0.95)[148, 163], One included study reported sufficient between-day intra-rater reliability of an experienced operator in measuring right hemidiaphragm thickness (ICC=0.98) [109]. Two included studies [109, 110] reported sufficient within-day inter-rater reliability (ICC=0.84-0.90) [110]of measuring right hemidiaphragm thickness by an operator of unknown experience and inter-rater reliability (ICC=0.95) [109] by an experienced operator but without specifying the time interval. Two studies [149, 163] did not state which side were measured reported sufficient between-day intra-rater and inter-rater reliability (ICC=0.94-0.98; 0.97-0.98)[149] and insufficient inter-rater (between experienced and novice operators) reliability (ICC=0.55-0.68) [163].

Four [109, 113, 148, 164] out of the seven (57%) included studies were rated as doubtful for the methodological quality of measuring diaphragm thickness. Two [149, 163] were rated as adequate and one was rated as inadequate[110]. Collectively, the quality of evidence for the intra and inter-reliability of using USG to measure diaphragm thickness was very low.

Diaphragm excursion: intra-rater and inter-rater reliability

Four included studies [109, 111, 154, 155] reported the reliability of using M-mode USG to measure left [154] and right [109, 111, 154, 155] diaphragm excursion by experienced operators, but the methodological quality of the included studies was doubtful. The between-day intra-rater reliability was consistently reported as sufficient on both sides (ICC=0.80-0.96) [109, 154]. However, the between-day inter-rater reliability was inconsistent (ICC=0.63-0.78) because insufficient reliability (ICC=0.63) was reported when measuring the diaphragm excursion during quiet breathing [111]. One included study reported intra-rater reliability but did not state the side of the hemidiaphragm and the measurement interval (ICC=0.79) [155]. There was low-quality evidence that the between-day intra-rater reliability of M-mode USG in measuring bilateral diaphragmatic excursion was sufficient. The evidence for others were very low.

Diaphragm stiffness: intra-rater and inter-rater reliability

Two included studies [115, 116] reported the reliability of using SWE to measure right diaphragmatic stiffness, while one of them [116] did not specify the time interval. The within-day intra-rater reliability was sufficient (ICC=0.93) [115], and the COSMIN rating was very good. Inter-rater reliability (ICC=0.96) was reported without specifying time interverbal [116]. There was low-quality evidence that the within-day intra-rater reliability of SWE in measuring right diaphragmatic stiffness was sufficient.

Diaphragm strain rate and motion velocity: intra-rater and inter-rater reliability

One included study [109] reported sufficient between-day intra-rater reliability of using STI to measure diaphragmatic strain rate (ICC=0.96), but COSMIN rating was

doubtful, and the evidence was very low. One included study [159] which used TDI to measure diaphragmatic motion velocity without specifying the time interval and reported sufficient reliability of intra and inter-rater reliability (ICC=0.96-0.99; ICC=0.89-0.98), COSMIN rating was doubtful and evidence was very low.

Intercostal muscle thickness and stiffness: inter-rater reliability

One included study measured intercostal muscle thickness [165] and one measured intercostal muscle stiffness [142]. Both studies reported sufficient within-day inter-rater reliability (ICC=0.92; ICC=0.80). The COSMIN ratings of both studies were doubtful, and the evidence was very low.

Abdominal muscle thickness: intra-rater and inter-rater reliability

One included study [162] reported sufficient within-day intra-rater reliability using B-mode USG to measure left TrA and IO thickness (ICC=0.76-0.82; ICC=0.78-0.87). Within-day inter-rater reliability of using B-mode USG to measure left TrA and IO was inconsistent (ICC=0.52-0.71; ICC=0.61-0.78) in different breathing phrases. The insufficient reliability reported in measuring muscles at the full inspiration phase. All the evidence was very low.

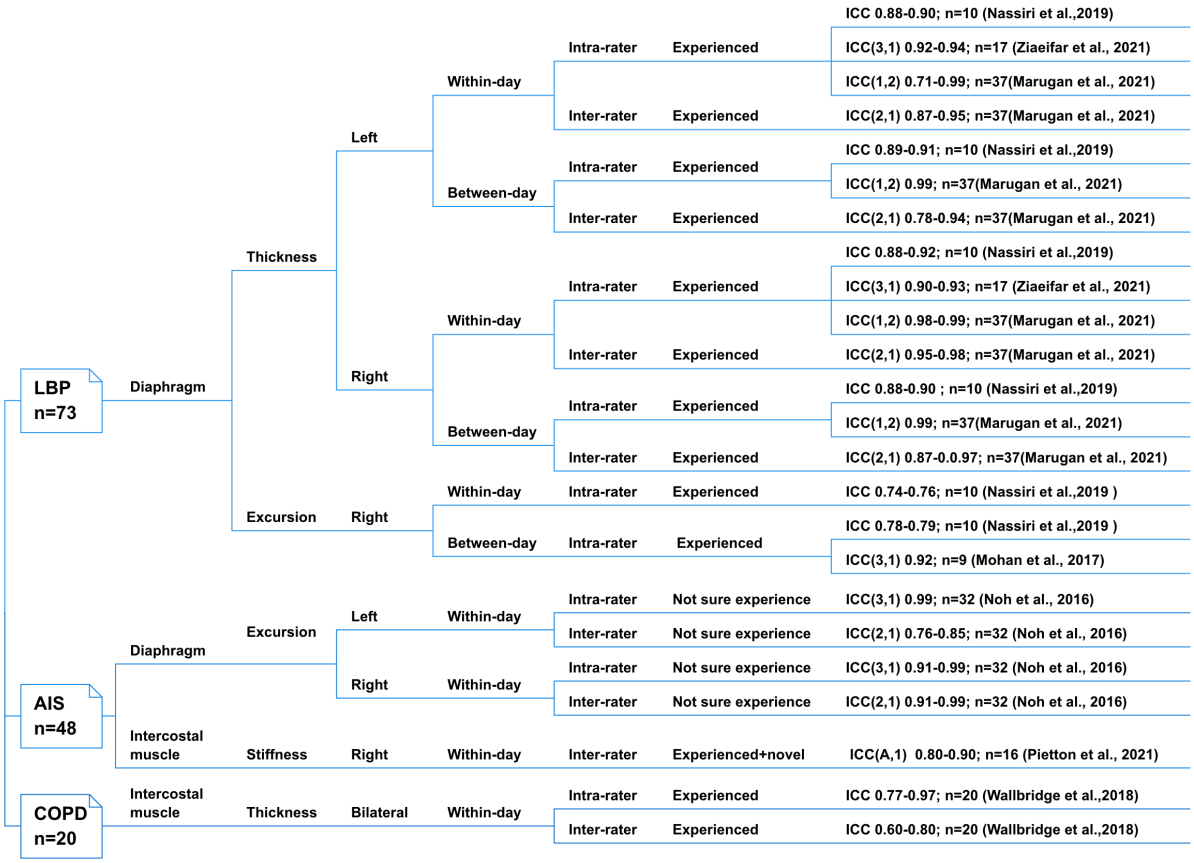

FIGURE 2. 3 Reliability of LBP, AIS, and COPD population**.** LBP = low back pain; AIS= adolescent idiopathic scoliosis; COPD= chronic obstructive pulmonary disease

LBP population

Diaphragm thickness: intra-rater and inter-rater reliability

Three included studies [112, 113, 147] reported sufficient intra- and inter-rater reliability of using B-mode USG for bilateral diaphragmatic thickness measurements with experienced operators (left: ICC=0.71-0.99; right: ICC=0.87-0.99). The COSMIN ratings were for the three studies were doubtful [113], adequate [112], and very good [147]. There was low-quality evidence that the within- and between-day intra- and inter-rater reliability of

USG in measuring bilateral diaphragmatic thickness in individuals with LBP in supine was sufficient.

Diaphragm-excursion: intra-rater and inter-rater reliability

Two included studies [113, 114] consistently reported sufficient within- (ICC=0.74-0.76) and between-day intra-rater reliability (ICC=0.78-0.92) in measuring right hemidiaphragm. The COSMIN ratings for both studies were doubtful and the level of evidence was very low.

Adolescent Idiopathic Scoliosis

Diaphragm-excursion and intercostal muscles-stiffness: intra-rater and inter-rater reliability

Two included studies reported consistently sufficient within-day intra- and inter-rater reliability in using M-mode USG to measure bilateral diaphragmatic excursion (ICC=0.76-0.99) [157] and using SWE to measure right intercostal muscle stiffness (ICC=0.80-0.90) [142] in teenagers with AIS. The COMSIN ratings of both studies were doubtful, and the relevant evidence was very low.

Chronic Obstructive Pulmonary Disease

Intercostal muscle thickness: intra-rater and inter-rater reliability

One included study [166] reported consistent sufficient within-day intra-rater reliability (ICC=0.77-0.97) and inconsistent within-day inter-rater reliability (ICC=0.60-0.80). The insufficient result was reported in measuring intercostal muscle thickness at right second and third intercostal levels. The COSMIN rating of this study was doubtful, and the evidence was very low.

2.4.5 Validity

The validity of relevant included studies, quality assessment for each study, and summary of evidence are shown in FIGURE 2.4 and SUPPLEMENTARY FILE 2.8.

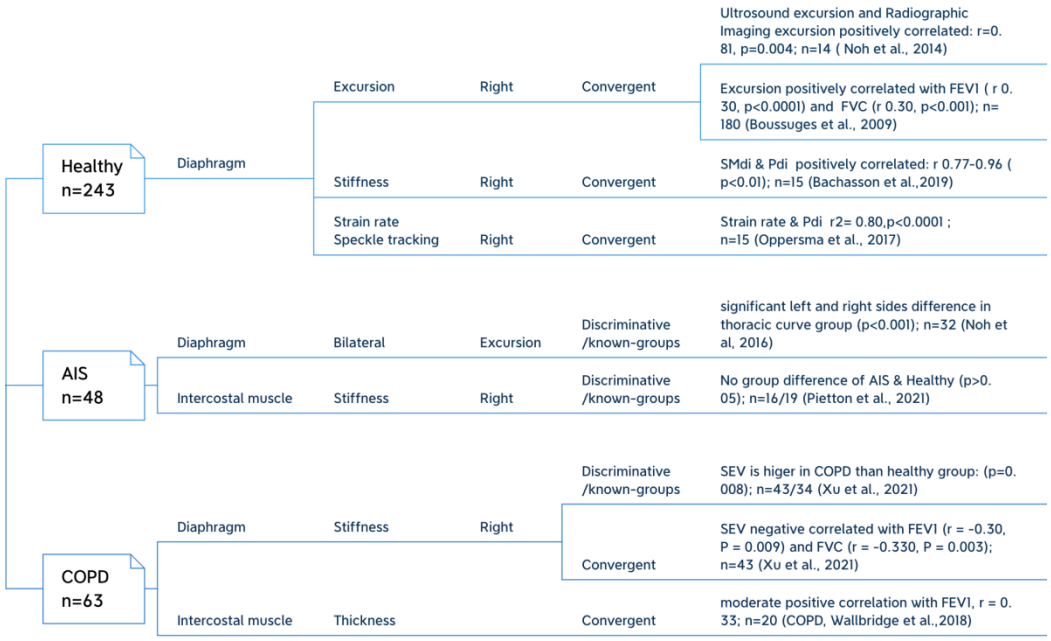

FIGURE 2. 4 Validity of included studies. AIS= adolescent idiopathic scoliosis; COPD= chronic obstructive pulmonary disease; Pdi=transdiaphragmatic pressure; FEV1=forced expiratory volume in the first second; FVC=forced vital capacity; SMdi=shear modulus of diaphragm; SEV=shear wave velocity

In Healthy population

Convergent validity

Four studies [99, 100, 154, 167] including 243 healthy participants reported different convergent validity of using different types of USG to evaluate diaphragmatic morphometry or functions. Positive correlations were noted between the diaphragmatic excursion as measured with M-mode USG and radiographic imaging (X-ray) [167], between the diaphragmatic excursion and forced expiratory volume in the first second (FEV1) or forced

vital capacity (FVC) [154], between diaphragmatic stiffness and transdiaphragmatic pressure (Pdi) [99], as well as between diaphragmatic strain rate and Pdi [100]. The methodological quality of these included studies was very good, and the validity values were all rated as sufficient. There was high-quality evidence to support the convergent validity between diaphragmatic excursion and FEV1 or FVC [154], while all the others were low.

In Adolescent Idiopathic Scoliosis population

Discriminative/known-groups validity

One included study reported a significant difference in the left and right side diaphragmatic excursion among participants with a thoracic curve, with an adequate COSMIN rating [157]. Another included study reported no significant group difference in stiffness of intercostal muscles between participants with and AIS [142], but the COSMIN rating was doubtful. The quality of evidence for both conditions were low.

In Chronic Obstructive Pulmonary Disease population

Convergent and discriminative/known-groups validity

One included study [115] reported both discriminative/known-groups and convergent validity of diagrammatic stiffness measurement. SEV in the COPD group was significantly higher than that of the healthy controls, and SEV was negatively correlated with FEV1 or FVC. Another included study [166] revealed a significant positive correlation between intercostal muscle thickness and FEV1. All these results were rated as sufficient. The methodological quality of convergent validity in these two studies was rated as doubtful and adequate respectively, and both of their evidence levels were very low. While the

methodological quality and quality of evidence of the first study on discriminative/known-groups validity was rated as very good and low respectively.

2.5 Discussion

Our review showed sufficient reliability and validity in each single study in using ultrasonography to assess the morphometry, function, and mechanical properties of diaphragm muscles in non-hospitalized individuals but with low-quality evidence. Low-quality evidence that the between-day intra-rater reliability of M-mode USG in measuring bilateral diaphragmatic excursion in healthy individuals [154], within-day intra-rater reliability of SWE in measuring right hemi-diaphragmatic stiffness in healthy individuals [115], and within-day intra- and inter-rater reliability, as well as between-day intra- and inter-rater reliability of B-mode USG in measuring bilateral diaphragmatic thickness in people with LBP [147] was sufficient. The quality of evidence regarding the reliability of using USG for measuring other diaphragmatic parameters was very low. Despite high-quality evidence supported the positive correlation between diaphragm excursion and FEV_1 or FVC in healthy participants [154], the quality of evidence for the validity of USG measurements and other comparators were low or very low.

There are several possible reasons to explain the low quality of evidence. According to the grading criteria, most of the included studies were downgraded by the small sample size and poor methodological quality. Because the included studies were heterogeneous in terms of the position of participants, breathing phase during measurements, the definition of operator's

experience, and the types of ICC model, they could not be pooled for meta-analysis. Therefore, the sample size for each measurement parameter in a given condition was very small. Additionally, most included studies were rated with doubtful methodological quality according to the latest version of the ClinROMs checklist [144]. Compared with the previously used COSMIN PROMs checklist (box6 for reliability assessment) which was designed for patient-reported outcome measures [145], the ClinROMs version was developed for clinician-reported outcome measures including readings based on imaging modalities and ratings based on observations such as USG. The studies on ClinROMs are more complicated as not only involve patients but also professionals even devices which means the design of the study with these additional aspects maybe more complex and may affect the quality. And the ClinROMs checklist also added items related to these additional aspects. Most of the included studies lost scores on items 4 and 5 (related to professionals) could be a verification that using new checklists affects the assessment of risk of bias. Four included studies published in 2021 developed their study design based on the ClinROMs checklists. Therefore, they were rated as very good or adequate [112, 115, 152, 168]. Collectively, earlier research that followed the previous COSMIN checklist in designing their studies yielded low methodological quality.

As expected, the intra-rater reliability was higher than the inter-rater reliability, and the reliability of experienced operators was higher than novice operators. The relatively lower inter-rater reliability in the current review concurs with previous findings on critically ill patients [137]. Novice operators have low reliability in performing USG measurements of muscles because USG is operator dependent. Specifically, the placement of a probe at the

target location (zone of apposition, subcostal, intercostal) and the selection of the best image on each measurement highly depends on the operator's experience. Such measurements are even more challenging for dynamic diaphragm measurements.

Although no meta-analysis was conducted, the reliability of measuring right hemidiaphragm seems to be higher than that of the left side. Using any type of USG to investigate diaphragm needs adjacent structures to provide a good acoustic window. Liver provides a good acoustic window for the right hemidiaphragm investigation, whereas the measure on the left hemidiaphragm is more challenging for novice operators given the smaller spleen window and the interference of gas in the gastrointestinal tract [169-171].

The comparators in convergent validity studies included Pdi, FEV_1, and FVC. Pdi is a golden standard for evaluating diaphragm function but it is invasive [137]. The strong positive correlation between Pdi and diaphragmatic stiffness [99] or strain rate [100] suggest that SWE and STI may noninvasively assess diaphragm functions. FEV_1 and FVC are commonly used to quantify respiratory function of patients with COPD [172]. The sufficient correlations between FEV_1 or FVC and respiratory muscle stiffness [115], thickness [166] and excursion [154] suggest that the SWE, B-mode and M-mode USG can be used to assess respiratory functions. Further studies should explore the measurement properties of other non-invasive measurements of respiratory muscle properties (e.g., magnetic resonance imaging).

The known-groups validity studies found that certain USG assessments of diaphragm parameters could be used to discriminate people with and without diseases [115, 142, 157].

Notably, the reported discriminative/known-groups validity in patients with AIS suggested that M-mode USG-measured diaphragmatic excursion might help differentiate the bilateral hemi-diaphragmatic function in patients with different severity of the thoracic curve [157]. However, the intercostal muscle stiffness cannot differentiate people with and without AIS [142], a study on patients with COPD suggests that SWE-measured diaphragmatic stiffness can differentiate people with and without COPD [115].

The evidence regarding SWE, STI, and TDI was low summarized from the limited number of studies. SWE generates shear waves that propagate through tissues in the transverse plane causing shear displacements, which can be tracked to calculate shear wave velocity or shear modulus [91]. Shear wave velocity is faster in stiffer tissues, but decreases significantly with the thickness in thin tissues, especially when the thickness is less than 1.5 cm [117, 118]. Therefore, shear wave velocity is affected by muscle mechanical properties and thickness in very thin tissues. Because both diaphragm and intercostal muscles are thin (0.13-0.76cm) [119], the validity of using SWE to measure inspiratory muscle stiffness should be interpreted with caution [120]. Further, the limited penetration depth, high sensitivity to sensor pressure and angle, and the dependence of shear modulus on the probe orientation are the disadvantages of SWE [91, 173]. Future studies should take muscle thickness into consideration if SWE is used to measure respiratory muscle stiffness.

Both STI and TDI are strain rate imaging, which measure the differences in motion and velocity within tissues. They are commonly used in echocardiographic imaging to assess regional myocardial function [174, 175]. Speckles are small groups of tissue pixels with

specific grayscale characteristics created by the interaction of ultrasound beams and tissues and can be used to calculate the tissue strain and strain rate [175]. STI technique identifies and tracks the same speckle throughout the movement cycle. While TDI measures the longitudinal strain and strain rate (one dimension, ultrasound beam should be parallel to the direction of tissue motion), STI is independent of the angle and beam directions, and allows the tracking in two dimensions [176]. Therefore, STI is better than TDI in investigating the motion of diaphragm which may better reflect diaphragmatic contractibility. More studies are warranted to use these two novel techniques to investigate respiratory muscles.

2.6 Limitations

The current review had several limitations. First, the included studies were heterogenous, which precluded meta-analysis. Second, the use of the updated and stricter ClinROMs checklist led to the downgrade of the quality of evidence, although it was essential. Third, no included studies evaluated the responsiveness of various USG measurements, which may limit its clinical usage.

2.7 Conclusions

This is the first systematic review on the evidence regarding the measurement properties of using various types of USG to evaluate respiratory muscle characteristics in non-hospitalized populations. Although separate included studies revealed sufficient reliability and validity of using these USG technologies to assess the morphometry, function,

and mechanical properties of respiratory muscles in non-hospitalized individuals, the respective quality of evidence was low due to the limited number of relevant studies. More high-quality large-scale studies are warranted to establish the reliability and validity of using various types of USG assessments to measure different respiratory muscle characteristics in different populations. And researchers should establish their own reliability before using ultrasonography/shear wave elastography as a measure for diaphragm muscle evaluations.

CHAPTER 3

Study 2: Reliability of ultrasound shear wave elastography for evaluating psoas major and quadratus lumborum stiffness: gender and physical activity effects

3.1 Abstract

Objective:

We aimed to assess the reliability of quantifying psoas major (PM) and quadratus lumborum (QL) stiffness with ultrasound shear wave elastography (SWE), and to explore the effects of gender and physical activity on muscle stiffness.

Methods:

Fifty-two healthy participants (18–32 years) were recruited. To determine reliability, 29 of them underwent repeated SWE measurements of PM and QL stiffness by an operator on the same day. The intra-class correlation coefficients ($ICC_{3,1}$), standard error of measurement (SEM), and minimal detectable change with 95% confidence interval (MDC_{95}) were calculated. The rest participants underwent a single measurement. Two-way MANCOVA was conducted for the effects of gender and physical activity on muscle stiffness.

Results:

The observed reliability for PM ($ICC_{3,1}$ = 0.89–0.92) and QL ($ICC_{3,1}$ = 0.79–0.82) were good-to-excellent and good, respectively. The SEM (kPa) was 0.79–1.03 and 1.23–1.28, and the MDC_{95} (kPa) was 2.20–2.85 and 3.41–3.56 for PM and QL, respectively. After BMI adjustment, both gender (PM: $F = 10.15$, $p = 0.003$; QL: $F = 18.07$, $p < 0.001$) and activity level (PM: $F = 5.90$, $p = 0.005$; QL: $F = 6.33$, $p = 0.004$) influenced muscle stiffness. The female and inactive groups exhibited higher stiffness in both muscles.

Conclusion: SWE is reliable for quantifying the stiffness of PM and QL. Female and physical inactivity may elevate PM and QL stiffness, underscoring the importance of

accounting for these factors in muscle stiffness investigations. Larger prospective studies are needed to further elucidate their effects.

3.2 Introduction

The psoas major (PM) and quadratus lumborum (QL) muscles are the prime movers and stabilizers of the lumbar spine [18, 50]. Dysfunction of these muscles may be associated with low back pain (LBP) [177-182].

The PM extends from T12 to the lesser tuberosity of the femur [50], increased PM tightness may exert excessive compression and shear force on the lumbar spine, thereby increasing the risk of LBP [49, 52, 64]. PM flexibility is clinically measured by the Modified Thomas test [66, 183, 184]. Prior studies have reported both significant [180, 182] and non-significant [62, 69] associations between hip flexor tightness as measured by this test and LBP. Similarly, a recent review revealed that the QL tightness, which manifested as limited lateral flexion, was associated with an increased risk of developing LBP [181]. The trunk lateral flexion is clinically measured by the distance of the fingertip to the floor [185, 186]. However, these clinical test results may be confounded by dysfunctions of surrounding structures (e.g. tightness of ligaments, joint capsule, or osseous constraint). Therefore, it is necessary to establish a reliable method to directly quantify PM and QL stiffness to better understand its association with LBP.

Ultrasound shear wave elastography (SWE), which is a non-invasive, convenient, and cost-effective method, has been developed as an objective, reproducible and the most promising modality for evaluating muscle stiffness in vivo [87, 88, 90, 91, 93, 94, 187, 188]. The application has been extended to muscles from various regions, including but not limited to the rotator cuff, multifidus, quadriceps, calf muscles, and masticatory muscles [91, 95-98].

SWE employs an acoustic radiation force pulse sequence to produce shear waves that travel perpendicular to the ultrasound beam and lead to temporary displacements. The stiffer the tissue, the higher the shear wave propagation velocity, which can be converted into Young's modulus of tissue (a definitive measure of the tissue's elastic property) [91, 92]. Although SWE has been used in a prior study to quantify the stiffness of distal PM at the groin level where part of PM has formed a tendinous architecture [50, 69], it remains unclear whether SWE can be used to measure the stiffness of PM muscle belly, where it attaches to the lumbar spine. The percentages of type I and type II fibres of the PM muscle gradually decrease and increase, respectively, from the upper to lower segments [55, 70]. Characterised by relatively higher proportions of type I or II fibres, the upper and lower segments are likely to play more roles in providing postural support and facilitating joint motions, respectively [55]. Therefore, measuring PM stiffness at the muscle belly near the lumbar spine may provide more insight into its association with LBP. Because using a curvilinear transducer (1-4 MHz) to measure liver stiffness at 4-5 cm below the skin yielded the smallest variability of findings [92], SWE may suit the measurement of PM and QL muscle stiffness at approximately 5 cm below the skin.

Given the above, this study aimed to evaluate: (1) the reliability of using ultrasound SWE measurements to quantify the stiffness (in terms of Young's modulus) of PM and QL muscles; and (2) the effects of genders and physical activity level on PM and QL stiffness given that known impact of gender or physical activity-related mechanical loading on skeletal muscle properties [83, 189, 190].

3.3 Material and Methods

Study design

The reliability study was designed according to the criteria of the updated version of the Consensus-based Standards for the Selection of Health Measurement Instruments (COSMIN) checklist for reliability methodological assessments [144]. A CHecklist for statistical Assessment of Medical Papers (CHAMP) was used to guide the statistical approach and reporting [191].

Sample size calculation

The sample size was calculated using a web-based sample size calculator for reliability studies [192]. The predetermined minimum acceptable intra-class correlation (ICC) was 0.7, with expected reliability ICC = 0.9, $\alpha = 0.05$, statistical power =80%, repeated measurements = 2, and the dropout rate = 20%. The calculated minimum sample size was 29.

Participant recruitment and procedures

Our study enrolled healthy individuals aged between 18 and 32 years from a university community and a sports training centre. Individuals were excluded if they experienced LBP, which is located between the lower margin of the 12^{th} rib and buttock crease with or without leg pain during the last 3 months [4]. Additionally, those who were obese, or presented with any diagnosed systematic disease, spinal pathological conditions, scoliosis, history of spine trauma or surgery, or an inability to maintain a side-lying position for a duration of 30 minutes were also excluded [193].

The study was approved by the Institutional Review Board. Participants visited an ultrasound laboratory for data collection. After providing informed consent, each participant completed a questionnaire encompassing demographic information such as age, gender, and BMI. Furthermore, participants reported the average duration of moderate-intensity or higher physical activity per week in the preceding month. The talk test, a reliable self-assessment tool, was employed to evaluate the intensity of physical activity [194]. The positive stage of the talk test refers to the ability to talk comfortably, and reaching the last positive stage suggests a moderate exercise intensity [195]. They were classified into three categories: physically inactive, physically active, and athletic. Specifically, the athletic category encompassed individuals undergoing rigorous sports training on a full-time basis (> 20 hours/week). The non-athletic participants were classified based on the criteria outlined by the Sedentary Behavior Research Network (SBRN) terminology consensus of 2017 [196]. Participants in the inactive group should engage in < 150 minutes/week of moderate-vigorous-intensity physical activity, while those in the active group should participate in ≥ 150 minutes/week of such activity.

The within-day intra-rater reliability was assessed by an operator who examined the stiffness of bilateral PM and QL muscles using SWE in 29 participants. This assessment was conducted twice with a 30-minute interval between. Another 23 participants were recruited to undergo a single SWE measurement of PM and QL muscle stiffness by the same operator in order to evaluate the effects of gender and physical activity on the stiffness of these two muscles (FIGURE 3.1).

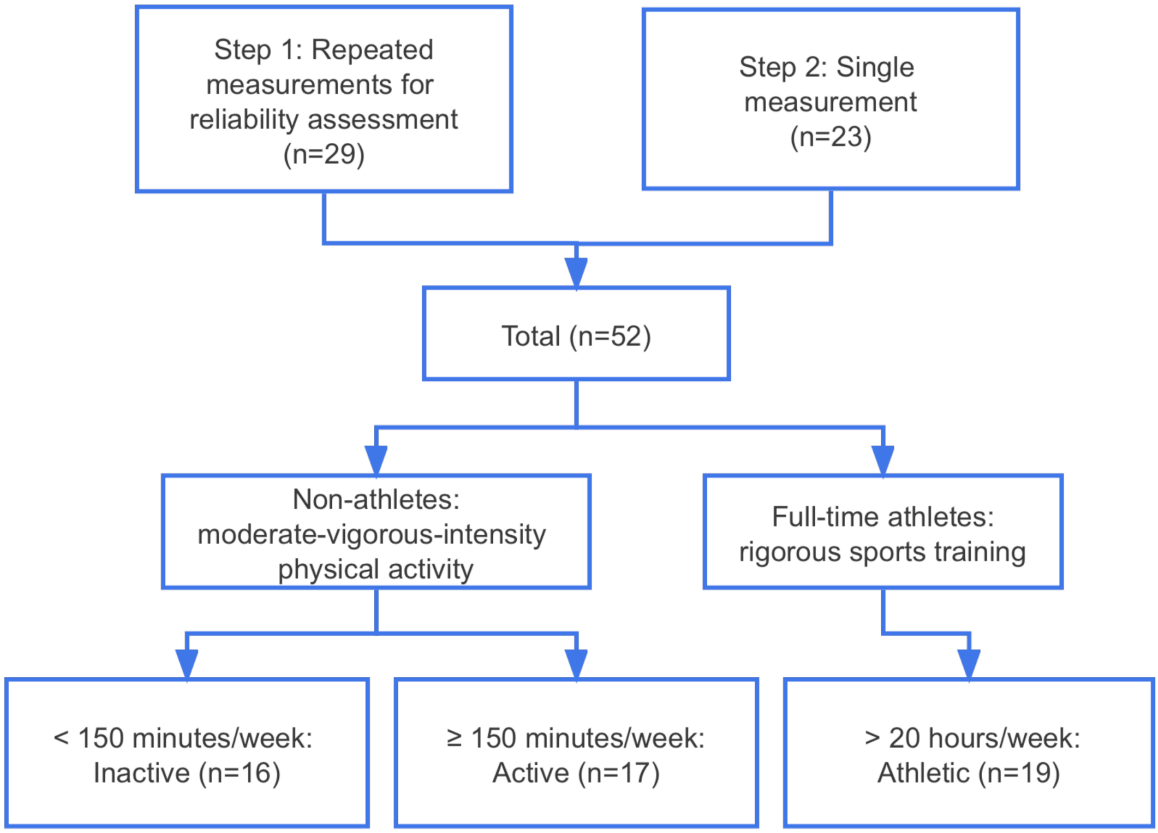

FIGURE 3. 1 Flowchart of the study

Ultrasound measurements

The data were collected by a physician with 16 years of clinical experience and 3 years of experience in using SWE ultrasonography. The procedure was supervised by a certified Registered Musculoskeletal Sonologist (RMSK) and Certified Interventional Pain Sonologist (CIPS) with 24 years of experience.

Preparation

All tests were conducted on Sunday afternoons, which were non-training days for athletes. Participants were advised to avoid eating and engaging in intensive exercise before the tests. They were asked to relax and rest in a supine position for 10 minutes in a room maintained at 25°C.

SWE of PM and QL

Participants adopted a lateral decubitus position with the spine and upper leg in a neutral position. Notably, a wedge-shaped cushion was placed behind the upper back to maintain the torso perpendicular to the plinth, and a square cushion was put between the upper legs to maintain the hip joint in a neutral position. A towel was added to support a neutral lumbar spine, if necessary (FIGURE 3.2).

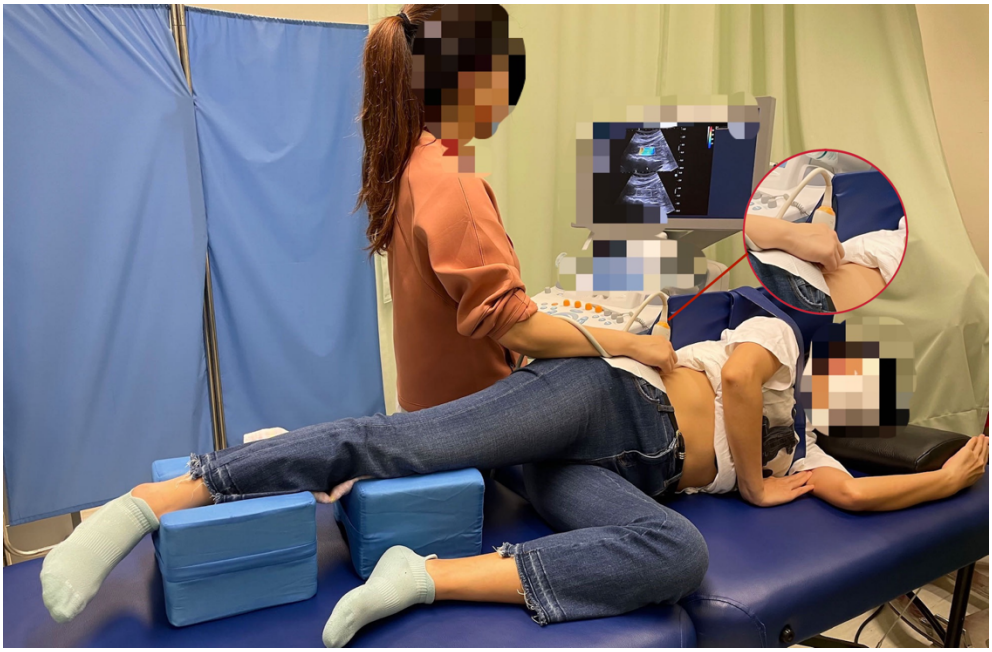

FIGURE 3. 2 Position of participants in measuring psoas major and quadratus lumborum

A Supersonic Imagine's Aixplorer® system with an UltraFast™ platform (Aix en Provence, France) was used to acquire real-time SWE images of bilateral PM and QL muscles. A 1-6 MHz low-frequency curvilinear probe was placed above the iliac crest along the mid-axillary line. The cranial end of the probe was pivoted posteriorly by approximately 20° until the L4 vertebra was visualized along the centre of the probe using the brightness-mode (B-mode) ultrasonography. PM is the muscle overlaying the vertebrae, while QL is the relatively hypoechoic muscle overlaying the PM (FIGURE 3.2 & 3.3).

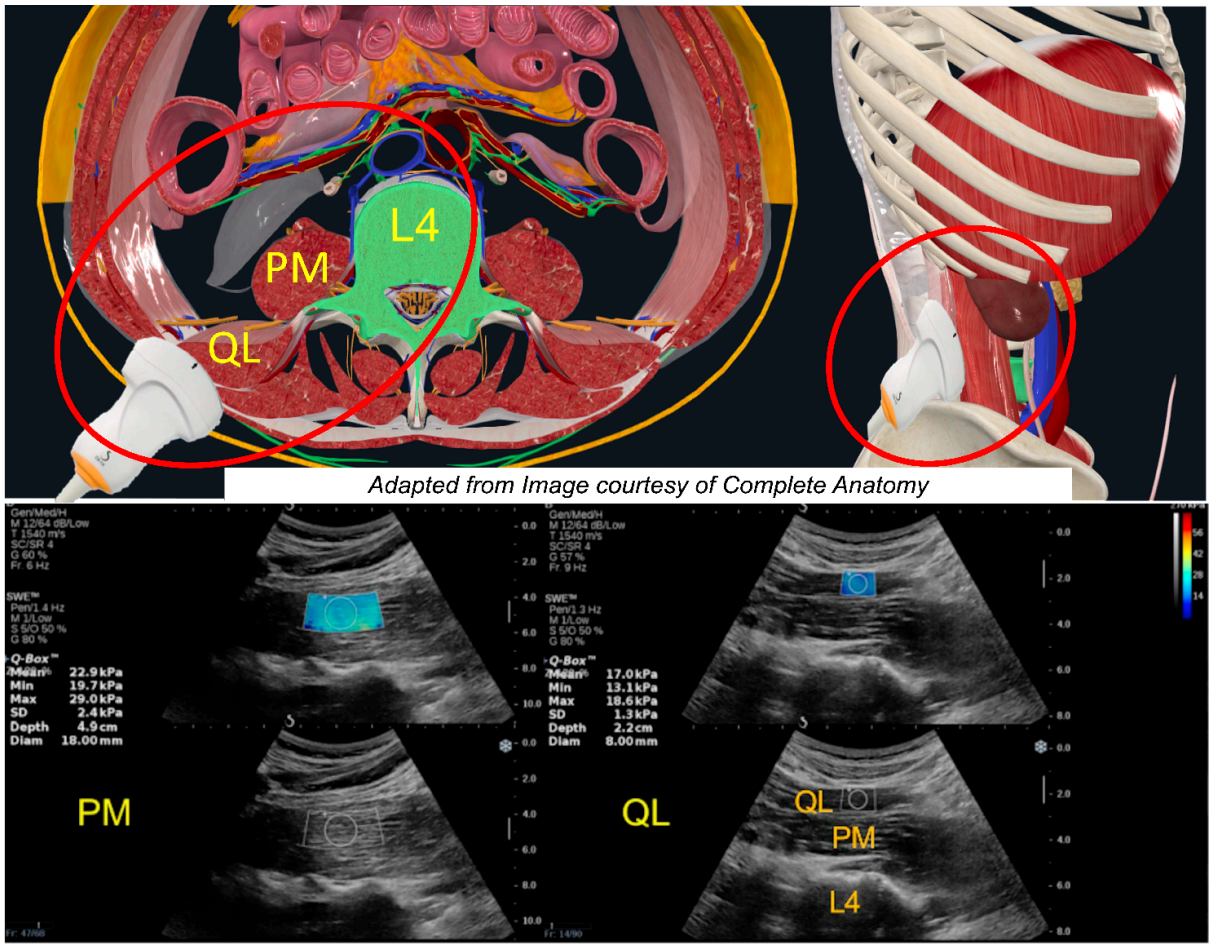

FIGURE 3. 3 Anatomical adjacencies and ultrasound shear wave elastography measurement of psoas major (PM) and quadratus lumborum (QL)

To capture the SWE images of the PM, the direction of the ultrasound probe was fine-tuned until it was oriented parallel to the long axis of muscle fibres with its central part perpendicular to the muscle fibres (FIGURE 3.3). SWE mode was then switched on and the blunted sector box of the region of interest (ROI) was placed on the identified muscle. Thereafter, the frequency was turned to penetration mode, and the focused area was adjusted automatically or manually to the depth of ROI. The ROI was filled with colour reflecting the magnitude of Young's modulus. A 10-second real-time cine loop was recorded, while the participant was holding his breath at the end of tidal expiration (FIGURE 3.3). To capture SWE images of QL, the transducer was toed toward the ipsilateral iliac crest slightly so that

the sound beam could parallel to the muscle long axis and transmit perpendicular to the muscle fibres. The ROI was located under the centre of the probe. A 10-second real-time cine loop was recorded at the end of tidal expiration (FIGURE 3.3). The image acquisition was started with the PM followed by QL, and from the right to the left side.

Off-line analyses were conducted after capturing all the images to avoid recall bias. Five images with homogenous and well-filled ROIs were selected from each 10-second video. A circled quantification box (Q-box) was drawn as large as possible along the midline of the ROI without overlapping the edge, while ensuring that the standard deviation of the readings in each Q-box was less than 20%. The mean value of Young's modulus (in kPa) in the Q-box was recorded. The average value from five images selected from the 10-second recorded video was then calculated.

Statistical analysis

IBM SPSS version 26.0 (IBM Corp., Armonk, NY, US) was used for the statistical analysis. The Shapiro–Wilk test was used to test the normality of data. Within-day intra-rater consistency was reported as intraclass correlation coefficient model 3 ($ICC_{3,1}$, single measurement) and 95% confidence intervals. ICC values < 0.5, 0.5–0.75, 0.75–0.9, and > 0.9 indicated poor, moderate, good, and excellent reliability, respectively.[197] Standard error of measurement (SEM) and minimal detectable change with 95% confidence (MDC_{95}) were calculated using the formulas,[198] SEM = standard deviation * √(1-ICC) and MDC_{95} = 1.96 * SEM * √2, respectively.

The stiffness of PM and QL muscle was determined by averaging the values of Young's modulus obtained from bilateral sides. To investigate the effect of gender and activity level on muscle stiffness, muscle stiffness data from the 29 participants during the first measurement of the reliability experiment and the data from 23 participants were pooled to run two-way MANCOVA for analysis. The BMI was entered as a covariate. Post-hoc pairwise comparisons were conducted on activity level when $p < 0.05$.

3.4 Results

A total of 52 healthy participants aged 18-32 years were recruited. Nineteen of them were full-time professional athletes. Descriptive information is presented in TABLE 3.1. Due to the poor image of PM muscle, data from one female was excluded.

TABLE 3. 1 Demographics of included participants (mean (SD))

By gender	**Total (*n* = 52)**	**Male (*n* = 33)**	**Female (*n* = 19)**	***p* value**
Age (y)	22.9 (3.2)	23.0 (3.4)	22.6 (2.9)	0.682
Height (m)	1.7 (0.08)	1.7 (0.07)	1.6 (0.05)	0.000**
Weight (kg)	57.9 (9.2)	62.4 (8.0)	50.1 (5.1)	0.000**
BMI (kg/m^2)	20.4 (2.3)	21.2 (2.0)	18.9 (1.9)	0.000**
Exercise/week (h) †	7.5 (0~38.0)	10.0 (0~36.0)	2 (0~38.0)	0.013*
By activity level	**Inactivity (*n* = 16)**	**Activity (*n* = 17)**	**Athletes (*n* = 19)**	***p* value**
Age (y)	22.5 (2.0)	24.2 (2.9)	22.0 (4.0)	0.089
Height (m)	1.7 (0.06)	1.7 (0.08)	1.7 (0.06)	0.000**
Weight (kg)	50.6 (6.4)	63.6 (10.2)	59.0 (5.8)	0.000**
BMI (kg/m^2)	18.2 (1.7)	21.1 (2.2)	21.6 (1.3)	0.000**
Gender (male/female)	5/11	14/3	14/5	0.005**
Reliability study	**Total (*n* = 29)**			
Age (y)	22.7 (2.9)			
Height (m)	1.7 (0.1)			

Weight (kg)	59.7 (9.8)
BMI (kg/m^2)	20.6 (2.2)
Gender (male/female)	21/8

Abbreviations: BMI = body mass index; SD = standard deviation; *: $p < 0.05$; **: $p < 0.01$; †: Median (range)

TABLE 3.2 shows the average values of Young's modulus, $ICC_{3,1}$, SEM, and MDC_{95} of the PM and QL assessed during the first and second measurements. Good-to-excellent and good within-day test-retest reliability was demonstrated in quantifying the Young's modulus of PM ($ICC_{3,1}$ = 0.89–0.92) and QL ($ICC_{3,1}$ = 0.79–0.82) muscles. The SEM and MDC_{95} of the PM were 0.79–1.03 kPa and 2.20–2.85 kPa, respectively; for the QL muscle, SEM and MDC_{95} were 1.23–1.28 kPa and 3.41–3.56 kPa, respectively.

TABLE 3. 2 Within-day test-retest reliability of PM and QL muscle measurements using SWE

	$ICC_{3,1}$	**Mean (SD) (kPa)**		**SEM (kPa)**		**MDC (kPa)**	
	(95%CI)	**Test 1**	**Test 2**	**Test 1**	**Test 2**	**Test 1**	**Test 2**
Right PM	0.92 (0.84, 0.96)**	19.62 (2.8)	20.13 (3.4)	0.79	0.96	2.20	2.67
Left PM	0.89 (0.78, 0.95)*	19.2 (2.7)	19.51 (3.1)	0.90	1.03	2.48	2.85
Right QL	0.79 (0.61, 0.90)*	22.25 (2.8)	21.96 (2.8)	1.28	1.28	3.56	3.56
Left QL	0.82 (0.65, 0.91)*	22.99 (2.9)	22.79 (3.0)	1.23	1.27	3.41	3.53

Abbreviations: CI = confidence interval; ICC = intra-class correlation; MDC = minimum detectable change; PM = psoas major; QL = quadratus lumborum; SD = standard deviation; SEM = standard error of measurement; SWE = shear wave elastography; *: good reliability: ICCs = 0.75–0.9; **: excellent reliability: ICC > 0.9

TABLE 3. 3 Effect of gender and activity level on PM & QL stiffness

Factor†	**Muscle**	**F**	***p* value**	**Observed Power**
Gender	PM	10.15	0.003**	0.88
	QL	18.07	0.000**	0.99
Activity level	PM	5.90	0.005**	0.85
	QL	6.33	0.004**	0.88

Abbreviations: PM = psoas major; QL = quadratus lumborum; **: $p < 0.01$; †: Analysed with BMI as the covariate

MANCOVA found that both the gender (PM: F = 10.15, $p = 0.003$; QL: F = 18.07, $p < 0.001$) and activity level (PM: F = 5.90, $p = 0.005$; QL: F = 6.33, $p = 0.004$) independently and significantly modify PM and QL stiffness (TABLE 3.3). Females showed 16% and 17% higher stiffness of PM (mean difference (MD) = 3.23, $p = 0.003$) and QL (MD = 3.65, $p < 0.001$) than males, respectively. Post-hoc pairwise comparisons for physical activity levels suggested that the inactive group had significantly higher PM and QL stiffness compared to the active (PM: MD = 4.10, $p = 0.002$; QL: MD = 3.81, $p = 0.001$) and athletic groups (PM: MD = 3.72, $p = 0.008$; QL: MD = 2.54 (<MDC_{95}), $p = 0.032$). A non-significant difference in absolute value was found between the active and athletic group (PM: MD = 0.374, $p = 0.764$; QL: MD = 1.27, $p = 0.233$) (FIGURE 4).

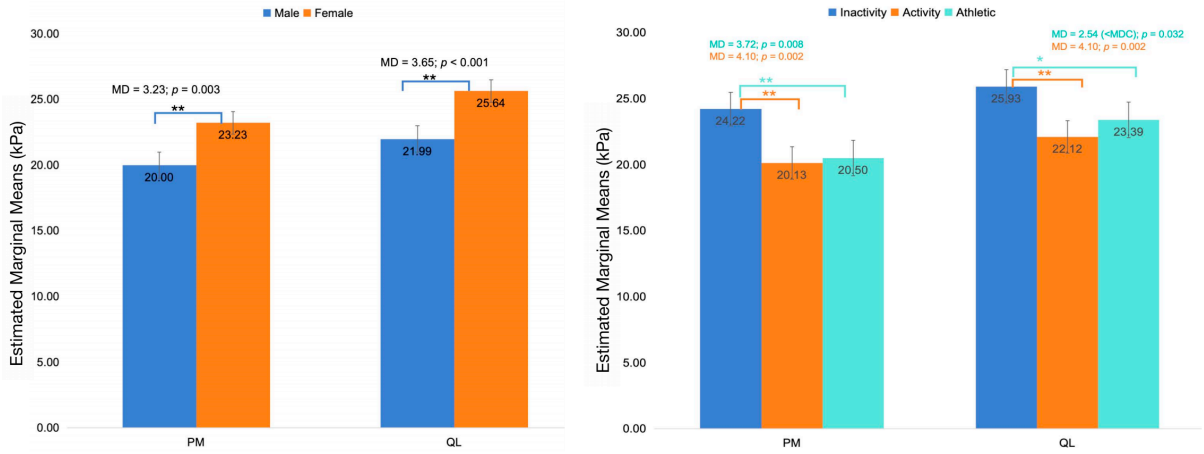

FIGURE 3. 4 Comparisons of psoas major (PM) and quadratus lumborum (QL) stiffness through pairwise analysis across diverse gender and activity Levels (MD = mean difference; MDC = minimum detectable change)

3.5 Discussion

Our study revealed that SWE was a reliable tool for quantifying PM and QL muscle stiffness. Specifically, good-to-excellent and good within-day intra-rater reliability was

observed when measuring the stiffness of PM and QL muscles using SWE. Furthermore, females and physically inactive significantly modified PM and QL muscle stiffness.

Within-day reliability

A previous study reported good reliability using ultrasound SWE in a supine position to measure the stiffness of the lower segment of the PM in the groin region [69], where part of the muscle belly had formed a tendinous architecture [50, 199]. The current study measured the stiffness of the upper segment of the PM muscle, located at a greater depth in the lumbar region, and obtained good-to-excellent within-day intra-rater reliability. Unlike the previous research, the lateral decubitus position in the current study provided a better acoustic window for improved visualisation of the PM muscle belly and minimised artifacts from internal organs and bowel gas. We chose the L4 vertebra level as the reference, where the muscle belly is the largest and relatively superficial, to avoid the proximal artifacts of the kidney and the distal artifacts of large blood vessels [200]. By following these technical details, we observed that SWE can provide reliable measurements on PM stiffness at its muscle belly.

The reliability of stiffness measurements for PM appeared to be better than that for QL. This may be because the QL has a relatively thinner quadrilateral shape and its variable pennation angles of muscle fibres pose more challenges for the measurement. To achieve optimal images with above-mentioned challenges, the probe was rocked toward the ipsilateral iliac crest to search for thicker portions of the QL muscles, and the central part of probe was oriented perpendicular to the muscle fibres. Another factor that may affect QL measurements

is the rib shadowing effect. Given the close anatomical position between the 12th rib and the QL muscle, rib shadowing may affect the elasticity map filling. To attain more accurate SWE readings, the probe should be slid downward or swept forward/backward to eliminate the rib shadowing. With these adjustments, SWE could provide good test-retest reliability on QL muscle measurements.

As this was the first reliability study quantifying the stiffness of these two muscles, no prior study was available for comparison. Additionally, the depth of PM imaging in our study is located up to 7 cm. Thus, our results demonstrated that SWE method may have the potential to measure the muscle stiffness of the PM at a depth of 7 cm. As in the prior study which measured PM stiffness at the groin region [69], we did not investigate the inter-rater reliability since only one operator was included in our study. However, the inter-rater as well as between-day reliability studies are warranted to ensure the further application of the method.

Interestingly, one female showed very poor elasticity map filling during the PM measurement, although there was no significant difference in her demographics with other participants. Individual factors such as tissue dehydration or estrogen changes in menstrual cycles might cause a poor elasticity map. Further research is necessary to explore the impacts of these factors.

The modifying effect of gender

Females demonstrated larger muscle stiffness than males, and the stiffness differences of both muscles (PM: 3.23 kPa; QL: 3.65 kPa) were greater than the respective MDC_{95} (PM:

2.20–2.85 kPa; 3.41–3.56 kPa), indicating that the differences were bigger than measurement errors. As more than 3,000 distinct genetic expressions have been found between male and female skeletal muscles [201]. Male and female muscle fibres diverge in both composition and dimensions, with males presenting a heightened prevalence of Type IIb fibres, greater pennation angles and larger cross-sectional areas (CSA) of muscle fibres [190, 202]. This dichotomy leads to males being attributed with augmented muscle cross-bridges and heightened maximal voluntary contraction (MVC) capabilities [190]. However, the stiffness of muscles is contingent upon two primary constituents: muscle fibres and intramuscular connective tissue (IMCT) [203, 204]. The IMCT is predominantly composed of the extracellular matrix (ECM), which exhibits notably higher stiffness in comparison to muscle fibres [205]. Research has indicated that the passive stiffness of muscles predominantly reflects the characteristics of the ECM [205, 206]. Meanwhile, larger muscle fibres were found to correlate with lower elastic modulus, potentially arising from comparatively reduced surrounding ECM [207]. Additionally, female may have higher fat content, which is reported to have higher stiffness, due to the effect of the sex hormone [190, 208, 209]. All the above evidence may elucidate our observed higher elastic modulus, or stiffness, in females as compared to males.

No prior research has examined gender differences in PM and QL stiffness. Nevertheless, our findings align with investigations on muscle stiffness of biceps brachii and brachioradialis [210, 211]. However, another study encompassing a broader age range of participants, spanning from 18 to 48 years (89% male), demonstrated higher stiffness in the

medial gastrocnemius muscle among males [212]. Muscle stiffness may increase with advanced age which could be attributed to alterations in collagen cross-linking within the ECM, potentially attenuating some aspects of gender-related effects [211, 213, 214]. However, this study did not consider the impact of participants' physical activity level, a factor that our study found to exert a significant influence on muscle stiffness. A similar condition that did not consider physical activity impact also existed in two other studies that reported statistically insignificant gender disparities in rectus femoris, biceps brachii, deltoid, pectoralis major, and trapezius muscles [215, 216].

The modifying effect of physical activity level

Similar to several prior studies [72, 86], we found lower muscle stiffness in athletes compared to the other two groups. Physical activity affects the mechanical loading on muscles. Studies have found that tendon properties alter in response to mechanical loading-related ECM changes [83, 84]. These studies found that physical inactivity would decrease collagen turnover within the ECM thus reducing tendon stiffness, while chronic loading in the form of physical training might enhance collagen synthesis thereby increasing the stiffness [83, 84]. Similar effects on ECM from loading have also been found in skeletal muscles [83], nevertheless, how muscle stiffness changes (including contractile and non-contractile elements) in response to mechanical loading-related ECM changes remains unclear [204].

Our results suggest a pronounced influence of physical inactivity on the elevation of paraspinal muscle stiffness (PM & QL). The findings are consistent with a prior investigation

that examined muscle stiffness in the biceps brachii and rectus femoris among master track and field athletes compared to a sedentary cohort [86]. That study revealed that master athletes exhibited reduced stiffness on the tested muscles than sedentary controls [86]. However, another study observed activity-induced reduction in some (semimembranosus) but not all (semitendinosus and biceps femoris) muscle bellies of hamstrings compared to a control group [72]. Additionally, sports-specific variations in hamstrings stiffness were noted among athletes participating in different sports, including skating, taekwondo, fencing, and soccer participants, sprinting, field hockey, and basketball [72]. Similarly, increased stiffness was observed in the rectus femoris but not in vastus medialis muscle belly among soccer players relative to the sedentary population [85].

Taken together, the influence of activity-induced mechanical loading on muscle stiffness appears to be contingent upon the diverse loading patterns associated with varying levels of activity, specific sports practices, and the involved muscle groups. The marginal discrepancy in QL stiffness observed between the inactive and athletic groups could potentially be attributed to divergent muscle responses to mechanical loading, and the modest sample size. Although the precise mechanism underlying the impact of loading on muscle stiffness remains elusive, the activity level warrants careful consideration when delving into research on muscle stiffness.

Limitations

The current study had some limitations. Firstly, we did not recruit obese participants, thus, their PM muscle might lie more superficial to capture better images. Although the curvilinear probe had the best measurement reliability at a depth of 4-5 cm based on a previous study [92], our findings suggested that it could be used to measure muscles at depths of up to 7 cm. Consequently, the technology can only be applied to non-obese individuals with PM located within 7 cm below the probe. Secondly, the sample size in each group was relatively small, although we got enough statistical power. Future studies with matched gender and activity level in each analysed group are warranted.

3.6 Conclusion

Ultrasound SWE is a reliable method to measure the passive stiffness of PM and QL muscles in healthy individuals and professional athletes. Our measurement approach could be applied to adults with PM located within 7 cm below the probe. Females and physically inactive individuals demonstrated heightened PM and QL stiffness. Further research should adopt the current measurement approach to evaluate the PM and QL stiffness in people with and without low back pain, and to determine the effects of exercise interventions on the stiffness of these two muscles after taking gender and physical activity level into consideration.

Chapter 4

Study 3: Diaphragm function in elite weightlifters with and without chronic low back pain and its impacts on sports performance

4.1 Abstract

The study aimed to compare diaphragm function between elite weightlifters with and without chronic low back pain (LBP); and to explore the associations between diaphragm function and sports performance. Forty-nine elite weightlifters aged 16 to 26 years were recruited, including 29 females (16 to 25 years, mean ± standard deviation (SD) = 19.93 ± 2.70 years) and 20 males (16 to 26 years, mean ± SD = 20.95 ± 2.68 years). Of these, 23 participants had chronic LBP. Diaphragm thickness and excursion were assessed using ultrasonography, and maximal inspiratory pressure (MIP) measured with POWERbreatheKH2, served as indicators of diaphragm contractility and strength, respectively. Sports performance was gauged through maximal snatch and clean and jerk lifts. Group differences and performance correlations were analyzed with consideration for confounders. The significance was set at $p \leq 0.05$. Weightlifters with chronic LBP demonstrated significantly lower diaphragmatic contractility: diaphragm thickening fraction (by 21%; mean difference (MD) = 0.09, $p = 0.04$, Cohen's d = 0.69) and diaphragm excursion (by 18%; MD = 0.99, $p < 0.01$, Cohen's d = 0.89) compared to non-LBP controls. Additionally, MIP was positively related to snatch (r = 0.34, $p = 0.02$) and clean and jerk (r = 0.43, $p < 0.01$) lifts. This study revealed that elite weightlifters with chronic LBP exhibit reduced diaphragm contractility, and inspiratory muscle force output (primary diaphragm) was associated with lifting performance. Incorporating diaphragm strengthening into training and rehabilitation might enhance performance and aid in LBP management, offering a dual benefit for athletes.

4.2 Introduction

Low back pain (LBP) is a predominant injury among elite weightlifters, with reported one-year prevalence rates ranging from 54% to 85% [217, 218]. The high occurrence of LBP not only compromised their performance but also posed a threat to their careers and resulted in enduring episodes throughout their lifetime [8].

Weightlifting is an Olympic sport that aims to lift the maximum weight above the head either in a single-stage movement/breath, as in the snatch, or a two-stage movement/two-breathes, as in the clean and jerk [9]. This high-loading sport exposes the lower back to an average compressive load exceeding 17,192 N during weightlifting [9, 122]. Ensuring lumbar stability is crucial for safe and efficient force transmission from the lower to the upper body, necessitating a rigid and stable trunk [34]. This stability is partly provided by the diaphragm, which acts not only as a primary muscle for respiration but also as a pivotal stabilizer for the lumbar and thoracic spines. Diaphragm may play a crucial role in preventing LBP and improving performance among weightlifters by enhancing trunk stability during overhead lifts [124, 125].

The diaphragm muscle attaches directly to the first three lumbar vertebrae and is recognized as a spine stabilizer [29, 30]. The contraction of the diaphragm can increase the stiffness of the lumbar spine, as well as harmoniously controls inspiration and postural stability [31-33]. Prior research has used ultrasonography to reliably evaluate the in vivo diaphragmatic function in individuals with and without LBP [113, 219]. Two studies have reported inferior diaphragm thickening, but not excursion (amount of distance shortened)

during contraction, in individuals with LBP compared to healthy controls [39, 40]. However, the decreased excursion was observed in people with LBP from Mohan et al.[41] Notably, these studies have not extensively explored this relationship in the context of elite weightlifting, where the demands and biomechanical stresses differ significantly from the general population [9, 122]. Additionally, the link between diaphragm function and sports performance remains largely unexplored, despite the diaphragm's critical role in maintaining intraabdominal pressure and spinal stability during weightlifting movements.

Given this gap, the study aims to illuminate the effects of chronic LBP on diaphragm function in elite weightlifters and to investigate the association between diaphragm function and sports performance. It hypothesizes that weightlifters with chronic LBP will demonstrate compromised diaphragm contractility and that superior diaphragm function will correlate with enhanced performance metrics in snatch and clean and jerk lifts.

4.3 Methods

Experimental Approach to the Problem

This observational study was designed to test whether chronic LBP in elite weightlifters affects diaphragm function and, in turn, performance. Diaphragm thickness and excursion were measured as muscle contractility through sonography and maximal inspiratory pressure (MIP) using POWERbreatheKH2, chosen for their direct relevance to muscle function and non-invasive nature [220, 221]. Chronic LBP presence, the independent variable, was hypothesized to correlate with these diaphragm measures and with lift

performance in the snatch and clean and jerk. The study design allowed us to investigate these relationships in a practical, athlete-friendly way, offering insights potentially valuable for training and rehabilitation.

Participants

G-power 3.1 was used to calculate the sample size. Based on the effect size (Cohen's d = 0.82) obtained from a prior study on diaphragm thickness change [39], $\alpha = 0.05$, and statistical power of 80%, the calculated sample size was 25 participants per group.

A consecutive convenience sampling method was used to recruit athletes from the weightlifter team at the Provincial Sports Training Center. The cohort consisted of 49 elite weightlifters, aged 16 to 26, with an approximate weekly training volume of 23 hours. This included 29 females (16 to 25 years, mean ± standard deviation (SD) = 19.93 ± 2.70 years) and 20 males (16 to 26 years, mean ± SD = 20.95 ± 2.68 years). The demographic characteristics, including age, BMI, sex, smoking habits, and years of training, showed no significant differences between weightlifters with chronic LBP (n=23) and those without (n=26), confirming the comparability of the two groups (TABLE 1). Weightlifters were eligible to join the chronic LBP group if they (1) were 16-30 years old [222]; (2) reached the national level [11]; (3) had chronic LBP, defined as non-specific pain/discomfort located between the lower rib margins and the buttock creases lasting for more than 3 months [223]; and (4) self-reported average pain intensity in the last 7 days for at least three out of 10 on the Numeric Pain Rating Scale (NPRS) [224]. They were excluded if they had pathological LBP (e.g., radicular pain, spinal canal stenosis, epidural abscess, compression fracture,

spondyloarthropathy, radiculopathy, malignancy, cauda equina syndrome), neurological disorder, malignant tumor, severe organ diseases, respiratory diseases, previous spinal surgery or other conditions that affected the present pain severity or daily training [223]. Weightlifters who did not experience any LBP in the last 3 months were recruited as non-LBP controls [225].

TABLE 4. 1 Demographics of included participants (mean (SD))

	Total (*n* = 49)	**NLBP (*n* = 26)**	**LBP (*n* = 23)**	***p* value**
Age (y)	20.3 (2.7)	19.9 (3.1)	20.9 (2.2)	0.199
Height (m)	1.62 (0.09)	1.62 (0.10)	1.62 (0.08)	0.826
Weight (kg)	67.36 (13.83)	66.11 (14.23)	68.78 (13.54)	0.505
BMI (kg/m^2)	25.46 (2.73)	25.04 (2.53)	25.93 (2.91)	0.259
Sex (male/female)	20/29	9/17	11/12	0.394
Smoking (Yes/No)	13/36	6/20	7/16	0.747
Training years	8.3 (2.7)	7.9 (2.9)	8.9 (2.3)	0.205

Abbreviations: BMI = body mass index; LBP = chronic low back pain; NLBP = non-low back pain; SD = standard deviation

Ethics approval for this study was obtained from the Institutional Review Board. Informed written consent was obtained from each participant and from the guardians of participants under the age of 18 before data collection. An experienced physiotherapist collected data at the ultrasound laboratory within the Hospital of Sports Training Centre. The demographics of athletes such as age, sex, body mass index (BMI), and smoking habit were collected. A diagnostic medical sonographer with more than 20 years conducted ultrasonic measurements. Physical tests were conducted by an experienced physiotherapist. Operators were blinded to the participant's history of LBP and demographic information.

Procedures

Diaphragm thickness and excursion

The Supersonic Imagine's Aixplorer® (France) system was used to quantify the diaphragm thickness and excursion. Brightness-mode images were collected using a high-frequency linear probe (4-15MHz), which was positioned between the right anterior and mid-axillary lines in the 8-10th intercostal space, with the participant in a hook-lying position and knees bent at 30 degrees [113]. The diaphragm was identified as the muscle situated between the pleural and peritoneal membranes, visualized as two white linear structures between the proximal and distal ribs (FIGURE 1a). Additionally, a distinctive white linear structure in the middle of the diaphragm was observed as a characteristic feature [226]. Diaphragm thickness at the end of tidal expiration (Tex) and at the end of maximal inspiration (Tin) were each measured three times. The mean value of Tex was calculated, while the maximal value of Tin from the three measurements was recorded.

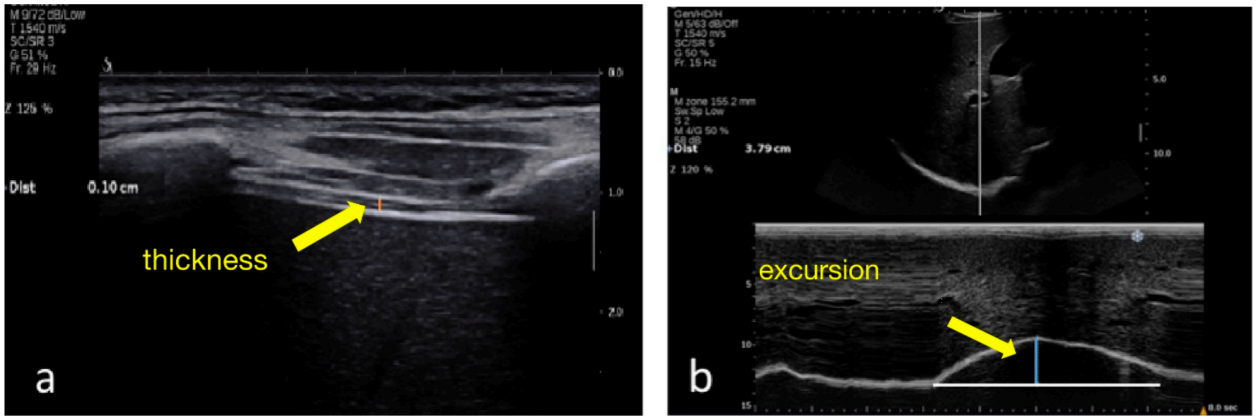

FIGURE 4. 1 Measurement of diaphragm thickness (a: orange line) under brightness-mode and excursion (b: blue line) under Motion-mode

Diaphragm excursion was measured in the same position using Motion-mode ultrasound, with a low-frequency curved probe (1-6MHz), positioned in the right subcostal area between the anterior axillary line and the midclavicular line [39, 171]. Diaphragm was identified as a bright hyperechoic line covering the liver [226]. (FIGURE 1b) The sweep speed was adjusted to its minimum, and the M-line was positioned perpendicular to the direction of diaphragmatic motion. The excursion during maximal inspiration was assessed through three measurements, and the maximum value was recorded for analysis. For individuals whose diaphragm depth rendered detection challenging in the standard mode, a switch to penetration mode was employed.

Offline measurements were conducted after all investigations to avoid recall bias. Before the main research, a preliminary experiment was carried out to evaluate the examiner's intra-rater reliability in determining the thickness and excursion of the diaphragm. Fourteen asymptomatic participants, who were not involved in the main study, underwent the identical experimental procedure with a half-hour gap between two ultrasound measurement sessions.

Maximal inspiratory pressure

MIP was measured with the POWERbreathe KH2 device (POWERbreathe Ltd, UK) to reflect the inspiratory muscle strength (primary diaphragm strength) [227]. Participants were instructed to inhale with a maximal effort at the residual volume against the resistance provided by the device. Tests were performed in an upright standing position after several practice trials to familiarize with the procedure. Each participant underwent three repetitions, and the most favorable result was used for analysis [228, 229].

Sports performance

Participants' best snatch and clean & jerk performance in the past month was extracted from the training records.

Statistical analysis

Diaphragm thickening fraction (DTF), along with excursion (shortening), was calculated to assess the diaphragm contractility as follows: DTF = (Tin – Tex)/Tex*100% [137, 226]. MIP (cmH_2O) and sports performance (kg) were normalized to body weight.

All the data were analyzed by IBM SPSS (version 28.0, New York, US). Intra-rater reliability was evaluated by the intraclass correlation coefficient model 3 ($ICC_{3,1}$, single measurement) with corresponding 95% confidence intervals. The standard error of measurement (SEM) and minimal detectable change with 95% confidence (MDC_{95}) were calculated using the following formulas: SEM = standard deviation * √(1-ICC), and MDC_{95} = 1.96 * SEM * √2, respectively [198].

Shapiro–Wilk test was used to test the normality of data. Independent t-test was performed to compare the demographics, and diaphragm function difference between LBP and non-LBP groups. Partial coefficient tests were conducted to assess the relationship between diaphragm function and sports performance taking sex, years of training, and whether experiencing LBP as confounding factors. Confounding factors were determined by regression analysis and prior studies [230, 231]. The significant level was set at $p < 0.05$.

4.4 Results

The average values (cm), $ICC_{3,1}$, SEM, and MDC_{95} of diaphragm thickness and excursion from 14 asymptomatic individuals involved in the reliability experiment were demonstrated in TABLE 2. Good to excellent within-day test-retest reliability was obtained for quantifying the diaphragm thickness at tidal expiration (Tex: $ICC_{3,1} = 0.89$) and maximal inspiration (Tin: $ICC_{3,1} = 0.92$), as well as excursion at maximal inspiration ($ICC_{3,1} = 0.92$) [197]. The SEM of the diaphragm Tex, Tin, and excursion measurements were 0.02 cm, 0.04 cm, and 0.43 cm, respectively, while MDC_{95} were 0.06 cm, 0.12 cm, and 1.20 cm, respectively.

TABLE 4. 2 Within-day test-retest reliability of right hemidiaphragm thickness and excursion measurements in asymptomatic individuals using Brightness-mode and Motion-mode ultrasound, respectively

	$ICC_{3,1}$	**Mean (SD) (cm)**		**SEM (cm)**		**MDC (cm)**	
	(95%CI)	**Test 1**	**Test 2**	**Test 1**	**Test 2**	**Test 1**	**Test 2**
Tex	0.89 (0.67, 0.96)*	0.11 (0.06)	0.10 (0.05)	0.02	0.01	0.06	0.04
Tin	0.92 (0.77, 0.97)†	0.28 (0.16)	0.27 (0.12)	0.04	0.03	0.12	0.09
Excursion	0.92 (0.77, 0.97)†	4.58 (1.53)	4.91 (1.49)	0.43	0.42	1.20	1.17

Abbreviations: CI = confidence interval; ICC = intra-class correlation; MDC = minimum detectable change; SEM = standard error of measurement; Tex = diaphragm thickness at the end of tidal expiration; Tin = diaphragm thickness at the end of maximal inspiration. *: good reliability: ICCs = 0.75–0.9; †: excellent reliability: ICC > 0.9

Comparison of diaphragm function between weightlifters with and without LBP

The independent t-test demonstrated significantly lower DTF (by 21%; mean difference (MD) = 0.09, $p = 0.04$, Cohen's d = 0.69) and diaphragm excursion (by 18%; MD

= 0.99, $p < 0.01$, Cohen's d = 0.89) in the LBP group. While no detectable difference in normalized MIP (MD = 0.05, $p = 0.77$) between the two groups. (FIGURE 2)

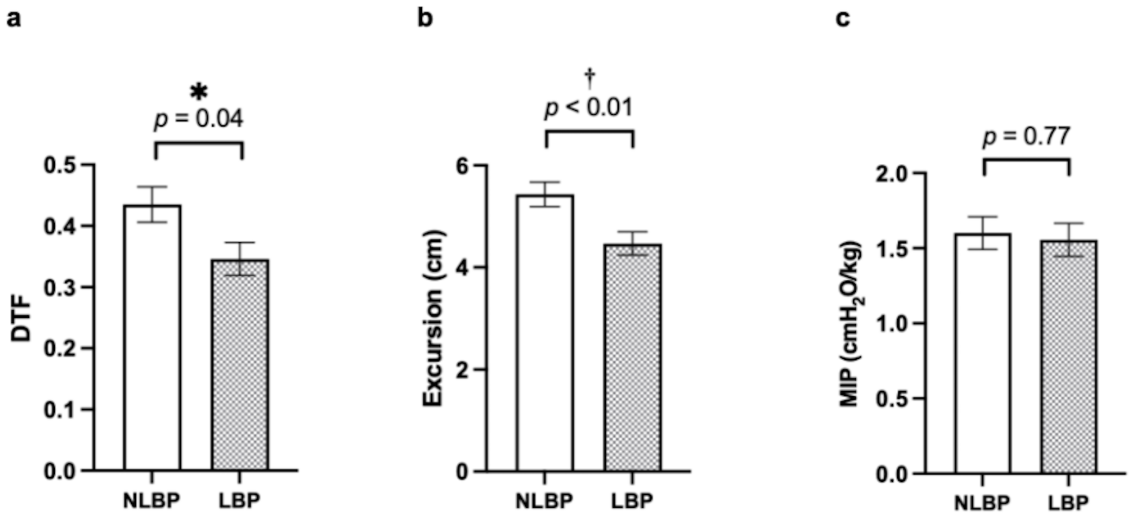

FIGURE 4. 2 Comparison of DTF (a), excursion (b), and MIP (c) in weightlifters with and without LBP. (*: p < 0.05; †: p < 0.01; LBP = low back pain; NLBP = non-low back pain; DTF = diaphragm thickness friction; MIP = maximal inspiratory pressure (normalized)

Correlation between diaphragm function and sports performance in weightlifters

The pooled data of all weightlifters showed significant positive correlations between normalized MIP and snatch (r = 0.34, $p = 0.024$), between MIP and clean & jerk (r = 0.43, $p = 0.004$) after considering sex, years of training, and LBP as covariates (FIGURE 3a & 3b). However, no significant correlation was found between diaphragm contractility (DTF or excursion) and performance ($p > 0.05$).

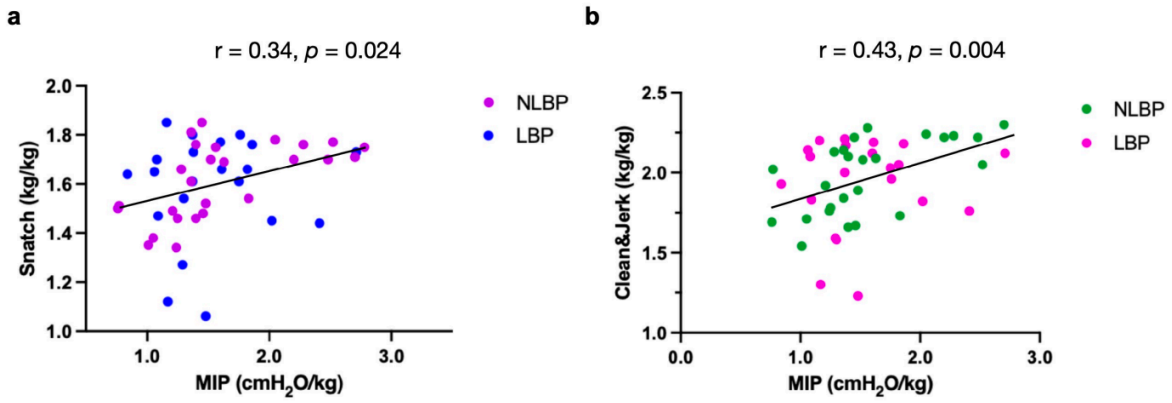

FIGURE 4. 3 MIP and sports performance (a: Snatch; b: Clean & Jerk). (LBP = low back pain; NLBP = non-low back pain; MIP = maximal inspiratory pressure (normalized))

4.5 Discussion

Our study revealed significant diaphragm contractility impairments in elite weightlifters with chronic LBP, underscoring the diaphragm's role beyond respiration, particularly in spinal stabilization and potentially in mitigating LBP. Furthermore, we identified a positive correlation between inspiratory muscle force output (primary diaphragm) and sports performance, highlighting the importance of diaphragm force output in elite weightlifters.

The diminished DTF and excursion which directly reflect diaphragm contractility observed in the LBP group echoed with previous findings in non-athletic populations [31, 39, 40, 103], suggesting a broader relevance of diaphragm dysfunction in LBP across different populations. Two prior studies reported non-notable differences in diaphragm excursion between individuals with and without LBP [39, 40]. The disparity could be attributed to distinct inclusion criteria and differences in the populations. Unlike our study, one of the two

studies recruited LBP individuals with positive straight leg raise test results, indicating potential neurological involvements [40]; the other study recruited older participants with a mean age of 38 years which may negatively affect diaphragm motion [39, 172].

The DTF and excursion are closely associated with LBP. First, the diaphragm has a direct attachment to the L1-3 lumbar vertebrae, with its fibers blending into the anterior longitudinal ligament [50]. A reduction in DTF and excursion suggests a compromised thickening and shortening of the diaphragm, reflecting a limitation in its force-generating capacity. This condition undermines the stability of the L1-3 lumbar vertebrae. Such instability can escalate the shearing forces at the L1-3 levels and exert additional strain on the muscle stabilizers and structural components of the lower lumbar segments, which are frequently associated with pain. Secondly, the diaphragm plays a crucial role in generating trans-diaphragmatic pressure, essential for sustaining intraabdominal pressure and minimizing axial compression on the spine [124, 125]. Reduced DTF and excursion can lead to inadequate trans-diaphragmatic pressure, thereby failing to establish sufficient intraabdominal pressure. This insufficiency potentially escalates the load on the lumbar spine. Third, the lateral arcuate ligament of the diaphragm, serving as an attachment site for diaphragmatic fibers at the lumbar vertebrae, connects with the anterior layer of the thoracolumbar fascia [50]. Increased thickness and stiffness of the thoracolumbar fascia in individuals with LBP have been reported [232-235]. As a result, the contractility and elasticity of the diaphragm in individuals with LBP may be restricted by the heightened stiffness of the thoracolumbar fascia. Therefore, the inferior DTF and excursion of the

diaphragm might induce excessive loading on the lumbar spine causing LBP; or might be a result of LBP-associated changes on the thoracolumbar fascia. This study extends the understanding by demonstrating similar patterns in an elite athletic cohort, where physical demands and performance pressures significantly exceed those encountered by the general population.

Aligning with prior research, no significant difference was observed in MIP between the LBP and asymptomatic groups [41, 43]. Muscles have two functions: force development and shortening. For respiratory muscles, force is typically estimated as pressure [172]. DTF and excursion are direct measurements of diaphragm muscle contractility, whereas pressure reflects overall muscle "output" rather than muscle contractility per se [172]. Trans-diaphragmatic pressure provides an estimate of diaphragm force output but requires invasive measurement. Given that the diaphragm contributes to approximately 70% of minute ventilation [236], MIP is commonly used as a convenient and straightforward measure, primarily reflecting diaphragmatic strength [227]. Another notable reason for measuring MIP instead of trans-diaphragmatic pressure is that even if the strength of the diaphragm decreases, it is hardly to train the diaphragm alone, but train the global inspiratory muscles, and the training intensity is usually determined based on the measurement results of MIP [227].

The lack of a noticeable difference in MIP between the LBP and non-LBP groups could be due to the compensatory engagement of accessory inspiratory muscles or other potential factors affecting muscle force generation (e.g., elasticity), even in the presence of

diaphragm contractile dysfunction. This suggests that changes in direct measurements of diaphragm muscle contractility, such as DTF and excursion, may be more sensitive indicators of alterations in muscle function than changes in muscle force output measurements like MIP in the context of LBP.

To our knowledge, this is the first study to link diaphragm function with weightlifters' performance, showing that higher MIP is associated with better lifting outcomes. This finding aligns with the prior studies in other sports involving aerobic (e.g., marathons, and cycling) and anaerobic activities (e.g., sprints) [237-241]. The highlighted primary mechanism underlying this relationship appears to be that higher MIP can improve blood and oxygen flow to muscles during intense exercise by reducing the competition for blood between respiratory and locomotor muscles [44, 242]. This effect is due to a diminished metaboreflex, which is triggered by respiratory muscle fatigue and leads to vasoconstriction in locomotor muscles [243]. A higher MIP suggests better respiratory efficiency and capacity, delaying respiratory muscle fatigue and enhancing muscle oxygenation, thereby improving performance [227, 244]. Factors such as cytokine release and changes in motor recruitment patterns may also contribute to this observed relationship [227].

A further possible interpretation of the observed positive correlation could be the improved efficiency in force transfer during weightlifting. This efficiency potentially arises from the diaphragm's function in preserving intra-abdominal pressure, stabilizing the trunk and allowing for better energy transfer from lower to upper body. Higher MIP, primarily produced by the diaphragm, supports this stability by balancing pressure between the chest

and abdominal cavities, crucial for trunk rigidity and safe force transfer. During intense lifting, the diaphragm and abdominal muscles work together, reducing spine load and increasing force generation [124, 125, 236]. The heightened engagement of the diaphragm serves to counteract torsional forces on the lumbar spine, while the synergistic co-contraction with all other inspiratory muscles aids in the proper expansion and stabilization of the ribcage. This coordinated effort, reflected by MIP, prevents the transfer of intraabdominal pressure from the abdominal cavity to the thorax, ensuring stability and also averting adverse hemodynamic and central nervous system effects [124, 133]. Our findings imply that training the diaphragm could improve weightlifting performance and might be beneficial in other sports requiring core stability.

However, we did not find any correlation between diaphragm contractility (DTF or excursion) and sports performance. This is not surprising, given that DTF (thickening) or excursion (shortening) represents only one dimension of diaphragm contraction, whereas MIP entails an active three-dimensional displacement of muscle volume [172]. This suggests that MIP, as an indicator of global muscle efforts (diaphragm and all other inspiratory muscles), maybe more closely linked to overall functional factors such as sports performance. Additionally, the difference in how these measurements were taken could also explain the discrepancy: DTF and excursion without load; MIP against resistance which somehow mimics the loading during lifting. Prior studies have shown a relationship between diaphragm excursion and MIP in the general population, but not in weightlifters or powerlifters [125,

245], suggesting they might use different strategies to adapt their diaphragm function for their sport.

Our findings contribute valuable insights but with several limitations. The cross-sectional nature limits our ability to draw causal conclusions. Secondly, we measured diaphragm function during maximal inspiration, a more practical condition, instead of during weightlifting. Additionally, we used MIP as an indicator of diaphragm strength, rather than trans-diaphragmatic pressure which is invasive. These choices necessitate careful interpretation of our findings. Nevertheless, our findings may suggest the applicability of this approach for assessing the diaphragm function or effectiveness of interventions in weightlifters. Additionally, the participants were elite weightlifters, our findings may not be generalized to athletes in other sports. Future research should focus on longitudinal studies to better understand the causal links and the impact of diaphragm training on LBP and performance in weightlifters.

Practical applications

This study has revealed inferior diaphragm contractility in weightlifters with chronic LBP. Higher inspiratory muscle force output (primary diaphragm) was associated with improved sports performance among elite weightlifters. The results offer actionable insights for coaches and health practitioners working with weightlifters. Diaphragm muscle, beyond its role in respiration, has emerged as a contributor to overall athletic performance and may influence back health.

Coaches could enhance athletes' performance and potentially reduce back pain by including diaphragm exercises in training routines. Health practitioners should note the link between diaphragm and LBP. Including diaphragm assessment in routine check-ups and exploring strengthening exercises could be beneficial in managing LBP in athletes. In summary, by monitoring diaphragm function and incorporating targeted respiratory muscle training, practitioners can address an often-overlooked aspect of athlete health and performance. Further research is recommended into specific diaphragm training protocols, which can then be refined and applied to enhance both the well-being and the competitive edge of weightlifters.

CHAPTER 5

Study 4: Beyond muscle strength and flexibility: exploring psoas major stiffness as a key factor in athletes' lower back pain

5.1 Abstract

Objectives: Despite the proposed link between psoas major (PM) muscle dysfunction and low back pain (LBP), the relationship remains unclear. This study aimed to investigate the association between PM muscle properties, particularly stiffness, and chronic LBP in elite athletes.

Design: Cross-sectional study.

Setting: This study was conducted at a provincial sports training centre.

Participants: Ninety-nine elite athletes (age: 10 to 32 years) from gymnastics and wushu teams were recruited. Fifty-three had chronic LBP.

Interventions: Not applicable.

Main Outcome Measures: PM muscle stiffness (measured by ultrasound shear wave elastography), strength, and flexibility were measured on both sides. LBP severity was assessed with the Numeric Pain Rating Scale and Oslo Sports Trauma Research Center Questionnaire on Health Problems. ANCOVA and partial correlation were conducted to analyze the association between PM stiffness and LBP, with regression analysis identifying confounding factors. Statistical significance was set at $P \leq 0.05$.

Results: Increased PM stiffness of the affected side was significantly associated with LBP, especially when the pain was on the dominant side (17.2% increase; mean difference [MD] = 3.21 kPa; $P < 0.001$) and to a lesser extent on the non-dominant side (8.7% increase; MD = 1.65 kPa; $P = 0.009$). Higher PM stiffness correlated with greater LBP-related dysfunction (r

= 0.349, $P = 0.020$). No associations were found between PM strength or flexibility and LBP (all $P > 0.05$).

Conclusions: PM muscle stiffness, but not strength or flexibility, is associated with chronic LBP and related dysfunctions. Addressing PM muscle stiffness might be crucial for preventing and managing LBP in high-risk sports. Further research is suggested to delineate the cause-effect relationships.

5.2 Introduction

Low back pain (LBP) is prevalent among athletes, with 1-year prevalence of up to 94% in high-risk sports like gymnastics [8]. Effective spinal stabilization, especially during dynamic movements, is essential for LBP prevention [17]. The psoas major (PM) muscle, attaching directly to the T12-L5 vertebrae, is vital for dynamic spinal stabilization, and its dysfunction is proposed as a factor in LBP [50-52].

Morphological studies of the PM muscle have yielded inconsistent results. Three studies have reported a reduced cross-sectional area of the PM in individuals with LBP compared to controls [56-58], while 4 other studies could not detect similar findings [18, 59-61]. Similarly, evaluations of PM muscle strength (often assessed with the iliacus as part of hip flexor strength) have produced conflicting outcomes, showing both increased and decreased strength in those with LBP [62, 63].

Notably, excessive PM tension has been implicated in vitro and in simulated models as contributing to heightened compressive and shear forces on the lumbar spine, particularly at the L5-S1 segment, potentially raising the risk of LBP [52, 53, 64, 65]. High muscle tension might indicate compromised muscle elasticity, leading to compromised dynamic stabilization capacity [246]. In this connection, research on PM tension and LBP has garnered interest, but results have been inconclusive. The Modified Thomas test, which assesses hip extension range, has been employed to estimate PM muscle tension, but results have been varied [66-68]. It is noteworthy that hip extension range can be influenced by other factors, including the extensibility of the iliacus muscle and surrounding soft tissues at the hip joint.

One recent study from Kitamura et al [69] employed ultrasound shear wave elastography (SWE), an objective technology for measuring tissue stiffness [91, 92], to quantify PM stiffness at the groin region. The authors found increased stiffness in swimmers with LBP compared to controls [69]. Notably, the measurement focused on the distal portion of the PM at the groin level, where a tendinous architecture has formed [50, 69]. The PM muscle exhibits a gradient in the distribution of type I and type II fibers from its upper to lower segments, corresponding to their distinct functions in postural support and joint motion facilitation [55, 70]. Given the information that modulation in muscle stiffness is different among the muscle heads of the quadriceps and hamstring associated with function in response to sports loading [71, 72], PM stiffness at the upper segment (muscle belly at lumbar region) which may be more closely linked with LBP, could differ from the distal tendinous junction. Whether an increase in PM stiffness at the lumbar segment also exists in individuals with LBP remains to be proven.

This study aimed to explore the associations between PM muscle properties, particularly stiffness, and its association with LBP. The objectives were to compare PM muscle stiffness, strength, and flexibility between elite athletes with and without chronic LBP; and to delineate how these muscle properties relate to LBP severity in afflicted athletes. We hypothesized that (1) athletes with chronic LBP would exhibit greater regional PM muscle stiffness, reduced muscle strength, and decreased flexibility in comparison to their healthy counterparts; (2) increases in PM stiffness and decreases in strength and flexibility would be associated with greater pain intensity and dysfunction in those with chronic LBP.

5.3 Methods

Participant Recruitment and Procedures

Full-time elite athletes were recruited from gymnastics and wushu teams at a provincial sports training center with the following inclusion criterion: (1) age between 10 and 40 years, (2) had pain situated between the lower margin of the 12th rib and the buttock crease, with or without leg pain, persisting or fluctuating for more than 3 months, and with a pain intensity rating of at least 3 on the Numeric Pain Rating Scale (NPRS) [4]. Exclusion criteria encompassed individuals with diagnosed systemic diseases, spinal pathologies, scoliosis, a history of spine trauma or surgery, or an inability to maintain a side-lying position for 30 minutes [193]. Athletes who had not experienced any LBP in the past 3 months were enrolled as the control group.

The study was approved by the Institutional Review Board of the University. Participants visited a laboratory in a sports hospital for data collection. All participants signed a consent form; for athletes under the age of 18, written consent was provided by their guardians. Following the informed consent process, participants completed a questionnaire detailing demographic information such as age, sex, body mass index (BMI), training years, training hours/week, and dominant side (the leg used in kicking a ball).

Measurements

The SWE measurements were captured by a skilled physician qualified as a Registered Musculoskeletal Sonographer and with 3 years of using SWE. Physical tests were

conducted by an experienced physiotherapist. Operators were blinded to the participant's history of LBP and demographic information. All procedures were conducted on Sunday afternoons, designated as non-training days for athletes.

Regional PM muscle stiffness

Ultrasound SWE (Supersonic Imagine's Aixplorer® system with the UltraFast™ platform (Aix en Provence, France)) was used to measure PM muscle stiffness at the L4 region. The measurement details were thoroughly discussed in our earlier study [247]. In brief, athletes were positioned laterally, ensuring a neutral alignment of the spine and upper leg. Real-time SWE images of bilateral PM muscles were acquired. Using a 1-6 MHz low-frequency curvilinear probe, we positioned it above the iliac crest along the mid-axillary line, then pivoted posteriorly to visualize the L4 vertebra just beneath the PM muscle. SWE images of the PM were captured by aligning the ultrasound probe parallel to the long axis of muscle fibers. The region of interest (ROI) was defined, and Young's modulus was assessed using a color-coded representation (FIGURE 5.1). A 10-second real-time cine loop was recorded during the participant's breath-holding at the end of tidal expiration. The measurements commenced from the right side and subsequently proceeded to the left side.

Offline analysis involved selecting five well-defined regions of interest (ROIs) from each 10-second video. A circled quantification box (Q-box) was drawn along the midline of each ROI, maximizing size without overlapping and maintaining a standard deviation within 20%. The recorded mean Young's modulus (in kPa) within the Q-box was then averaged from five selected images in the 10-second video.

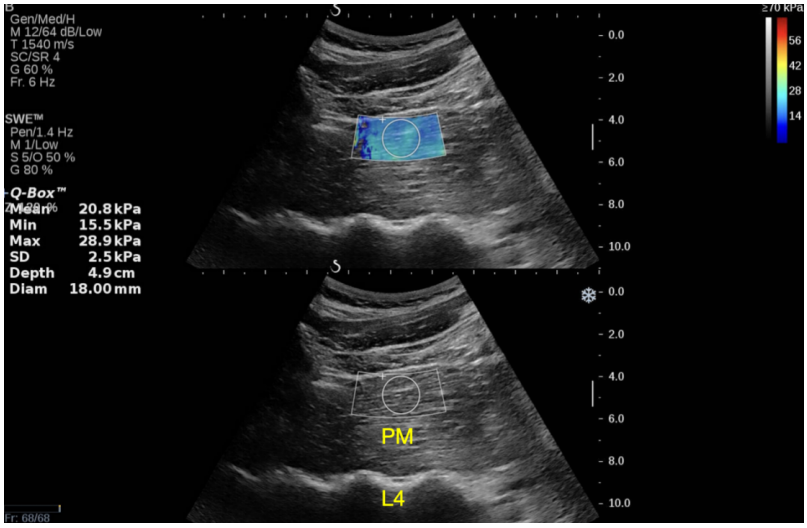

FIGURE 5. 1 Anatomical adjacencies and ultrasound shear wave elastography measurement of psoas major (PM)

Psoas Major Strength Test

PM muscle strength was measured with a wireless microFET®2 digital Handheld Dynamometer (HHD) (Hoggan Scientific, LLC), operated by an experienced physical therapist. Participants were supine with a stabilized pelvis, and the leg was positioned at 60 degrees of hip flexion, 30 degrees of abduction, and 20 degrees of external rotation, with knee extended [248, 249]. The HHD was placed just proximal to the superior pole of the patella to avoid the participation of rectus femoris, and resistance was applied via the Handheld dynamometer. Following an 80% maximum effort practice trial, subjects completed three maximal voluntary contractions with a 60-second rest in between, and the peak force was recorded as the measure of strength.

Within-day intra-rater test-retest reliability was conducted and yielding high reliability for left (Intraclass Correlation Coefficients $[ICCs]_{3,1} = 0.88$, 95% Confidence Interval [CI] [0.67, 0.96]) and right ($ICC_{3,1} = 0.86$, 95% CI [0.64, 0.95]) sides.

Flexibility test

The Modified Thomas test was used to assess PM muscle flexibility in supine lying [66]. A goniometer (Baseline® Plastic Goniometer, 360 degree - 12" HiRes™) was used to measure the range of hip extension during the test. The lateral aspect of greater trochanter was used as the fulcrum, the lateral midline of femur as distal arm, and the lateral midline of pelvis as the proximal arm to measure the true range of hip extension [250, 251].

Low Back Pain Severity

For those athletes with chronic LBP, the pain location was recorded as unilateral ("left" or "right") or "bilateral" (affecting both sides). LBP intensity over the past 7 days was evaluated by the NPRS from 0 ("no pain") to 10 ("worst pain") [252]. LBP-related disability specific to athletes was estimated using the Oslo Sports Trauma Research Center Questionnaire on Health Problems (OSTRC-H) [253]. The OSTRC-H includes 4 domains (4 questions): sports participation, training volume, sports performance, and pain. Each question has four answers, scoring 0, 8, 17, or 25, with higher total scores indicating greater severity.

Data Reduction and Statistical Analysis

Young's modulus for the PM muscle stiffness, PM strength normalized by body weight, and hip extension range were collected for both dominant and non-dominant sides. Athletes with LBP were categorized as LBP_dom (experiencing pain on the dominant side) and LBP_ndom (experiencing pain on the non-dominant side) groups. For control comparisons, Control_dom and Control_ndom indicate the dominant and non-dominant sides of the non-LBP athletes.

Data analysis was performed using IBM SPSS version 26.0 (IBM Corp., Armonk, NY, US). The normality of the data was assessed using the Shapiro-Wilk test. Firstly, pooling all data together, logistic regression analyses explored the association between the presence of LBP and the stiffness of the PM muscle, adjusting for potential confounders. Subsequently, comparisons of PM stiffness, PM strength, and hip extension range between LBP_dom and Control_dom, as well as between LBP_ndom and Control_ndom groups were conducted with analysis of covariance (ANCOVA). Confounding factors were determined through independent samples t-tests ($p < 0.1$) for demographics and regression analysis for specific variables (stepwise). The values of the difference in PM stiffness were compared to the minimal detectable change with 95% confidence interval (MDC_{95}) reported in our prior study [247]. Additionally, for those athletes with LBP, partial correlation was applied to explore the correlation between PM stiffness, strength, flexibility, and pain severity. Statistical significance was set at $p < 0.05$.

5.4 Results

In this study, 99 elite athletes aged 10 to 32 years from gymnastics and wushu teams were enrolled. About half (53 athletes) reported chronic LBP, with 69.8% (37 athletes) experiencing bilateral LBP. In total, 46 athletes had pain on the dominant side and 44 athletes experienced pain on the non-dominant side (FIGURE 2). TABLE 1 shows the demographic information. Significant differences in BMI were noted when comparing both the LBP_dom and LBP_ndom groups to the non-LBP control group.

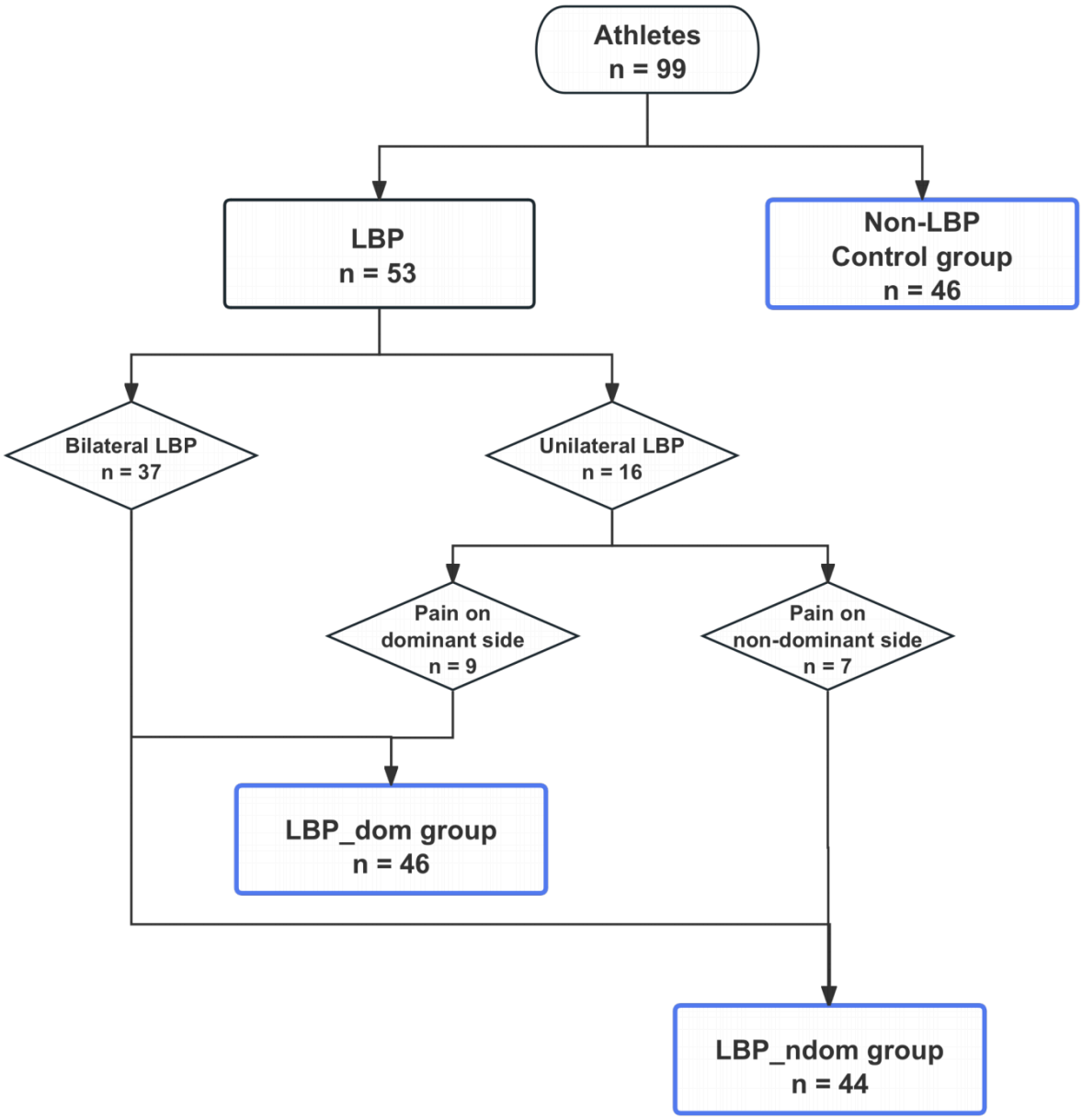

FIGURE 5. 2 Flowchart and grouping of athletes. (Abbreviations: LBP = low back pain; LBP_dom/LBP_ndom = athletes experiencing pain on the dominant side/non-dominant side)

TABLE 5. 1 Demographics of included participants (mean (SD))

	LBP (n = 53)	LBP_dom (n = 46)	LBP_ndom (n = 44)	Non-LBP Control (n = 46)	p value LBP_dom & Control	p value LBP_ndom & Control
Gymnastic/Wushu	34/19	30/16	28/16	35/11	0.252	0.198
Sex (M/F)	25/28	23/23	21/23	21/25	0.676	0.844

Age (y)	17.9 (4.6)	18.2 (4.7)	17.8 (4.4)	16.3 (5.9)	0.089[a]	0.199
BMI (kg/m^2)	20.2 (2.3)	20.3 (2.3)	20.3 (2.4)	18.6 (2.5)	0.000**	0.002**
Training years (y)	10.3 (4.9)	10.5 (5.2)	10.0 (4.9)	8.8 (5.9)	0.147	0.302
Training hours/week	28.7 (8.2)	28.0 (8.2)	28.3 (8.6)	30.5 (10.3)	0.211	0.279
Bilateral/Unilateral	37/16	37/9	37/7			

Abbreviations: BMI = body mass index; LBP = low back pain; SD = standard deviation; LBP_dom/LBP_ndom = athletes experiencing pain on the dominant side/non-dominant side (including both with unilateral and bilateral pain); Control_dom/Control_ndom = the dominant side/non-dominant side of athletes in the non-LBP control group. [a]: $p < 0.1$; **: $p < 0.01$

Comparison of PM stiffness, strength, and flexibility in athletes with and without LBP

ANCOVA revealed that LBP significantly influenced PM stiffness of the affected side under both conditions (LBP_dom, F = 22.13, $P < 0.001$, observed power = 0.996; LBP_ndom, F = 7.05, $P = 0.009$, observed power = 0.747), after adjusting for age and BMI as confounding variables. Pairwise comparisons demonstrated significantly higher PM stiffness of the affected side in LBP_dom group (by 17.2%; mean difference [MD] = 3.21 kPa > MDC_{95}; $P < 0.001$) and LBP_ndom group (by 8.7%; MD = 1.65 kPa < MDC_{95}; $P = 0.009$) compared to the non-LBP control group, respectively (FIGURE 3a and 3b). No significant group differences were observed in the PM strength nor hip extension range (all $P > 0.05$) controlling for age, BMI, and sports.

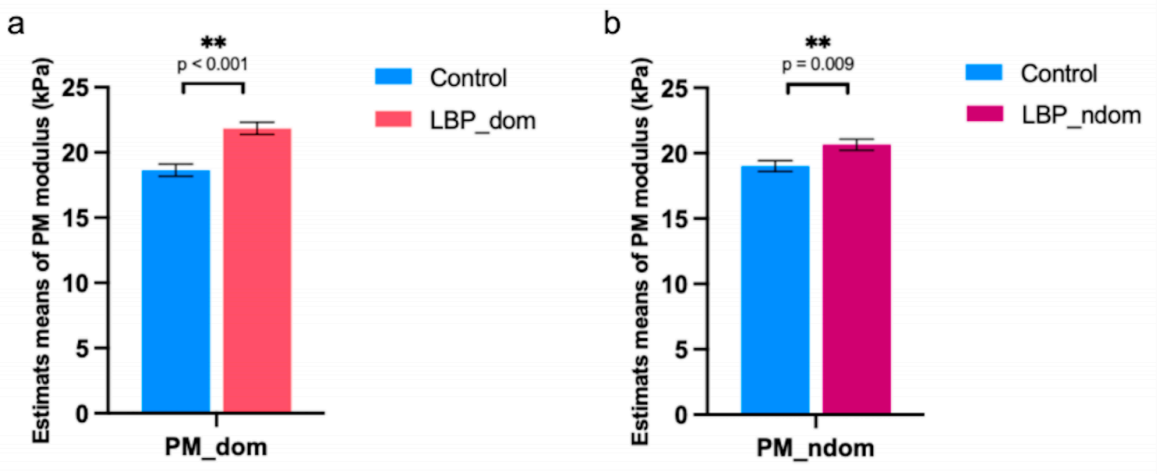

FIGURE 5. 3 Psoas major (PM) stiffness of the affected side between LBP and non-LBP control group. (a) Comparison of PM_dom between LBP_dom group and control group; age and BMI as covariates. (b) Comparison of PM_ndom between LBP_ndom group and control group; BMI and sex as covariates. (Abbreviations: BMI = body mass index; LBP_dom = athletes experiencing pain on the dominant side; LBP_ndom = athletes experiencing pain on the non-dominant side; PM_dom = PM stiffness of the dominant side; PM_ndom = PM stiffness of the non-dominant side. **: $p < 0.01$)

Associations between PM stiffness, strength, flexibility and LBP-related pain and dysfunction

FIGURE 4 illustrates that among athletes experiencing pain on the dominant side (LBP_dom group), there was a significant positive correlation between PM stiffness and OSTRC-H scores ($r = 0.349$, $P = 0.020$) after adjusting for sport type and weekly training hours. Among athletes experiencing pain on the non-dominant side (LBP_ndom group), a trend of association was detected between PM stiffness and intensity of pain ($r = 0.295$, $P = 0.055$) with sex adjusted. No association was detected between muscle strength or flexibility and LBP-related pain or dysfunction.

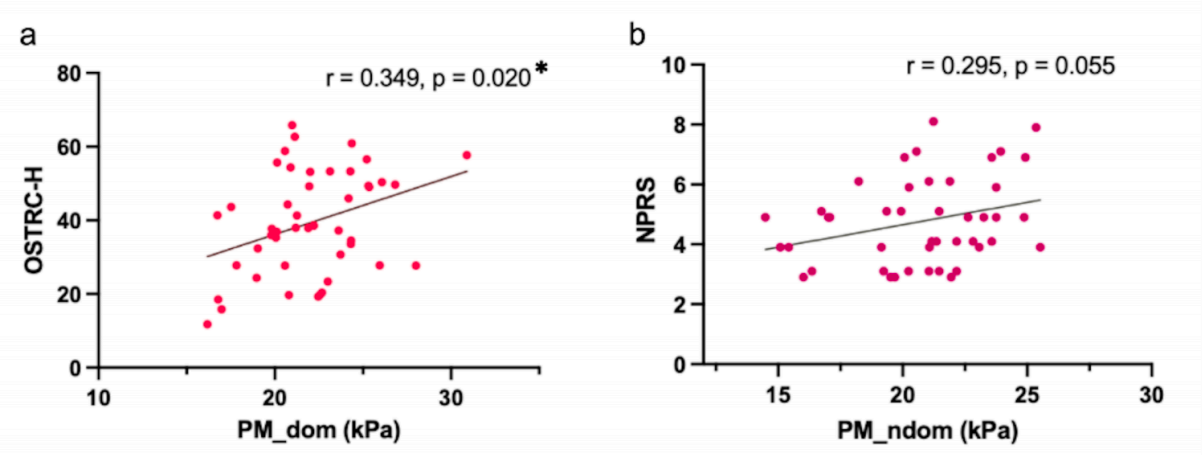

FIGURE 5. 4 Association between psoas major (PM) stiffness and severity of LBP. (a) LBP-dom group: partial correlation between PM_dom and OSTRC-H; sport type and weekly training hours as covariates. (b) LBP_ndom group: partial correlation between PM_ndom and NPRS; sex as covariates. (Abbreviations: LBP_dom = athletes experiencing pain on the dominant side; LBP_ndom = athletes experiencing pain on the non-dominant side; NPRS = Numeric Pain Rating Scale; OSTRC-H = Oslo Sports Trauma Research Center Questionnaire on Health Problems; PM_dom = PM stiffness of the dominant side; PM_ndom = PM stiffness of the non-dominant side. *: $p < 0.05$)

5.5 Discussion

This study aimed to explore the associations between PM muscle properties and chronic LBP. We detected an increase in PM muscle stiffness on the affected side in athletes experiencing chronic LBP compared to controls. Additionally, greater stiffness of the PM muscle is related to more severe LBP-related dysfunctions among those with chronic LBP on the dominant side.

Athletes with chronic LBP has increased PM stiffness than non-LBP control

Our findings of higher PM stiffness in the LBP group support our hypothesis and also with the study from Kitamura et al[69] This heightened stiffness suggests a reduction in muscle elasticity, which could impair muscle performance, particularly the ability to dynamically control movement during vigorous hip actions.[246] Dynamic stabilization of the spine is crucial for preventing LBP; therefore, increased PM stiffness might elevate LBP risk by compromising this dynamic stabilization of the lumbar spine. Furthermore, prior research, both in vitro and in simulated models, has shown that excessive PM tension can exert undue shearing force on the lumbar spine, especially affecting the L5-S1 region, thereby increase the risk of LBP.[52, 53, 64, 65] Thus, it is plausible that increased PM stiffness causally contributes to the development of LBP.

The potential explanation for the increasing of PM muscle stiffness is sports-specific loading. As the earlier research illustrated, activity-induced modulation on muscle stiffness might depend on multiple factors such as loading patterns, levels of activity, sports-specific requirement and involved muscle groups.[72, 247] Gymnastics and wushu athletes have similar PM muscle physical demands: frequently engage in high-velocity trunk bending and extensive hip flexion and extension.[126] The PM muscle, functioning concurrently as a spinal stabilizer and hip flexor, may adapt under conditions requiring rapid excessive hip flexion by shifting type I fibres to fast-twitch type II fibers.[55] This shift could conceivably enhance the muscle's ability to flex the hip, potentially compromising its stabilizing function. To compensate for the reduced stabilization from the contractile components, the intramuscular connective tissue (IMCT) may undergo adaptive stiffening to meet functional

demands.[254] Long-term mechanical loading leads to an increase in the synthesis of type I collagen fibers within the IMCT, contributing to a heightened state of stiffness:[83, 84, 254] a characteristic notably possesses in higher measure in IMCT compared to muscle fibers.[205, 206] The increased stiffness may transiently compensate for static stabilization of the spine, while dynamic stabilization is compromised due to reduced muscle elasticity. Consequently, this could contribute to the development of LBP.

During long-term training, the PM muscle on the dominant side may encounter relatively greater challenges and exhibit a more robust biomechanical response, especially in activities that require maintaining spinal stability and performing motions such as frequent high-speed kicking with the dominant leading leg. The alterations in muscle fiber composition and the increase in IMCT stiffness are expected to be more pronounced on the dominant side, where the physical demands are typically greater.[254] This may explain our finding of the more pronounced increase in PM stiffness when pain occurred on the dominant side.

On the other hand, co-contraction of PM and back extensors dynamically stabilizes the lumbar spine.[51] Lund et al.'s pain-adaptation model suggests that chronic pain inhibits the α-motor neurons of the painful muscles and activates the antagonists.[255, 256] Pain perceived at the low back might trigger the antagonistic flexors, causing a PM muscle spasm and subsequently, a chronic increase in muscle stiffness.[255] In addition, the pain-induced motor adaptation model proposed by Hodges et al.[257] suggests a deliberate strategy to limit movement and safeguard the painful area, potentially leading to a redistribution of activity

within and between muscles. This adaptation could enhance muscle activity and stiffness to maintain lower back stability.[82] In this context, LBP may be a cause of increased PM stiffness. Due to our study's cross-sectional design, the cause-and-effect relationship between PM stiffness and LBP could not be established. Future research could utilize resting electromyography to explore whether LBP is associated with PM spasms that may lead to increased stiffness; or whether reducing muscle tension could alleviate LBP. Such knowledge is essential in formulation of preventive and management strategies for LBP.

Association between PM stiffness and severity of LBP

Our study also delineated the association between PM stiffness and LBP-related dysfunction amongst athletes with chronic LBP. Greater PM stiffness is associated with higher OSTRC-H scores, indicating more severe dysfunction, though this association was not observed with pain intensity. Increased stiffness may act as a protective mechanism to limit movement, prevent further injury, and potentially reduce pain.[257] PM muscle contributes to trunk and hip flexion that are the fundamental movements for gymnastics and wushu athletes. This stiffness might lead to reduced sports participation, training volume, sports performance, and pain intensity. Therefore, the LBP-related dysfunction may be more directly influenced by muscle stiffness. The association was primarily observed when pain was on the dominant side, aligning with the greater sports demands placed on this side among athletes. These findings suggest that PM stiffness impacts both LBP and sports performance.

PM strength and hip extension range are not associated with LBP

Our study did not detect significant difference in PM strength and flexibility between athletes with and without chronic LBP. Previous research using hip flexion to assess PM strength reported both increased and decreased strength in those with LBP.[62, 63] In this study, we adopted a different approach which more focused on PM muscle rather than all hip flexors.[248, 249] The Modified Thomas test, which assesses hip extension range, might be confounded by the condition of other tissues and joint function. In this connection, although improvements in range of motion were observed after stretching exercises, no change in regional muscle stiffness was noted.[258, 259] This suggests that changes in joint range might not be related to muscle stiffness of a single muscle.

Taking together, a regional increase in PM muscle stiffness, but not in strength or flexibility, was detected among elite gymnastics and wushu athletes with chronic LBP compared to controls. Thus, targeted interventions to reduce regional PM stiffness may offer substantial benefits for athletes dealing with chronic LBP.

Limitations

This study has several limitations. Firstly, being cross-sectional, it cannot establish cause-and-effect relationships. Whether increased muscle stiffness is a cause or consequence of LBP remains unclear, necessitating longitudinal or experimental research. Secondly, we only analyzed the pain-affected side due to the limited number of athletes with unilateral pain. Future studies with larger cohorts experiencing unilateral back pain could provide insights into changes in both affected and unaffected sides. Lastly, our research only enrolled gymnastics and wushu athletes, who experience high loading on the lower back associated

with extreme movements, which may limit the generalizability to other sports, such as weightlifting, where LBP is often related to compression.

5.6 Conclusions

Our study presents increased PM muscle stiffness, particularly on the dominant side, in elite gymnastics and wushu athletes with chronic LBP. Greater PM stiffness was associated with worse disability. However, no similar relationship was found for muscle strength or flexibility. These findings suggest that addressing PM muscle stiffness might be crucial for preventing and managing LBP in high-risk sports.

CHAPTER 6

Study 5: Increased stiffness is evidenced in the deep but not superficial lumbar multifidus muscle in professional athletes with chronic low back pain

6.1 Abstract

The study aimed to compare differences in deep (DLM) and superficial (SLM) lumbar multifidus stiffness in professional athletes with and without chronic low back pain (CLBP). Ninety-nine (18 to 27 years) professional athletes including those with CLBP (n=38) from weightlifting, badminton, and track and field were recruited. Ultrasound shear wave elastography (SWE) was employed to measure Young's modulus (as an indicator of stiffness) of DLM and SLM at the L4/5 facet joint level. Two-way analyses of covariates were utilized to examine the effects of CLBP and sports on DLM and SLM stiffness while age, sex, BMI, and years of training were considered as confounding factors. The significance was set at $p < 0.05$. Athletes with CLBP demonstrated significantly higher Youngs' modulus of DLM on the dominant (by 17.73%, mean difference (MD) = 2.52kPa, $p = 0.001$) and non-dominant sides (by 13.54%, MD = 1.83kPa, $p = 0.046$) as compared to pain-free counterparts. Conversely, the Young modulus of SLM but not DLM significantly differed amongst the three types of athletes. Post-hoc analyses revealed that Young's modulus of SLM on the non-dominant side was significantly greater amongst weightlifters than badminton players (by 51.76%, MD = 8.97kPa, $p = 0.010$) or track and field athletes (by 72.01%, MD = 11.01kPa, $p = 0.008$). These results highlight the impact of CLBP and sport type on multifidus muscle stiffness, suggesting targeted clinical assessments and reconditioning strategies focusing on DLM for those with LBP and on SLM for athletes in trunk extension-intensive sports.

6.2 Introduction

The high occurrence of low back pain (LBP) is a concern for athletes and frequently emerges as a substantial impediment to their sports careers [8]. Lumbar multifidus muscle, well-recognized for its role in stabilizing the lumbar spine, is thought to be a potential factor linked to the onset of LBP [76]. Beyond extensive studies on its morphology, investigating muscle elastic property yields additional and clinically relevant insights [87].

Muscle elasticity refers to a muscle's capacity to resist deformation under external force or revert to its original shape after the force removal [93]. Alternation in muscle elastic property (stiffness) may be related to physiological or pathological conditions [91]. Ultrasound shear wave elastography (SWE) is an objective, non-invasive, and reproducible method for quantifying tissue elasticity, allowing *in vivo* assessment of muscle stiffness [87]. The stiffer the tissue, the faster the shear wave travels through it. The speed of shear waves can be converted into Young's modulus, which is commonly employed to express tissue stiffness [93].

Utilizing ultrasound SWE, elevated lumbar multifidus stiffness has been observed in both athletes and the general population experiencing LBP [79, 80]. However, lumbar multifidus can be distinguished into deep (DLM) and superficial (SLM) layers, each possessing distinct structural characteristics and functions [23, 73]. As a segmental stabilizing muscle during lumbar movements, DLM is thought to have a stronger association with LBP [23, 73]. Studies consistently reveal delayed or reduced muscle activation in DLM, but not SLM, in individuals with LBP, aligning with their functional roles [35, 82]. In this context,

differential changes in the lumbar multifidus stiffness may exist in individuals with LBP. DLM could potentially be more affected by LBP. This information could contribute to the development of more targeted and personalized assessments and interventions of lumbar multifidus in individuals with LBP.

Unlike DLM, SLM is responsible for spinal movements (extension and rotation) [73]. The SLM stiffness may be more affected by external mechanical demands imposed by various activities (e.g., sports activities or manual lifting) to meet distinct spinal requirements. Physical properties of musculoskeletal tissues can be influenced by mechanical loading arising from various physical activities [83, 247]. Previous studies have illustrated sports-specific alterations in muscle stiffness attributed to sport-specific loading [72, 86]. Consequently, SLM stiffness might increase in tandem with the escalating loading applied along the muscle's working direction.

While DLM and SLM stiffness may be modulated differentially due to LBP or types of sports activities, no studies have tested this hypothesis. The current study aimed to examine the differential modulation of DLM and SLM stiffness, quantified as Young's modulus, in relation to chronic LBP and sport-specific involvements. We hypothesized that 1) DLM stiffness would be higher in athletes with LBP than asymptomatic controls; and 2) SLM stiffness significantly differed amongst athletes participated in different types of sports.

6.3 Methods

Experimental Approach to the Problem

Our observational study investigated how CLBP and involvement in three distinct types of sports affect DLM and SLM stiffness, utilizing SWE for measurement. SWE was chosen due to its non-invasive nature and proven reliability in objectively quantifying DLM and SLM stiffness in vivo. We selected CLBP and sports type as independent variables to explore their specific influences on the lumbar spine, critical for athletic health and performance. The choice of sports (weightlifting, badminton, and track and field) reflected a range of physical demands on lumbar multifidus providing a comprehensive view of how different athletic activities might modulate lumbar multifidus stiffness. This approach was tailored to validate our hypothesis by examining the interaction between athletic discipline, CLBP, and lumbar stiffness, aiming to inform targeted interventions for athletes.

Participants

The study was approved by the Institutional Review Board and was conducted at the ultrasound laboratory of Sports Hospital. Following informed consent, participants completed a questionnaire gathering demographic data, including age, sex, body mass index (BMI), years of training, and dominant side (the leg used in kicking a ball).

Inclusion criteria were: 1) full-time professional athletes aged 18 to 40 from weightlifting, badminton, and track and field (sprinter) teams at a Provincial Sports Training Center; 2) nonspecific LBP located between the lower margin of the 12th rib and the buttock crease, with or without accompanying leg pain; 3) LBP for more than 3 months, with a pain intensity of at least 3 out of 10 on an 11-point Numeric Pain Rating Scale (NPRS), where 0 means no pain and 10 indicates the worst imaginable pain. Athletes who did not experience

LBP within the past 3 months were recruited as asymptomatic controls. Exclusion criteria included systemic diseases, spinal pathologies, scoliosis, spine trauma or surgery history, or inability to maintain a prone position for 30 minutes [193].

A total of 104 professional athletes (aged 18 to 27 years) from weightlifting, badminton, as well as track and field (sprinters) teams were recruited. Among them, 43 participants reported CLBP, with 38 having bilateral pain and 5 experiencing unilateral pain. Considering the divergent findings in existing literature regarding the effects of pain on the morphology and activation of muscles on both the ipsilateral and contralateral sides [260, 261], and recognizing the potential influence of alterations in muscle morphology and activation on muscle stiffness, we opted to include only the 38 athletes with bilateral LBP (totally: n = 99, LBP: n = 38) in our data analysis (FIGURE 1). This decision was made to eliminate the potential confounding effects of unilateral pain in our data analysis so as to increase statistical power.

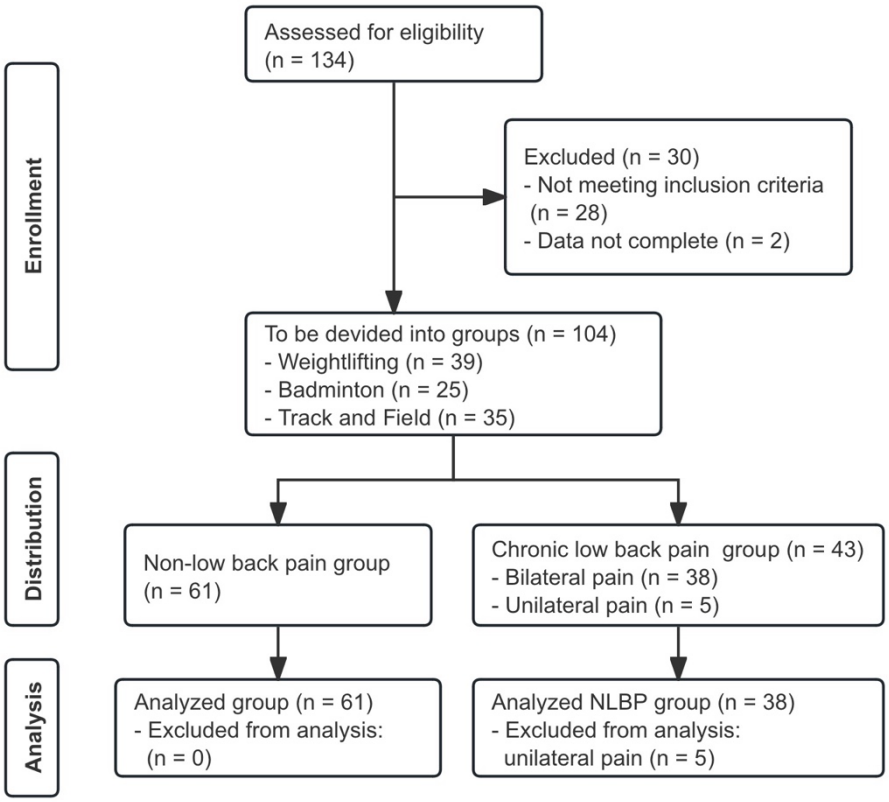

FIGURE 6. 1 CONSORT flow diagram of the study

TABLE 1 shows demographic information. Athletes experiencing CLBP tended to exhibit a higher BMI, and badminton players generally had more years of training compared to other groups. Considering the potential substantial influence of sex on muscle stiffness, as suggested by previous research [262], age, sex, BMI, and training years were considered as confounders.

TABLE 6. 1 Demographics of included participants (mean (SD))

	Total (*n* = 99)	**NLBP (*n* = 61)**	**LBP (*n* = 38)**	**p value**
Age (y)	21.3 (2.3)	21.0 (2.2)	21.8 (2.3)	0.089[a]
Height (m)	1.70 (0.09)	1.70 (0.10)	1.69 (0.08)	0.619
Weight (kg)	66.13 (11.53)	63.71 (9.34)	70.11 (13.66)	0.015*
BMI (kg/m^2)	23.00 (3.29)	22.05 (2.35)	24.61 (4.00)	0.000**
Sex (male/female)	50/49	29/32	21/17	0.537
Years of training (y)	8.84 (3.68)	8.57 (3.79)	9.21 (3.54)	0.645

	Weightlifting (*n* = 39)	Badminton (*n* = 25)	Track and Field (*n* = 35)	p value
Age (y)	21.2 (2.4)	22.0 (2.28)	21.0 (2.09)	0.217
Height (m)	1.64 (0.09)	1.75 (0.07)	1.73 (0.08)	0.000**
Weight (kg)	70.76 (14.15)	65.34 (7.67)	61.54 (8.28)	0.002**
BMI (kg/m^2)	26.17 (2.71)	21.38 (1.30)	20.54 (1.40)	0.000**
Sex (male/female)	19/20	11/14	20/15	0.580
Years of training (y)	9.31 (2.73)	12.32 (1.97)	5.35 (2.55)	0.000**

Abbreviations: SD = standard deviation; NLBP = non-low back pain; LBP = low back pain; BMI = body mass index. [a]: $p < 0.1$; *: $p < 0.05$; **: $p < 0.01$

Procedures

The ultrasonography measurements were gathered by a skilled physician qualified as a Registered Musculoskeletal Sonographer and with 3 years of using SWE. The operator was blinded to the participant's history of LBP and demographic information. All tests were conducted on Sunday afternoons, which were non-training days for athletes. Participants were advised to avoid eating and engaging in intensive exercise before the tests. They were asked to relax and rest in a supine position for 10 min in a room maintained at 25°C.

The SWE imaging was conducted using the Supersonic Imagine's Aixplorer® system with an UltraFast™ platform (Aix en Provence, France). Participants were positioned prone with arms at their sides and a cushion placed under the abdomen to minimize lumbar lordosis and reduce muscle tension in the lumbar region [79]. A linear transducer (2.0–10.0 MHz) was placed on the spinous process of the fourth lumbar vertebra (L4) and then swept approximately 2cm laterally to locate the L4/5 facet joint, serving as a reference for multifidus measurements. To visualize the multifidus muscles, the transducer was rotated clockwise by approximately 10–20 degrees for the left side and counterclockwise for the

right side, as DLM lies over the L4/5 facet joint and is overlapped by SLM (FIGURE 4.2) [263]. Discrimination between DLM and SLM was achieved based on the distinct orientations of their muscle fibers. The transducer was carefully adjusted until it aligned parallel to the long axis of the muscle fibers. Subsequently, the SWE mode was activated, and a rectangular region of interest (ROI) was positioned over the identified muscle area. The ROI was color-filled to represent Young's modulus magnitude. A 10-second real-time cine loop was recorded for both DLM and SLM on both sides, starting with DLM and followed by SLM, initially on the left side and then on the right side.

Offline analyses were conducted after capturing all images to prevent recall bias. From each 10-second video, five uniform and well-filled images were chosen. In each selected image, a circular quantification box (Q-box) covered the ROI's midline, preventing edge overlap and maintaining a standard deviation of readings below 20%. The mean Young's modulus value (measured in kPa) within the Q-box of each image was recorded (FIGURE 4.2). Subsequently, the average value from the five selected images was calculated.

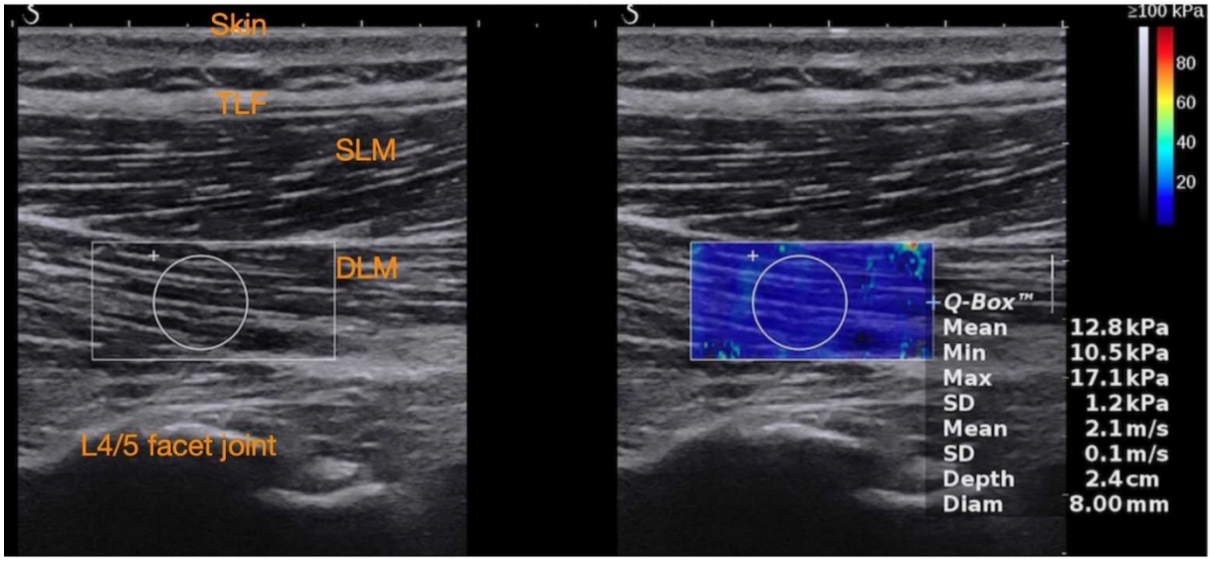

FIGURE 6. 2 The locations and ultrasound shear wave elastography measurement of the deep (DLM) and superficial (SLM) lumbar multifidus with L4/5 facet joint as reference

Prior to the main study, an experiment was conducted to assess the intra-rater reliability of the examiner in measuring DLM and SLM stiffness. Fifteen asymptomatic participants, not part of the main study, underwent the same experimental procedure with a 30-minute interval between the two rounds of SWE measurements.

Statistical analysis

Statistical analyses were carried out using IBM SPSS version 26.0 (IBM Corp., Armonk, NY, USA). The normality of the data was assessed using the Shapiro-Wilk test. Intra-rater consistency was reported as intraclass correlation coefficient model 3 ($ICC_{3,1}$, single measurement) with corresponding 95% confidence intervals. Standard error of measurement (SEM) and minimal detectable change with 95% confidence (MDC_{95}) were calculated using the following formulas: SEM = standard deviation * √(1-ICC), and MDC_{95} = 1.96 * SEM * √2, respectively.

To examine the impact of Chronic LBP (CLBP) and types of sport on the DLM and SLM stiffness, two-way analyses of covariate (ANCOVAs) were employed. Demographic variables with significant between-group differences ($p < 0.1$), including age, sex, BMI, and training years, were entered as covariates in the analysis. Post-hoc pairwise comparisons were performed when $p < 0.05$.

6.4 Results

The average Young's modulus, $ICC_{3,1}$, SEM, and MDC_{95} of DLM and SLM from 15 healthy individuals involved in the test-retest reliability experiment were demonstrated in TABLE 2. Good and excellent within-day test-retest reliability was obtained for quantifying Young's modulus of DLM ($ICC_{3,1}$ = 0.87–0.89) and SLM ($ICC_{3,1}$ = 0.91–0.93) muscles. The SEM and MDC_{95} of the DLM measurement were 0.67–0.70 kPa and 1.69–1.94 kPa, respectively, while those SEM and MDC_{95} for the SLM measurement were 0.69–1.01kPa and 1.91–2.80 kPa, respectively.

TABLE 6. 2 Within-day test-retest reliability of DLM and SLM muscle measurements in healthy individuals using shear wave elastography

	$ICC_{3,1}$ (95%CI)	**Mean (SD) (kPa)**		**SEM (kPa)**		**MDC (kPa)**	
		Test 1	**Test 2**	**Test 1**	**Test 2**	**Test 1**	**Test 2**
Left DLM	0.89 (0.71, 0.96)*	13.48 (2.1)	13.54 (2.0)	0.70	0.67	1.94	1.85
Right DLM	0.87 (0.66, 0.96)*	12.37 (1.9)	12.61 (1.7)	0.67	0.61	1.85	1.69
Left SLM	0.93 (0.80, 0.98)**	17.37 (2.6)	17.36 (2.6)	0.70	0.69	1.94	1.91
Right SLM	0.91 (0.75, 0.97)**	15.89 (3.4)	16.02 (3.1)	1.01	0.94	2.80	2.61

Abbreviations: DLM = deep lumbar multifidus; SLM = superficial lumbar multifidus; ICC = intra-class correlation; SD = standard deviation; SEM = standard error of measurement; MDC = minimum detectable change; CI = confidence interval. *: good reliability: ICCs = 0.75–0.9; **: excellent reliability: ICC > 0.9

As demonstrated in TABLE 3, CLBP emerged as a significant factor influencing DLM stiffness on the side of the dominant (F = 11.77, p = 0.001, observed power = 0.92) and non-dominant legs (F = 4.16, p = 0.046, observed power = 0.52). Post-hoc pairwise comparisons revealed that athletes with CLBP exhibited 17.73% higher DLM stiffness on the side of the dominant leg (mean difference (MD) = 2.52 kPa, p = 0.001) and 13.54% on the non-dominant leg (MD = 1.83 kPa, p = 0.046) compared to pain-free counterparts (FIGURE 3).

TABLE 6. 3 Effects of CLBP and type of sport on DLM and SLM stiffness[a]

	CLBP			Sport		
Muscle	**F**	**p value**	**Observed Power**	**F**	**p value**	**Observed Power**
DLM_dom	11.77	0.001**	0.92	0.63	0.536	0.15
DLM_ndom	4.16	0.046*	0.52	2.85	0.066	0.54
SLM_dom	0.54	0.464	0.12	1.16	0.319	0.28
SLM_ndom	0.01	0.946	0.05	4.85	0.011*	0.79

Abbreviations: CLBP = chronic low back pain; DLM = deep lumbar multifidus; SLM = superficial lumbar multifidus; dom = dominant side; ndom = non-dominant side. *: $p < 0.05$; **: $p < 0.01$; [a]: Analysed with age, gender, BMI, and training years as covariates. All the significant changes are more than minimal detectable change with 95% confidence (MDC_{95}).

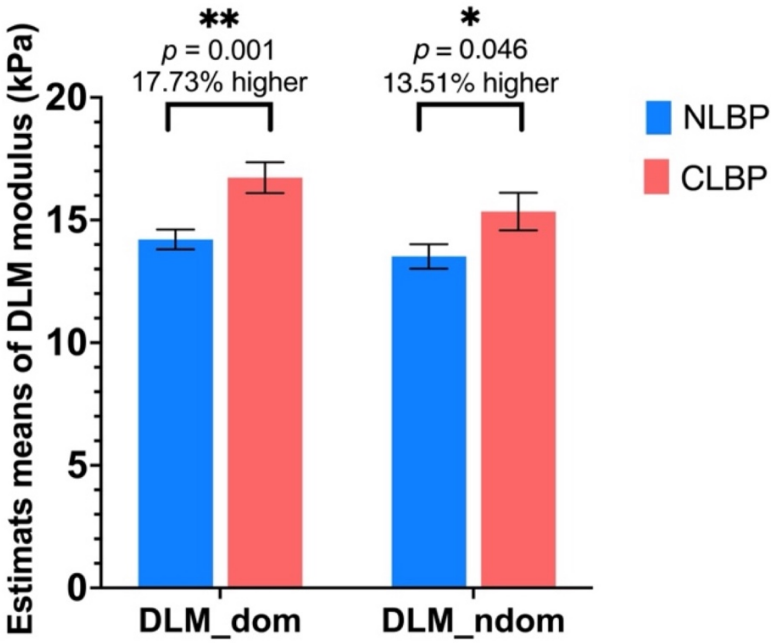

FIGURE 6. 3 Comparison of DLM muscle stiffness in athletes with and without CLBP. Abbreviations: CLBP = chronic low back pain; NLBP = non-low back pain; DLM = deep lumbar multifidus; dom = dominant side; ndom = non-dominant side. *: $p < 0.05$; **: $p < 0.01$.

Additionally, types of sports significantly influenced SLM stiffness of the side of the non-dominant legs ($F = 4.85$, $p = 0.011$, observed power = 0.79). Weightlifters displayed significantly greater SLM stiffness than badminton players (by 51.76%; MD = 8.97 kPa, $p = 0.010$), or track and field athletes (by 72.01%; MD = 11.01 kPa, $p = 0.008$). However, there was no significant difference between the badminton and track and field athletes (MD = 2.04 kPa, $p = 0.597$) (FIGURE 4).

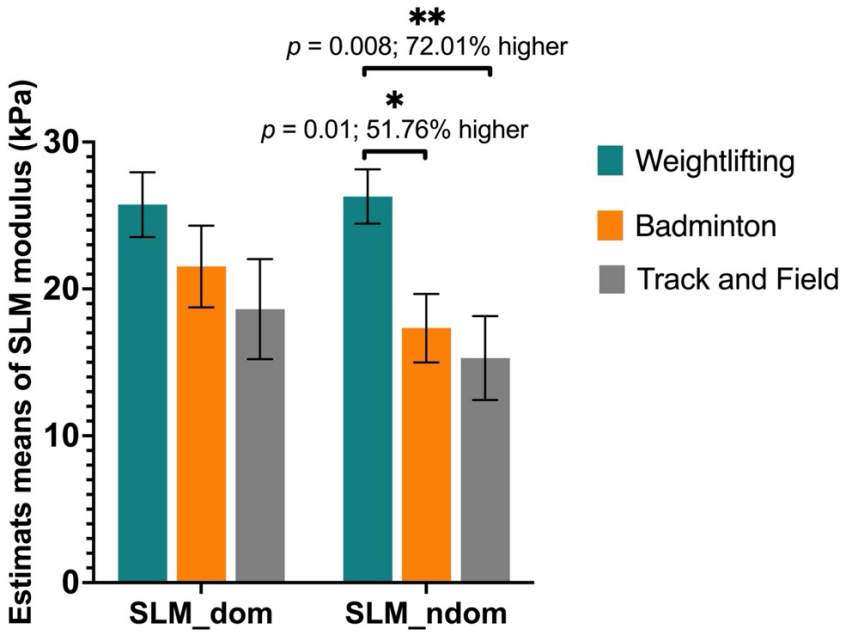

FIGURE 6. 4 Comparison of SLM muscle stiffness in athletes from different sports. Abbreviations: SLM = superficial lumbar multifidus; dom = dominant side; ndom = non-dominant side. *: $p < 0.05$; **: $p < 0.01$.

6.5 Discussion

Our study indicated that CLBP and sports involvement differentially altered the DLM and SLM stiffness. Specifically, significantly higher bilateral DLM stiffness was observed in athletes with CLBP than asymptomatic controls. Further, weightlifting athletes showed significantly higher SLM stiffness on the non-dominant leg side than badminton and track and field athletes.

Earlier studies found that individuals with LBP had significantly higher lumbar multifidus stiffness than healthy individuals [79-81]. Research has revealed reduced cross-sectional area (CSA) and lean muscle index, as well as increased fatty infiltration and fibrosis in the lumbar multifidus among the LBP population [23, 76]. They suggest a decrease in the percentage of the contractile component and an increase in the intramuscular connective

tissue (IMCT). The IMCT, primarily composed of the extracellular matrix, exhibits significantly higher stiffness compared to muscle fibers [205]. The shift in tissue composition might contribute to the observed increase in muscle stiffness. Additionally, the acidic environment in tissues during chronic pain and inflammation could be another factor inducing higher stiffness [264]. Low PH levels may lead to hyaluronan (HA) accumulation in the extracellular matrix, which increases the viscosity of connective tissue. These alterations would decrease the lubrication and gliding of layers of connective tissues and muscle fibers [265]. These potential changes may collectively contribute to an overall increase in lumbar multifidus stiffness in individuals with CLBP.

Our study built on previous findings to precisely and revealed that increased muscle stiffness was only evidenced in DLM but not SLM in athletes with CLBP. The selective increase in DLM stiffness of athletes with CLBP may be attributed to the unique function of DLM. Studies have shown reduced lean muscle proportion in DLM, as well as selective deactivation of DLM, but not SLM, among individuals with CLBP [23, 35]. These changes might contribute to our observed differential increase in DLM stiffness in athletes with CLBP. Compared to SLM, DLM is characterized by a shorter and smaller size, and higher percentage of slow twitch type I muscle fibers, which contribute to its role as a spinal stabilizer [23, 73]. The DLM contractile dysfunction would potentially compromise spinal stability. Research has documented a shift in multifidus muscle fibers from type I to type II in individuals with LBP [266]. This suggests a diminished fatigue-resistance capacity of DLM. However, the fast-switched nature of SLM as a prime mover may remain unaffected. As

such, DLM may heighten tension to maintain spinal stability during various sports activities. Concurrently, the non-contractile components (IMCT) of DLM may also undergo adaptive stiffening to meet functional demands [254]. Moreover, the observed elevation in DLM stiffness across all three sports could imply a universal influence of CLBP on the DLM mechanical property, regardless of the type of sports activity. This uniformity provides valuable insights into the selective negative effects of CLBP on DLM across a range of athletic contexts.

Interestingly, our findings contradicted those of Murillo et al.[267] who found higher stiffness in SLM but not DLM in individuals with LBP among university staff and students aged between 22 and 55 years. Murillo et al.[267] speculated that the increased stiffness observed in the SLM in the LBP group could be attributed to fibrotic proliferation of connective tissues, although no research has suggested selective fibrotic proliferation in SLM without the DLM involvement. The discrepancy between our findings may be ascribed to other factors (e.g., age, sport participation, or differences in data analysis approaches). Age-related changes in homeostasis and metabolism can potentially alter muscle properties [205]. Additionally, physical loading from different sports activities may impact the stiffness of some related muscles [72]. Given that our recruited professional athletes were under the age of 40, their characteristics might differ from those in Murillo et al. study [267]. Moreover, their study compared the average Young's modulus of both sides, while our research involved separate comparisons of the dominant and non-dominant sides, considering the

functional roles of both legs and the significant impact of physical loading on the lumbar spine.

This is the first research to investigate the impact of different sports on lumbar multifidus stiffness. Persistent loading from physical training can enhance molecular and cellular activity, leading to an augmented synthesis of type I collagen within the extracellular matrix [204]. The resulting increase in muscle stiffness could be attributed to a higher net synthesis of type I collagen fibers [204]. Previous research has demonstrated sport-specific changes in muscle stiffness. Specifically, increased stiffness was observed in rectus femoris but not in vastus medialis muscle among soccer players, and young female track and field athletes compared to sedentary individuals [85, 86]. Similarly, sports-specific variations in hamstring stiffness (semimembranosus but not semitendinosus or biceps femoris) were noted among athletes in sports such as skating, taekwondo, and fencing, but not among those playing soccer, sprinting, field hockey, or basketball [72].

As SLM is responsible for gross spinal motion, its stiffness may increase in response to sport-specific mechanical loading in order to generate and transfer forces effectively to meet the demands of sports performance [83]. Our study recruited athletes from sports with diverse trunk movement requirements (e.g., unidirectional, bidirectional, slow, and rapid), and revealed the highest SLM stiffness among weightlifters, followed by badminton players and then sprinters. The observed variations in SLM stiffness across these sports may be attributed to different movement patterns and mechanical adaptations associated with each sport. Weightlifting, characterized by trunk extension with extreme loading, may explain the

predominantly higher SLM stiffness. Badminton players require repetitive trunk extension and rotation, which may explain the second-highest increased in SLM stiffness. However, sprinters, who mainly require trunk stability over mobility, exhibit relatively lower SLM stiffness. Nevertheless, it is worth to note that despite these differences, spinal stabilization appears to be a core and essential component across the three sports, which is evidenced by a similar decrease in DLM stiffness among athletes with CLBP.

Additionally, the posterior surface of SLM inserts into the thoracolumbar composite, forming connections with muscle bands fused to the inner aspect of the overlying aponeurosis of the erector spinae and gluteus maximus [268]. This observation gives additional evidence that SLM may play a role in extensive movements in sports and could undergo remodeling through prolonged sports-specific training. Moreover, its attachment to the thoracolumbar fascia provides support for the findings of SLM influencing the non-dominant side rather than the dominant side. Considering that the thoracolumbar fascia extends diagonally, crossing over the midline and connecting with the fascia of the gluteus muscles [83, 268], it implies that motions on the dominant side (kicking side) might involve the contraction of SLM on the opposite side (non-dominant side). However, the increased stiffness of bilateral DLM in athletes with CLBP suggests that the stabilizing role of DLM is not specific to one side.

The current study had some limitations to be acknowledged. First, the current cross-sectional study precluded the establishment of causal relationships. It remains uncertain whether the observed increase in muscle stiffness is a response or cause of CLBP. Future prospective studies or interventional studies should clarify whether changes in DLM or SLM properties are related to the corresponding changes in clinical outcomes in people with LBP. Second, the identified alterations in DLM and SLM stiffness were only measured from athletes. Future investigations should compare the DLM and SLM stiffness between athletes and non-athletes with and without CLBP. Third, our study only analyzed athletes experiencing bilateral LBP. Subsequent research is warranted to compare muscle mechanical properties between the painful and non-painful sides in individuals with unilateral LBP. This approach may reveal potential localized effects of LBP on muscle stiffness in a more nuanced manner. Fourth, we only recruited athletes involved in three sports with distinct demands in back movements. Our findings might not be generalized to other sports.

6.6 Practical Applications

Our study provides actionable insights for coaches and practitioners on applying lumbar multifidus stiffness data to enhance athletic training and rehabilitation, particularly in addressing CLBP across various sports disciplines. Understanding the increased stiffness in the DLM among athletes with CLBP underscores the importance of incorporating targeted exercises that promote DLM flexibility and strength. These interventions can alleviate pain, aid in recovery, and reduce the risk of pain recurrence.

Sport-specific variations in LM stiffness necessitate adjustments in training programs. For weightlifters, incorporating specific warm-up and cooldown routines that focus on the SLM can help prepare the body for the demands of heavy lifting and facilitate recovery. Athletes in badminton and track and field require a balanced approach that addresses both DLM and SLM, supporting the agility and speed essential to these sports.

Moreover, early detection of changes in LM stiffness can serve as a preventative measure against CLBP and related injuries. Regular assessments, possibly through SWE, can inform training modifications and proactive health measures, potentially reducing injury rates and optimizing athlete performance. Enhancing core stability through targeted LM interventions not only benefits spinal health but may also improve overall athletic performance by ensuring a stable foundation for power generation and movement efficiency. Implementing these findings in practice fosters a multidisciplinary approach, involving collaboration among coaches, athletes, and healthcare providers.

CHAPTER 7

Summary and discussion

7.1 Key findings from the three cross-sectional studies to compare muscle mechanical properties between athletes with and without LBP

7.1.1 Inferior diaphragm contractility in weightlifters with chronic LBP

The study unveiled a notable decrease in diaphragm contractility among those weightlifter suffering from LBP compared to controls. Findings indicated that weightlifters with chronic LBP exhibited reduced diaphragm contractility, which may compromise lumbar stability either through its direct attachment to the lumbar spine or its influence on intra-abdominal pressure. Additionally, a positive correlation was found between inspiratory muscle force output (primarily from the diaphragm) and weightlifting performance.

These insights are invaluable for health practitioners and coaches managing athletes in high-load sports like weightlifting. By integrating diaphragm strengthening exercises into regular training and rehabilitation programs, there is a potential not only to alleviate LBP but also to enhance athletic performance. These findings underscore the importance of comprehensive respiratory and core muscle training in sports where lumbar loading is a major concern, advocating for a holistic view in athletic training regimens.

7.1.2 Psoas major stiffness, but not strength or flexibility, is evidenced in athletes with chronic LBP

Using our newly developed protocol in quantifying PM stiffness, heightened stiffness in this muscle was detected in athletes with chronic LBP compared to controls. Such observation could not be detected in muscle strength or flexibility. More importantly, greater

PM stiffness was associated with more severe LBP-related dysfunctions, suggesting a direct link between PM stiffness and LBP severity.

These findings highlight the importance of muscle mechanical properties in back health. The role PM stiffness has been recognized clinically. Stretching and muscle release at the distal portion are the commonly used approaches for the PM muscle. However, the current study suggests that releasing tension of the muscle belly of the PM at the lumbar region may be more effective. Additionally, the significant relationship between PM stiffness and LBP-related dysfunctions underscores the importance of this muscle in LBP. This finding suggests that clinicians should routinely assess PM stiffness in individuals with LBP. Moreover, these observations emphasize the potential benefits of targeted interventions aimed at maintaining or improving the elasticity of the PM muscle, which could help alleviate or potentially prevent LBP in athletes.

7.1.3. Differential modulation on lumbar multifidus stiffness by sport participation and chronic LBP

LM stiffness was found to be differentially influenced by the presence of LBP and sports participation in athletes. Specifically, the presence of LBP was associated with increased stiffness in the DLM muscle, while the type of sport affected the stiffness of the SLM muscle.

These new findings enhance our understanding of the distinct roles of the DLM and SLM muscles. The DLM muscle appears to be more closely associated with spinal pathologies, while the SLM muscle may be more involved in functions related to specific

sports requirements. Therefore, targeted release of DLM muscle stiffness could be beneficial for athletes with chronic LBP, whereas conditioning programs for the SLM should be tailored to athletes engaged in sports that emphasize trunk extension to improve muscle compliance.

7.2 Integration of key findings

7.2.1 Compromised muscle mechanical properties in sports injury

Our findings are underpinned by the comprehensive model for sports injury causation outlined in **Chapter 1**, which posits that injuries occur when the mechanical loading exceeds the body's tolerance limit or when the tolerance level itself is reduced. Muscle mechanical properties, such as stiffness and strength, are identified as critical internal risk factors [13, 14]. Specifically, the impairment in these properties can lead to a decreased ability to govern body response under load, thereby increasing the risk of injury [14]. In line with the sports injury model, our findings have affirmed that heightened DLM and PM stiffness, as well as inferior diaphragm contractility are related to chronic LBP in athletes. The compromised mechanical properties of these paraspinal stabilizers might reduce their ability of lumbar stabilization and their capacity to response and transfer loading during the sports-specific activities, ultimately heightening the risk of developing LBP. Nevertheless, the cross-sectional nature of the present studies could not establish the cause-effect relationship between muscle stiffness and LBP.

7.2.2 Stiffness: a valuable indicator for LBP in addition to other factors

The stiffness of paraspinal stabilizers, such as the DLM and PM, is significantly influenced by chronic LBP. Our research has highlighted increased stiffness in these muscles in athletes with LBP, suggesting that localized muscle stiffness should be assessed in addition to muscle strength and morphology. In this connection, muscle stiffness of PM, but not strength was correlated with LBP-related dysfunction.

7.2.3 Sports-specific adaptations of stiffness

The stiffness of the SLM, a spinal mover, is significantly influenced by sports-specific loading. This muscle's stiffness response to mechanical loading varies according to its role during physical activities. For instance, in weightlifters, SLM stiffness is considerably higher than in badminton players and sprinters. This increase can be attributed to the rigorous demands of back flexion and extension prevalent in weightlifting, where the SLM undergoes frequent and intense extension loading. As a result, its stiffness is substantially greater than in sports where back extension is less critical.

Furthermore, the PM demonstrates a dual function as both a stabilizer and a mover, which affects its stiffness characteristics. In sports like gymnastics and wushu, which involve high-velocity and dynamic movements, the stiffness of the PM is more accentuated on the dominant side that is subjected to greater loads. This observed variation highlights the complex interplay between muscle function and sports-specific mechanical demands, underscoring the need for targeted training and rehabilitation strategies that reflect the unique biomechanical challenges faced by athletes in different disciplines.

7.2.4 Integrating muscle functions

Although our project did not directly examine the interconnectedness of LM, PM, and diaphragm, their direct anatomical attachments on lumbar spine suggest a collective contribution to spinal stability. In addition, the diaphragm plays a crucial role in generating intra-abdominal pressure, contributing significantly to core stability. Together, they function cohesively to impact athletes' LBP and performance. Additionally, PM connects with the medial arcuate ligament of diaphragm and insert into the lumbar vertebral body. As observed in dynamic ultrasound, both the diaphragm and PM thicken during inhalation, and thin during exhalation, indicative of their coordinated function. Increased stiffness in the PM may restrict the contraction and gliding of diaphragm. Similarly, dysfunction in the LM might compromise the stability of spinal segments, affecting the diaphragm's role in generating intra-abdominal pressure and overall core stability.

The comprehensive examination of paraspinal muscles in our project contributes to a wider and deeper understanding of chronic non-specific LBP in athletes. By identifying specific muscle properties of each specific muscle and their adaptations to sports-related activities, we lay the groundwork for more effective, personalized interventions. Future research should further explore the intricate dynamics between these muscles to enhance our ability to prevent and treat LBP in athletes. Furthermore, the results of individual muscles may also suggest that the assessment and intervention on LBP maybe more effective on combination of all related muscles instead of single target.

7.3 Limitations

While this project provides valuable insights into the relationships between muscle mechanical properties and chronic LBP in athletes, several limitations must be acknowledged.

Firstly, the cross-sectional design of our studies limits our ability to establish causal relationships. It is unclear whether the observed increases in DLM and PM stiffness and the compromised diaphragm contractility are causes or consequences of chronic LBP. There is a critical need for longitudinal studies that would track the progression of these muscle mechanical properties (such as the stiffness of DLM and PM, and the contractility of the diaphragm) over time and their relationship with LBP. Additionally, interventions designed to improve the elasticity of DLM and PM, such as dry needling, deep friction massage, or stretching, along with methods to enhance diaphragm contractility, including inspiratory muscle training or adjustments to diaphragmatic breathing patterns, could prove crucial in the effective management and prevention of LBP. Furthermore, since passive muscle stiffness predominantly reflects the stiffness of the IMCT, biochemical studies could be valuable in investigating the mechanisms of how IMCT alterations occur at various structural levels such as the sarcolemma, endomysium, perimysium, and epimysium in the context of LBP. Additionally, exploring the interactions between these connective components and the corresponding contractile elements at different hierarchical levels, ranging from myofibrils and muscle fibers to fasciculi and the muscle belly, could provide novel and deeper insights into the biomechanical dynamics involved.

Secondly, most of the data derive from specific groups of athletes, which may not universally represent all sports disciplines. For instance, the study on diaphragm function exclusively involved weightlifters. This group has unique and demanding requirements for both spine stabilization and respiration. As such, these findings might not be generalizable to other sports that do not share these intense dual demands. Similarly, the research on PM muscle stiffness was conducted primarily with gymnasts and wushu practitioners. These athletes have specific functional needs that may not be applicable to those in other sports disciplines, potentially limiting the broader applicability of our results. To enhance the validity and applicability of these findings, future studies should include a more diverse range of sports to ensure that the results can be generalized across different athletic populations.

In addition, we did not investigate the interrelationship among the LM, PM, and diaphragm muscles to provide a more integrated understanding of their collective impact on chronic LBP. While individual correlations of these muscles with LBP are documented, the manner in which they coordinate to enhance core stability and influence LBP and athletic performance remains unclear. Future studies should consider examining these muscles collectively to understand their interactions and integrated effects on LBP.

Lastly, with the innovative use of SWE to measure PM stiffness at the lumbar region, reliability has only been established for individuals with a PM muscle depth of up to 7cm from the probe. Conducting extensive intra- and inter-rater reliability studies involving a diverse range of participants will help establish more dependable assessment protocols.

By addressing these limitations and incorporating these suggestions, future research can significantly advance our understanding of chronic non-specific LBP in athletes and enhance the efficacy of preventive and therapeutic strategies. This comprehensive approach will not only improve outcomes for athletes but also contribute to the broader field of sports medicine and rehabilitation.

CHAPTER 8

Conclusions

8.1 Conclusion

This project has thoroughly investigated the relationship between muscle mechanical properties and chronic non-specific LBP in athletes, focusing on several key paraspinal stabilizers from various locations along the lumbar spine. Our findings reveal critical links between the passive stiffness of these muscles and chronic LBP. Specifically, we observed compromised contractility of the diaphragm in weightlifters with LBP and increased stiffness in the PM and DLM muscles in athletes with chronic LBP compared to controls. These findings highlight the importance of muscle mechanical properties, particularly stiffness, as a crucial modifiable risk factor in the development of LBP among athletes.

8.2 Significance and the application

The implications of our research are profound, extending into the fields of sports medicine, physical therapy, and athletic training. This research has enriched our knowledge on muscle mechanical properties and LBP, and also the potential to enhance both preventative and therapeutic strategies for managing LBP, as well as improving sports performance in athletes:

- **Academic and Clinical Outreach**: By addressing significant gaps in our understanding of biomechanical factors related to LBP, this project offers valuable insights that could influence future clinical practices and academic research in the field of sports injuries. Potential applications of these findings include longitudinal

and interventional clinical studies, as well as biological research investigating how muscle properties change at various histological levels.

- **Routine Muscle Stiffness Assessment:** The establishment of reliable protocols for using SWE to assess muscle stiffness is a significant advancement. This non-invasive technique can be seamlessly integrated into routine evaluations to proactively manage athlete health, potentially allowing for early identification and mitigation of LBP risks.
- **Preventive Exercise Programs for LBP**: Identification of the role of specific muscle properties of each muscle regarding to LBP allows for the creation of targeted preventive exercise programs. It may include combinative exercises specifically designed to maintain DLM and PM muscle elasticity and diaphragm function, potentially reducing the likelihood of developing LBP.
- **Tailored Rehabilitation for LBP:** The data support personalized rehabilitation protocols that address the specific muscle mechanical properties and functional demands of athletes from different sports. This may include developing differentiated assessment and intervention programs specifically for DLM and SLM based on their roles in lumbar stabilization and dynamic movements, respectively. And for athletes experiencing LBP, particularly focusing on enhancing the elasticity of the PM muscle could be prioritized over strengthening exercises initially to better manage pain and improve function. This tailored approach ensures that rehabilitation protocols are not only specific to the muscle but also customized to the individual athlete's needs and

the demands of their sports, potentially improving recovery outcomes and reducing the risk of recurrence.

- **Optimized Training Regimens**: By integrating the assessment and modification of muscle stiffness and diaphragm contractility into regular training routines, coaches and trainers can design refined training regimens. Focusing on the specific muscle properties critical for each sport, trainers can help athletes improve their functional capabilities while simultaneously minimizing the risk of injuries. For instance, tailored conditioning programs could be designed for the SLM in athletes participating in sports that involve intensive trunk extension, to promote muscular adaptation. Additionally, comprehensive respiratory and core muscle training could be prioritized in sports where lumbar loading is prevalent. This proactive strategy is crucial for maintaining long-term athlete health and ensuring continuous improvement in performance levels.

8.3 Suggestions for further studies

Based on the findings from our research, several directions are suggested for future studies:

- Longitudinal studies could monitor changes in the stiffness of the PM, DLM, and diaphragm function over time, investigating whether these changes can predict the prevalence and severity of LBP. Such studies would provide stronger evidence for

causal relationships and help determine whether alterations in muscle properties are precursors to LBP or a result of it.

- For interventional research, studies could focus on effective methods to enhance the elasticity of the PM and DLM (such as dry needling), as well as diaphragm contractility (inspiratory muscle training). Assessing the impact of these interventions on LBP severity and athletic performance could help identify therapeutic strategies to prevent or manage LBP.
- At the biological level, histological research could investigate changes in muscle composition, linking these changes to variations in stiffness and examining the interactions between connective tissue and contractile elements in muscle behavior. Additionally, studies have shown that LBP and muscle strength, power, and endurance are linked to gene expression. Therefore, exploring the relationship between muscle stiffness and gene expression could be a promising avenue for future research.

APPENDIX

APPENDIX I Ethical Approval

THE HONG KONG POLYTECHNIC UNIVERSITY
香港理工大學

To	Fu Siu Ngor (Department of Rehabilitation Sciences)		
From	Pang Marco Yiu Chung, Chair, PolyU Institutional Review Board		
Email	marco.pang@	Date	24-Apr-2023

Application for Ethical Review for Teaching/Research Involving Human Subjects

I write to inform you that approval has been given to your application for human subjects ethics review of the following project for a period from 01-Jul-2022 to 01-Jul-2024:

Project Title:	In search of muscle morphology, mechanical properties and function at the lumbo-pelvic region in elite athletes with and without chronic low back pain
Department:	Department of Rehabilitation Sciences
Principal Investigator:	Fu Siu Ngor
Project Start Date:	01-Jul-2022
Project type:	Human subjects (clinical)
Review type:	Expedited Review
Reference Number:	HSEARS20220527005

You will be held responsible for the ethical approval granted for the project and the ethical conduct of the personnel involved in the project. In case the Co-PI, if any, has also obtained ethical approval for the project, the Co-PI will also assume the responsibility in respect of the ethical approval (in relation to the areas of expertise of respective Co-PI in accordance with the stipulations given by the approving authority).

You are responsible for informing the PolyU Institutional Review Board in advance of any changes in the proposal or procedures which may affect the validity of this ethical approval.

Pang Marco Yiu Chung

Chair

PolyU Institutional Review Board

APPENDIX II Information sheet (English and Chinese)

INFORMATION SHEET

Project title:

In search of muscle morphology, mechanical properties and function at the lumbo-pelvic region in elite athletes with and without chronic low back pain

Invitation:

As a full-time athlete at the Ersha Training Centre, you are referred from the Centre Director to participate in a study conducted by Prof. Amy Fu, who is a staff member of Department of Rehabilitation Sciences in The Hong Kong Polytechnic University. The project has been approved by the Human Subjects Ethics Sub-committee (HSESC) (or its Delegate) of The Hong Kong Polytechnic University (HSESC Reference Number: HSEARS20220527005).

Aim of the project:

The purpose of this cross-sectional study is to investigate whether the morphology, mechanical properties and function at the lumbo-pelvic region are related with chronic low back pain in elite athletes.

What do volunteers for the study have to do?

We will investigate your muscles at the lumbo-pelvic region with ultrasound machine and also measure your respiratory parameters when you breath. Last, you are invited to fill in questionnaires relating to low back pain and your function. It is hoped that this information will help us to understand how these muscles related to low back pain.

Is there any discomfort during the examination?

There is no discomfort during the ultrasound examination. There is no risk involved in the ultrasound examinations. The American Institute of Ultrasound in Medicine addressed the clinical safety of Diagnostic Ultrasound in 1988:″No confirmed biological effects on patients or instrument operators caused by exposure at intensities typical of present diagnostic ultrasound instruments have been reported.” The breathing testing garget is approved by the NHS of the UK. It should cause no harmful side effects when used properly in majority of people.

What is the potential benefit?

You will have better understanding of your muscle function. The results of study may shed new lights for low back pain prevention and rehabilitation for athletes.

Confidentiality:

Only the aforementioned principal investigator and co-investigators will have access to any of your data or images captured in the course of the study. All information related to you will remain confidential and will be identifiable by codes only known to the researcher. You can also request access to and correct of any of the personal data you provide for the project.

You have every right to withdraw from the study before or during the measurement without penalty of any kind. The whole investigation will take about 1 hour.

If you would like to obtain more information about this study, please contact Prof Amy Fu (tel.: 2766-6726 / email: amy.fu@).

If you have any complaints about the conduct of this research study, please do not hesitate to contact Miss Vangie Chung, Secretary of the Human Subjects Ethics Sub-Committee of The Department of Rehabilitation Sciences, The Hong Kong Polytechnic University in writing (c/o Research Office of the University) stating clearly the responsible person and department of this study as well as the HSESC Reference Number. You can also contact Ms Chung at (852) 27664629 orVangie.chung@ 。

Thank you for your interest in participating in this study.

Prof. Amy Fu
Principal Investigator

Hung Hom Kowloon Hong Kong 香港 九龍 紅磡
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Website 網址 www.polyu.edu.hk

THE HONG KONG
POLYTECHNIC UNIVERSITY
香港理工大學

相關資訊

研究課題:

研究患有和不患有慢性腰痛的高水準運動員腰骨盆區域的肌肉形態、機械特性和功能

邀請:
作為广东二沙体育訓練中心的全職運動員，中心主任轉介閣下參與這項研究。負責人是符少娥教授（香港理工大學康復治療科學系）。這項研究已被香港理工大學人體試驗倫理委員會許可（HSESC 編碼: HSEARS20220527005）。

研究目的:

此研究旨在研究高水準運動員腰骨盆区域肌肉性能與慢性腰痛的關聯性。

如果我參加這項研究，接下來我該怎麼做?

獲得閣下的同意後，我們將首先使用超聲波儀器測量腰骨盆区域相關肌肉（如膈肌、多裂肌，腰大肌等）的相關狀態，然後會使用呼吸測量儀測量各項呼吸參數（可反應膈肌的功能）。最後閣下將填寫疼痛和功能問卷。我們希望通過這些測試獲取資訊，從而更好地理解以上肌肉的性能是否與腰痛有關。

參與這項研究有什麼風險?
超聲波檢查無任何不適，也無任何風險。根據美國醫學超聲波學會在 1988 年發表關於醫學用超聲波的臨床安全問題:“沒有已肯定的不良影響是由於使用醫學用超聲波而發生在病人和操作員上”。呼吸測量儀經醫療服務系統認證，在正常使用中對絕大多數人無不適反應。

參與這項研究有有什麼受益?

閣下將全方面瞭解到閣下的相關肌肉功能狀況。研究的結果可能為運動員腰痛的預防和治療提供新的思路與方向。

我參與這項研究受到保密碼？:

我們會收集閣下與此研究有關的個人資訊。閣下所有的私人資料及與此研究相關的醫學資訊都將受到嚴格保密。閣下的資訊將編號后輸入資料庫，只有前述研究人員會看到閣下的相關記錄。

閣下隨時可以要求退出此項研究。整個研究過程需要大概 2 小時。

如果閣下希望獲得更多這項研究的訊息，請聯係符少娥教授（電話：27666726；電郵：amy.fu@　　）。

如果您對這項研究的行為有任何投訴，請立即與香港理工大學人類道德操守小組委員會秘書鍾楚瑜小姐聯繫（電話：2766-6429; 电子邮件地址 Vangie.chung@　　），並明確說明負責人，研究人員和部門，以及上述列出的審批編號聯絡。。

感謝閣下參與這項研究。

符少娥教授
項目負責人

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APPENDIX III Consent form (English and Chinese)

CONSENT TO PARTICIPATE IN RESEARCH

In search of muscle morphology, mechanical properties and function at the lumbo-pelvic region in elite athletes with and without chronic low back pain

I _____ hereby consent to participate in the captioned research conducted by Prof. Amy Fu.

I understand that information obtained from this research may be used in future research and published. However, my right to privacy will be retained, i.e. my personal details will not be revealed.

The procedure as set out in the attached information sheet has been fully explained. I understand the benefit and risks involved. My participation in the project is voluntary.

I acknowledge that I have the right to question any part of the procedure and can withdraw at any time without penalty of any kind

Name of participant _____

Signature of participant _____

Name of Parent or Guardian (if applicable) _____

Name of researcher _____

Signature of researcher _____

Date _____

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THE HONG KONG
POLYTECHNIC UNIVERSITY
香港理工大學

參與研究同意書

研究患有和不患有慢性腰痛的高水準運動員腰骨盆區域的肌肉形態、機械特性和功能

本人_____同意參與由 **符少娥** 教授開展的上述研究。

本人知悉此研究所得的資料可能被用作日後的研究及發表，但本人的私隱權利將得以保留，即本人的個人資料不會被公開。

研究人員已向本人清楚解釋列在所附資料卡上的研究程序，本人明瞭當中涉及的利益及風險；本人自願參與研究項目。

本人知悉本人有權就程序的任何部分提出疑問，並有權隨時退出而不受任何懲處。

參與者姓名 _____

參與者簽署 _____

家長或監護人(如適用) 姓名 _____

家長或監護人(如適用) 簽署 _____

研究人員姓名 _____

研究人員簽署 _____

日期 _____

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APPENDIX IV The Oslo Sports Trauma Research Center Questionnaire on Health Problems (OSTRC-H) (English and Chinese)

OSTRC Overuse Injury Questionnaire

Part 2: Lower Back Problems

Please answer all questions regardless of whether or not you have problems in your lower back. Select the alternative that is most appropriate for you, and in the case that you are unsure, try to give an answer as best you can anyway.

The term "lower back problems" refers to pain, aching, stiffness or other problems in your lower back.

Question 1

Have you had any difficulties participating in normal training and competition due to lower back problems during the past week?

- ☐ Full participation without lower back problems
- ☐ Full participation, but with lower back problems
- ☐ Reduced participation due to lower back problems
- ☐ Cannot participate due to lower back problems

Question 2

To what extent have you reduced you training volume due to lower back problems during the past week?

- ☐ No reduction
- ☐ To a minor extent
- ☐ To a moderate extent
- ☐ To a major extent
- ☐ Cannot participate at all

Question 3

To what extent have lower back problems affected your performance during the past week?

- ☐ No effect
- ☐ To a minor extent
- ☐ To a moderate extent
- ☐ To a major extent
- ☐ Cannot participate at all

Question 4

To what extent have you experienced lower back pain related to your sport during the past week?

- ☐ No pain
- ☐ Mild pain
- ☐ Moderate pain
- ☐ Severe pain

OSTRC-H2 问卷

Q1 最近 7 天是否因为腰痛影响训练或比赛？

1. 没有腰痛，不受影响
2. 有腰痛，但不影响训练或比赛
3. 因为腰痛而减少了训练或比赛
4. 因为腰痛而完全不能参与训练或比赛

Q2 最近 7 天由于腰痛，多大程度上调整了你的训练计划或比赛？

1. 没有调整
2. 轻度调整
3. 中度调整
4. 重大调整

Q3 最近 7 天由于腰痛，多大程度上影响了你的运动表现？

1. 不影响
2. 轻度影响
3. 中度影响
4. 重度影响

Q4 最近 7 天与你的运动相关的腰痛程度如何？

1. 没有疼痛
2. 轻度疼痛
3. 中度疼痛
4. 重度疼痛

APPENDIX V Athletes Disability Index Questionnaire (ADI) (English and Chinese)

This Questionnaire is Designed to Assess How Low Back Pain is Affecting Your Sports and Daily Activities. Please Read the Following Questions Carefully and Choose the Option That Best Describes Your Current Situation.

1. Low Back Pain:
   - ☐ I have no pain.
   - ☐ I have mild pain.
   - ☐ I have moderate pain.
   - ☐ I have severe pain.

2. Stretching exercises:
   - ☐ I can perform all stretching exercises without any back pain.
   - ☐ I can perform all stretching exercises but some of them are painful.
   - ☐ I cannot perform some stretching exercises because of my back pain.
   - ☐ I cannot perform any stretching exercises because of my back pain.

3. Strengthening/weight training exercises
   - ☐ I perform all strength/resistance exercises without pain.
   - ☐ I can perform all strength/resistance exercises but some with pain.
   - ☐ There are some strength/resistance exercises I can't perform due to back pain.
   - ☐ I have completely quit strength/resistance exercises because of pain.

4. Your sport-specific moves or skills
   - ☐ I perform all drills without any pain or restriction.
   - ☐ I perform all drills, but I feel some pain.
   - ☐ I cannot perform some of my drills because of pain.
   - ☐ I cannot perform any sport-specific drills.

5. Movement involving back rotations or change of direction
   - ☐ I have no problem rotating my back or changing direction.
   - ☐ I can perform back rotation and direction changing activities but some with pain.
   - ☐ I am restricted in rotating my back and/or changing direction due to pain.
   - ☐ I cannot perform rotational back movements or change direction because of pain.

6. Sitting
   - ☐ I can sit on any chair (surface) for as long as required.
   - ☐ I can sit as long as required but I experience some pain.
   - ☐ I have to leave the chair earlier than required because of pain.
   - ☐ I can only sit for a short while because of pain.

7. Walking
   - ☐ I can walk on level and sloped surfaces, as well as stairs; without any pain
   - ☐ I can only walk on level surfaces without experiencing pain.
   - ☐ My walking duration or speed has been affected by pain.
   - ☐ The pain has severely limited my ability to walk.

8. Sleep
   - ☐ I have no pain or restrictions while sleeping.
   - ☐ I can sleep without pain if I position myself in a certain way(s).
   - ☐ I sleep less than before because of the pain.
   - ☐ My sleep has been totally disrupted.

9. Personal care (putting on socks and shoes, going to the bathroom)
   - ☐ I can perform all personal-care activities without pain.
   - ☐ I am capable of performing them, but they sometimes cause pain.
   - ☐ I cannot perform some of my personal care due to pain.
   - ☐ I need assistance for almost all personal care activities.

10. Fear of causing pain or damaging the back
   - ☐ I have no fear of pain while performing sports activities/exercises.
   - ☐ I perform my training despite the fear of pain.
   - ☐ Fear of pain prevents me from performing some activities/movements.
   - ☐ Fear of pain has made me stop performing sports activities/exercises.

11. Leisure activities
   - ☐ I perform my leisure activities without any pain.
   - ☐ Despite some pain, I do all of my leisure activities.
   - ☐ I avoid some recreational activities due to pain.
   - ☐ I avoid almost all recreational activities due to pain.

12. Sexual Activity
   - ☐ I do not experience any back pain or limitations during sexual activity.
   - ☐ I have maintained my sexual activity but I do experience some back pain.
   - ☐ I have had to reduce sexual activity due to pain.
   - ☐ I completely refrain from sexual activity because of the back pain.

运动员功能障碍指数问卷（ADI）

姓名_____　　性别 男 / 女　　年龄

运动专项 _____ 日期

本问卷旨在调查腰痛对您运动和日常活动的影响。请仔细阅读以下问题，根据您的**最近 7 天**的情况勾选最合适的选项。共 11 题。

1. 是否有腰痛：
   ① □没有。
   ② □轻微。
   ③ □中度。
   ④ □严重。
2. 拉伸训练：
   ① □能够全部完成，没有产生任何腰痛。
   ② □能够全部完成，但某些拉伸动作会产生腰痛。
   ③ □因为腰痛，某些拉伸动作无法进行。
   ④ □因为腰痛，所有拉伸动作都无法进行。
3. 力量或负重训练：
   ① □能够全部完成，没有产生任何腰痛。
   ② □能够全部完成，但某些练习会产生腰痛。
   ③ □因为腰痛，某些力量或抗阻练习无法进行。
   ④ □因为腰痛，所有力量或抗阻练习都无法进行。
4. 你的专项训练：
   ① □能够完成所有训练，没有产生任何腰痛。
   ② □能够完成所有训练，但会感觉到一些腰痛。
   ③ □因为腰痛，某些训练动作无法进行。
   ④ □因为腰痛，所有训练动作都无法进行。
5. 涉及背部旋转或变向的动作：
   ① □能够全部完成，没有产生任何腰痛。
   ② □能够全部完成，但某些动作会产出腰痛。
   ③ □因为腰痛，某些背部旋转或变向动作受限制。
   ④ □因为腰痛，所有背部旋转或变向动作都无法进行。
6. 坐姿：
   ① □在任何椅子（平面）上坐很久都不会产生腰痛。
   ② □可以坐很久，但是会有一些腰痛。
   ③ □因为腰痛，不能坐很久。
   ④ □因为腰痛，只能坐很短时间。
7. 行走：

① □在平地、斜坡、楼梯上行走，都不会产生腰痛。

② □只有在平地上行走，才不会产生腰痛。

③ □因为腰痛，无法走太久或太快。

④ □因为腰痛，无法正常行走。

8. 睡觉：

① □睡觉时没有任何腰痛。

② □只有在特定的体位睡觉才不会产生腰痛。

③ □因为腰痛，睡眠质量下降。

④ □因为腰痛，无法正常睡眠。

9. 个人护理（穿袜子、穿鞋子、沐浴等）：

① □所有个人护理都没有产生腰痛。

② □可以进行个人护理，但是有时候会产生腰痛。

③ □因为腰痛，某些个人护理无法进行。

④ □因为腰痛，几乎所有个人护理都需要协助。

10. 是否害怕产生腰痛或害怕损伤腰部：

① □在训练时，不害怕产生腰痛或腰部损伤。

② □尽管害怕产生腰痛，但还会继续训练。

③ □因为腰痛，某些训练或动作不敢去做。

④ □因为腰痛，不敢去做任何训练。

11. 休闲活动：

① □任何休闲活动中都没有产生腰痛。

② □尽管受到一些腰痛影响，仍可以正常进行休闲活动。

③ □因为腰痛，避免进行部分休闲活动。

④ □因为腰痛，避免所有休闲活动。

12. 性行为：

① □在性行为中没有产生任何腰痛或限制。

② □尽管受到一些腰痛影响，仍可以正常进行性行为。

③ □因为腰痛，必须减少性行为。

④ □因为腰痛，必须停止性行为。

SUPPLEMENTARY FILE (Chapter 2)

Supplementary File 2.1 Searching strategy

SUPPLEMENTARY FILE 2.1 Searching strategy

Step 1	reliabilit* or repeatabilit* or reproducibilit* or validit* or validation or responsiveness or temporal change* or change* over time
Step 2	ultrasonograph* or ultrasound* or ultrasonic or sonography or echograph* or shear wave or shear modulus or elastic* modulus or elastogra* or elastic* imaging*
Step 3	respiratory muscle* or ventilatory muscle* or breathing muscle* or diaphragm* or intercostal adj3 muscle* or inspiratory adj3 muscle*
Step 4	1 and 2 and 3

Supplementary File 2.2 Updated criteria for good measurement properties

SUPPLEMENTARY FILE 2.2 Updated criteria for good measurement properties

Measurement property	Rating*	Criteria
Reliability	+	ICC or weighted Kappa ≥ 0.70
	?	ICC or weighted Kappa not reported
	–	ICC or weighted Kappa < 0.70
Hypotheses testing for construct validity ‡	+	The result is in accordance with the hypothesis†
	?	No hypothesis defined (by the review team)
	–	The result is not in accordance with the hypothesis†

The COSMIN criteria[145]

Abbreviations: AUC = area under the curve，ICC = intraclass correlation coefficient.

***** *"+" = sufficient, "–" = insufficient, "?" = indeterminate.*

† *The results of all studies should be taken together and it should then be decided if 75% of the results are in accordance with the hypotheses.*

‡ *Generic hypotheses[145]:*
1. Correlations with (changes in) instruments measuring similar constructs should be ≥0.50.
2. Correlations with (changes in) instruments measuring related, but dissimilar constructs should be lower, i.e., 0.30-0.50.
3. Correlations with (changes in) instruments measuring unrelated constructs should be <0.30.
4. Meaningful changes between relevant (sub)groups (e.g., patients with expected high vs low levels of the construct of interest)

Supplementary File 2.3 Definitions of quality levels from adapted GRADE approach

SUPPLEMENTARY FILE 2.3 Definitions of quality levels from adapted GRADE approach

Quality level	Definition
High	We are very confident that the true measurement property lies close to that of the estimate* of the measurement property
Moderate	We are moderately confident in the measurement property estimate: the true measurement property is likely to be close to the estimate of the measurement property, but there is a possibility that it is substantially different
Low	Our confidence in the measurement property estimate is limited: the true measurement property may be substantially different from the estimate of the measurement property
Very low	We have very little confidence in the measurement property estimate: the true measurement property is likely to be substantially different from the estimate of the measurement property

The definitions are from adapted GRADE approach in Prinsen et al., 2018[145]

** Estimate of the measurement property refers to the pooled or summarized result of the measurement property of ClinROMs or PROMs.*

Supplementary File 2.4 Characteristics of included studies

SUPPLEMENTARY FILE 2.4 Characteristics of included studies

Author	Study design	Participant population	Examiners	Equipment parameters	Target Muscle(s)	Transducer location	Movement	Measurement property
Amerijckx et al.[52], 2020; Belgium	Observational study	Healthy n=67 Male n=31 Female n=36 mean ± SD Age: 22 ± 2 y BMI: 23 ± 3 kg/m^2	2 examiners	Esaote MyLab TM one device (Italy) ; 6-13 MHz linear probe; B-mode	Left TrA, IO	Placed transverdally, 2.5cm medially of the mis-axillary line and halfway between the lowerest rib and ilium	End of natural breathing cycle, end of maximal inspiration, end of maximal expiration	Thickness
Bachasson et al.[29], 2019; France	Observational study	Healthy n=15 Male n=11 mean(range) Age 32(18-43) BMI 24(2.6) Female n=4 age 28(20-44) BMI 21.3(1.3)kg/m^2	A trained operator	Aixplorer Ultrasound scanner (V11.2; SuperSonic Imagine, Aixen Provence, France); 10- to 2-MHz linear transducer; SWE mode	Right diaphragm	ZOA, on the posterior axillary line vertical to the chest wall at the 8th to 10th intercostal space	NR	Stiffness
Baldwin et al.[44], 2011; Australia	Observational study	Healthy n=13 Male n=6 Female n=7 mean(range) Age 33(20-73) y BMI 25.7 (19.2–30.8) kg/m^2	NR	75L38EA with the DP-6600, Shenzhen China; linear array US transducer 10 MHz; B-mode	Right diaphragm	ZOA, against the chest wall at the mid-axillary line of the 9th intercostal space	Expiration to the target volumes of end-expiration	Thickness
Blaney et al.[53], 1998; Australia	Observational study	Healthy n=12 mean(range) Age 18.9(18-22) y	An experienced sonographer	ATL-HDI 3000; M-mode	Diaphragm	NR	Uncoached tidal breathing, upper chest breathing, diaphragmatic breathing, thoracic expansion	Excursion
Boussuges et al.[55], 2009; France	Observational study	Healthy n=210 Male: mean ± SD (range) Age 50±14(20-17) y BMI 23±4 (18–35)kg/m2 Female: Age 49±16(21-77)y BMI 25±5 (16–45)kg/m2	2 examiners	Mylab 30CV; Esaote, Genoa, Italy; 2.5 to 3.5 MHz transducer array; M-mode	Both left and right diaphragm	Right: subcostal area between the midclavicular and anterior axillary lines Left: subcostal area between anterior and mid axillary lines	Quiet breathing, voluntary sniffing, and deep breathing	Excursion
Brown et al.[42], 2018; US	Observational study	Healthy n=45 Female n=31 mean (SD) Age 26.0 (3.4) y BMI 23.4 (2.9) kg/m^2	1 novice ultrasonographer, received 8 hours of training in ultrasonography	GE Medical Systems, Milwaukee, WI; 8.0 MHz linear array transducer; B-mode	right diaphragm	Zone of apposition, right anterior axillary line and the ninth intercostal space	Peak-inspiration and end-expiration (quiet)	Thickness
Cappellini et al.[40], 2021; Italy	Cross-sectional Study	Healthy n=10 male n=5, female n=5 Male: mean(range) Age: 31(30–32) y BMI: 22.82 (21.65–23.99) kg/m^2 Female: Age: 32(29–36) y BMI: 21.54 (19.14–23.94) kg/m^2	3 operators, a radiologist, a resident with basic knowledge and skills in ultrasonography, a medical student; all trained for ten sessions on how to recognize the anatomical landmarks used in the protocol proposed	Esaote MyLab 25 System (Esaote, Genoa, Italy); 12 MHz linear probe; B-mode; M-mode	Both left and right diaphragm	Zone of apposition	End-inspiration, end-expiration	Thickness

Table continues on next page

SUPPLEMENTARY FILE 2.4 Characteristics of included studies (continued)

Author	Study design	Participant population	Examiners	Equipment parameters	Target Muscle(s)	Transducer location	Movement	Measurement property
Dres et al.[140], 2020; France	Cross-sectional Study	Healthy n=23	2 examiners, both experienced in respiratory muscles ultrasound	10-15 MHz linear array transducer; M-mode	Parasternal intercostal muscle	Positioned perpendicular to the anterior thorax surface in the longitudinal scan, at the level of the second right intercostal space, approximately 6-8 cm lateral to the sternal edge with a window visualizing the 2nd and 3rd ribs	End-expiration and at peak inspiration	Thickness
Flattres et al.[116], 2020; France	Cross-sectional Study	Healthy n=15 mean±SD Age: 26.7 ± 4.6y mean(range) BMI: 22.6 (19.9–26.3) kg/m^2	2 examiners, an expert with 4 years of experience in the field of skeletal muscle ultrasound; a novice. Both were trained by the SuperSonic Imagine engineer	SuperSonic Imagine, AixenProvence, France; 4–15MHz linear transducer; SWE mode	Right diaphragm	Zone of Apposition, at the 8th–10th intercostal space between the right anterior and midaxillary lines	End of expiration	Stiffness
Harper et al.[149], 2013; US	Cross-sectional Study	Healthy n=150 mean±SD Age 50.6 ± 17.8y BMI 27.9 ± 5.3kg/m^2	2 examiners, trained for several weeks	LOGIQ e; GE Healthcare, Waukesha, WI; 7- to 13- MHz linear array transducer; B-mode	Both left and right diaphragm	Placed transversely over the lowest intercostal space	End of quiet inspiration; end of quiet expiration	Thickness
Marugán et al.[147], 2021; Spain	Cross-sectional Study	Athletes with non-specific lumbopelvic pain n=37, male n=25, female n=12 mean±SD Age: 31.64 ± 5.56y BMI: 23.14 ± 2.37kg/m^2	2 examiners, more than 4y experience working with the ultrasound technique	Ecube i7; Alpinion Medical System; Seoul, Korea; Linear probe, 8-12MHz; B-mode	Both left and right diaphragm	Perpendicularly placed with respect to the last intercostal space following the mid-axillary line from the inferior edge of the 11th rib to the superior edge of the 12th rib of the thorax	At maximum inspiration, maximum expiration	thickness
Mohan et al.[114], 2017; Thailand	Observational study	Non-specific low back pain n=9 mean(range) Age 23.33(1.58) y BMI 23.61 (6.31) kg/m^2	1 examiner, trained from medical imaging department with 3y of experience	HD 3; Philips Ultrasound, Bothell, USA; 3.5MHz convex transducer; B-mode	Right diaphragm	Placed over the right subcostal region	NR	Excursion
Nassiri et al.[113], 2019; Iran	Cross-sectional study	Pelvic girdle pain (PGP) n=10 Healthy control n=10 PGP: mean±SD Age 26.10 ± 5.87y BMI 24.43 ± 2.03kg/m2 Control: Age 30.90 ± 7.73y BMI 23.48 ± 2.32kg/m^2	1 examiner: an experienced physiotherapist in musculoskeletal ultrasonography	Ultrasonic Scanner, Qsono, China; B-mode with a 7 - 13 MHz linear array transducer; M-mode: curve transducer	B-mode: both sides diaphragm M-mode: right diaphragm	B-mode: anterior to the anterior axillary line in the intercostal space between the 7th and 8th, or 8th and 9th ribs, at which the diaphragm was more easily visualized M-mode: right mid-clavicular line immediately below the costal margin with firm pressure, and directed medially, cephalad, and dorsally	The end of expiration in quiet breathing; maximal inspiration	Thickness Excursion

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SUPPLEMENTARY FILE 2.4 Characteristics of included studies (continued)

Author	Study design	Participant population	Examiners	Equipment parameters	Target Muscle(s)	Transducer location	Movement	Measurement property
Noh et al.[157], 2016; Korea	Observational study	AIS female n=32 Thoracic curve: n=17 mean±SD Age 14.1 ± 1.9 Cobb angle 29.5 ± 17.0y Thoracolumbar curve: n=15 Age 14.3 ± 1.8y Cobb angle 20.7 ± 7.9	2 examiners	SONOACE X4, Medison, Seoul, Korea; 3.5 MHz curvilinear transducer; M-mode	Both left and right diaphragm	Sub-costal spaces between the midclavicular and anterior axillary lines (right); Sub-costal spaces between the anterior and mid axillary lines (left)	At the end of inspiration and expiration during tidal breathing	Excursion
Noh et al.[153], 2014; Korea	Observational study	Healthy n=14 male n=9 female n=5 mean±SD Age 28.4 ± 3.0y	NR	SONOACE 6000, Medison, Seoul, Korea; 3.5 MHz sector transducer; M-mode	Right diaphragm	Right sub-costal margin between the midclavicular and anterior axillary lines	At the end of inspiration and expiration during tidal breathing	Excursion
Oppersma et al.[100], 2017; Netherlands	Observational study	Healthy n=15 male n=7 mean(range) Age 21.3 (2.3) y BMI 21.6(1.7) kg/m^2	NR	Vivid E 9TM ultrasound machine (General Electric Healthcare, Horton, Norway); 9-MHz linear transducer; Speckle tracking	Right diaphragm	Right anterior axillary line longitudinal to the body axis (between the 9th-11th intercostal space)	At end expiration, end inspiration	Strain
Orde, et al.[158], 2016; US	Observational study	Healthy n=50 female n=28 mean(range) Age 37(30.2-39.8) y BMI 22.8 (20.4-24.9) kg/m^2	2 examiners: Australian Intensive Care specialist, board certified in standard and advanced echocardiography in America	Vivid E9, General Electric Healthcare, Milwaukee, WI); linear array transducer (2.5-8 MHz) and a phased array transducer (1.6-6 MHz); M-mode; Speckle tracking	Right diaphragm	Thickness & strain: right anterior axillary line at approximately the ninth intercostal space Excision: subcostally on the right mid-clavicular line	From the end of expiration through the end of inspiration	Thickness Excursion Strain
Pietton et al.[142], 2021; France	Cross-sectional Study	Healthy: n=19 mean±SD Age: 12.6 ± 1.7y BMI: 19.3±2kg/m^2 14 girls and five boys AIS: n=16 Age: 13 ±2.5 y BMI: 17.9±1.6kg/m^2 15 girls and one boy	3 examiners: 2y, 6m, 2m experience of ultrasound measurements	Aixplorer (Supersonic Imagine, Aixenprovence, France); Linear; SWE mode	Right intercostal muscle	T5-T6 right intercostal space, at the mid-axillary line	During normal breathing and in apnea. Apnea was performed at tidal volume	Stiffness
Scarlata et al.[151], 2019; Italy	Cross-sectional Study	Healthy n=66 Male n=30 Female n=36 mean (SD) Age: 40 (15)y BMI: 24.2 (3.5) kg/m^2	2 examiners	Exagyne - Echo Control Medical-ECM, Angoulme, France; linear probe; B-mode, M-mode	Right diaphragm	Placed on the line between the eighth and ninth intercostal spaces, midway between the antero- and mid-axillary lines	End of deep inspiration, end of normal expiration	Thickness
Scarlata et al.[156], 2018; Italy	Observational study	Healthy n=100 Male n=49 mean (SD) Age 40 (15)y BMI 24.4 (3.8) kg/m^2	3 examiners: experienced	ECM [Echo Control Medical] in Angouleme, France; convex probe and frequencies between 2.5 and 3.5 MHz; M-mode	Right diaphragm	Placed subcostal, right and anterior to the mid-clavicular line	Quiet and deep breathing	Excursion

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SUPPLEMENTARY FILE 2.4 Characteristics of included studies (continued)

Author	Study design	Participant population	Examiners	Equipment parameters	Target Muscle(s)	Transducer location	Movement	Measurement property
Soilemezi et al.[159], 2020; Greece	Cross-sectional Study	Healthy: n=20 male n=10 female n=10 Age range 25-48y	2 examiners	Philips Sparq ultrasound machine ; phased array 2–4 MHz probe; Tissue Doppler imaging (TDI)	Right diaphragm	Placed in the subcostal position between the midclavicular and anterior axillary lines	Breathing spontaneously	Diaphragmatic motion velocity
Wallbridge et al.[139], 2018; Australia	Observational study	Stable COPD n=20 Male n=16 Female n=4 mean(range) Age 71.5 (62.3–78.8) y BMI 23.5 (20.9–30) kg/m^2	An examiner: with 8 years of ultrasound experience and qualifications in respiratory ultrasound. Images were reviewed by a second reader with respiratory ultrasound experience to assess inter-rater reliability	Shenzhen Mindray Bio-Medical Electronics Co. Ltd. Shenzen, China; 6–14 MHz linear; B-mode	Bilateral intercostal muscles	2nd and 3rd parasternal intercostal muscles bilaterally	End-tidal inspiration	Thickness
Xu et al.[115], 2021; China	Cross-sectional Study	Stable COPD: n=43 mean±SD Age: 64.5± 7.9y BMI: 22.6± 3.3kg/m^2 Control: n=34 Age: 63.8± 7y BMI: 24± 2.8kg/m^2	1 examiner: 3y experience and was thoroughly trained in using SWE on the diaphragm	Logiq E9 (GE Healthcare, Wauwatosa, WI, USA) ultrasound system; 9 MHz linear transducer; SWE mode	Right diaphragm	Zone of apposition, between the right anterior and midaxillary lines vertical to the chest wall at the 8th to10th intercostal space	End of expiration	Stiffness
Ziaeifar et al.[112], 2021; Iran	Case-control study	LBP n=37 mean±SD Age 38.29 ± 10.95y BMI 24.65 ± 3.01kg/m^2 Healthy: n=34 Age 32.82 ± 10.43y BMI 23.38 ± 3.48kg/m^2	An experienced and expert radiologist	Toshiba, Aplio 300, Tokyo, Japan; Excursion: 3.5 MHz curvilinear transducer; M-mode. Thickness: 7.5 MHz linear array transducer; B-mode	Both left and right diaphragm	Excursion: the lower intercostal area between the midclavicular and anterior axillary lines for the right diaphragm and between the anterior and midaxillary lines for the left side. Thickness: zone of apposition, between the mid and anterior axillary lines on the right and left sides, typically between the 8th and 10th intercostal spaces diaphragm with the transducer spanning two ribs	Quiet breath; Deep breath	Excursion Thickness

Abbreviations: BMI = body mass index; NR= not reported, TrA= Transverse abdominals; IO= internus obliquus

Supplementary File 2.5 Ultrasound measurement approach

SUPPLEMENTARY FILE 2.5 Ultrasound measurement approach

Target Muscle(s)	Measurement property	Position	Equipment parameters	Transducer location	Movement
Diaphragm	Thickness: right,[41,43-44] bilateral[40,42,45-47]	Supine,[147-149] semi-recumbent position,[150-152] or hook-lying position,[112, 113]; supine, sitting, and standing.[148]	B-mode, M-mode[45] high-frequency (7-13MHz) linear array probe	Zone of apposition (ZOA): along the 8th-11th ribs between the mid and anterior axillary lines	At the end of quiet expiration and the end of maximal inspiration; at different breathing volumes[150]
	Excursion: right,[47,56,57,][114, 158] bilateral,[112, 153, 154] non-specified[155]	Supine,[153, 156, 157] semi-recumbent[114, 158] hook-lying,[112, 113] standing,[154] sitting.[155]	M-mode, low-frequency (2.5-3.5MHz) curve probe	subcostal area: left side was located between the mid-axillary and anterior axillary line; right side was located between the anterior axillary line and midclavicular line	From the end of expiration to the end of maximal inspiration
	Stiffness: right[99, 115, 116]	Supine,[115, 116] or semi-recumbent position.[99]	SWE mode, high-frequency (4-15MHz) linear array probe	ZOA	At the end of tidal expiration
	Strain[100, 158]	Semi-recumbent position	Speckle tracking, 2.5-9MHz linear transducer	ZOA	At end of expiration, end inspiration
	Motion velocity[159]	Semi-recumbent position	Tissue doppler, phased array 2-4MHz probe	Subcostal position between the midclavicular and anterior axillary lines	Tidal breathing
Intercostal muscles	Thickness[160]	Supine	B-mode, high-frequency (6-14MHz) linear array probe	2nd-3rd intercostal muscles	At the end of tidal inspiration
	Stiffness[161]	Supine	SWE mode, high-frequency (4-15MHz) linear array probe	T5-T6 right intercostal space along the mid-axillary line	At the end of tidal breathing
Abdominal muscles (TrA and IO)	Thickness[162]	Standing	B-mode, high-frequency (6-13MHz) linear array probe	2.5cm medially of the mid-axillary line and halfway between the lowest rib and ilium	At end of quiet expiration, maximal inspiration, and maximal expiration

Abbreviations: TrA= transverse abdominals; IO= internus obliquus; ZOA=zone of apposition; SWE=shear wave elastography

Supplementary File 2.6 Quality assessments and level of evidence based on all included studies – Reliability

SUPPLEMENTARY FILE 2.6 Quality assessments and level of evidence based on all included studies – Reliability

Targeted Muscle	Measurement Property	Study	Operator Experience	Position	Sample Size	Methodological quality (COSMIN)	Results rating						Evidence level
							Within-day		Between-day		Not sure interval		
							Intra-rater	Inter-rater	Intra-rater	Inter-rater	Intra-rater	Inter-rater	
Diaphragm-Left	Thickness	*Nassiri et al., 2019*	Experienced	Hook lying, pillow under knees, arms on sides	10	Doubtful	+						
		Nassiri et al., 2019	Experienced	Hook lying, pillow under knees, arms on sides	10	Doubtful	+		+				
		Cappellini et al., 2021	Experienced	semi-recumbent position, head up45	10	Adequate	+						Within-day intra-rater low (+)
		Ziaeifar et al., 2021	Experienced	spine, knees bend 30 degree, arms cross over the chest	17	Adequate	+						
		Marugan et al., 2021	Experienced	supine without pillow	37	Very good	+	+	+	+			
		Cappellini et al., 2021	Novice	semi-recumbent position, head up45	10	Adequate	-						
Diaphragm-Right	Thickness	*Nassiri et al., 2019*	Experienced	Hook lying, pillow under knees, arms on sides	10	Doubtful	+						
		Nassiri et al., 2019	Experienced	Hook lying, pillow under knees, arms on sides	10	Doubtful	+		+				
		Cappellini et al., 2021	Experienced	semi-recumbent position, head up45	10	Adequate	+						
		Orde et al., 2016	Experienced	semi-recumbent position, head up45	10	Doubtful			+			+	Within-day intra-rater moderate, (+)
		Ziaeifar et al., 2021	Experienced	spine, knees bend 30 degree	17	Adequate	+						
		Marugan et al., 2021	Experienced	supine	37	Very good	+	+	+	+			
		Cappellini et al., 2021	Novice	semi-recumbent position, head up45	10	Adequate	-						
		Brown et al., 2018	Novice	supine, sitting, standing	45	Doubtful	+						
		Baldwin et al., 2011	Unspecified	semi-recumbent position	10	Doubtful					+		
		Scarlata et al., 2019	Unspecified	recumbent position	66	Inadequate	+	+					
Diaphragm-Left	Excursion	*Boussuges et al., 2009*	Experienced	standing	180	Doubtful			+			+	Low, (+)
		Noh et al., 2016	Experienced	supine	32	Doubtful	+	+					Very low, (+)
Diaphragm-Right	Excursion	*Scarlata et al., 2018*	Experienced	spine	42	Doubtful	+			+/-			
		Orde et al., 2016	Experienced	semi-recumbent position, head up45	10	Doubtful			+			+	Between-day intra-rater: moderate, (+)
		Boussuges et al., 2009	Experienced	standing	180	Doubtful			+			+	
		Nassiri et al., 2019	Experienced	Hook lying, pillow under knees, arms on sides	10	Doubtful	+		+				
		Mohan et al., 2017	Experienced	head elevated to 30 degree	9	Doubtful			+				
		Noh et al., 2016	Experienced	supine	32	Doubtful	+	+					
Diaphragm-Right	Stiffness	*Xu et al., 2021*	Experienced	supine	15	Very good	+						Low, (+)
		Flattres et al., 2020	Experienced	supine	15	Doubtful					+		Very low, (+)
		Flattres et al., 2020	Novice	supine	15	Doubtful					+		Very low, (+)
		Flattres et al., 2020	Experienced +novice	supine	15	Doubtful						+	Very low, (+)
	Strain rate	*Orde et al., 2016*	Experienced	semi-recumbent position, head up45	10	Doubtful			+			+	Very low, (+)
	Motion velocity	*Soilemezi et al., 2020*	Experienced	supine with back elevated at 30 degree	20	Doubtful					+	+	Very low, (+)
Intercostal muscle	Thickness	*Dres et al., 2020*	Experienced	supine	23	Doubtful		+					Very low, (+)
		Wallbridge et al., 2018	Experienced	supine	20	Doubtful	+	+/-					Very low, (+)
	Stiffness	*Pietton et al., 2021*	Experienced	supine	16	Doubtful		+					Very low, (+)
		Pietton et al., 2021	Experienced	supine	16	Doubtful		+					Very low, (+)
TrA-Left	Thickness	*Amerijckx et al. 2020*	Experienced	standing	67	Doubtful	+	+/-					Very low, (+)
IO-Left	Thickness	*Amerijckx et al. 2020*	Experienced	standing	67	Doubtful	+	+/-					Very low, (+)

Abbreviations: TrA= Transverse abdominals; IO= internus obliquus; Not sure=not sure time interval

Supplementary File 2.7 Quality assessments and level of evidence of using ultrasonography measurements for respiratory muscles in separated populations – Reliability

SUPPLEMENTARY FILE 2.7 Quality assessments and level of evidence of using ultrasonography measurements for respiratory muscles in separated populations – Reliability

Polupation	Targeted Muscle	Measurement Property	Study	Operator Experience	Position	Sample Size	Methodological quality (COSMIN)	Results rating						Evidence level
								Witnin-day		Between-day		Not sure interval		
								Intra-rater	Inter-rater	Intra-rater	Inter-rater	Intra-rater	Inter-rater	
Healthy	Diaphragm-Left	Thickness	*Nassiri et al., 2019*	Experienced	Hook lying, pillow under knees, arms on sides	10	Doubtful	+						Very low, (+)
			Cappellini et al., 2021	Experienced	semi-recumbent position, head up45	10	Adequate	+						Very low, (+)
			Cappellini et al., 2021	Novice	semi-recumbent position, head up45	10	Adequate	-						Very low, (-)
	Diaphragm-Right	Thickness	*Nassiri et al., 2019*	Experienced	Hook lying, pillow under knees, arms on sides	10	Doubtful	+						Very low, (+)
			Cappellini et al., 2021	Experienced	semi-recumbent position, head up45	10	Adequate	+						Very low, (+)
			Cappellini et al., 2021	Novice	semi-recumbent position, head up45	10	Adequate	-						Very low, (-)
			Brown et al., 2018	Novice	supine, sitting, standing	45	Doubtful	+						Very low, (+)
			Scarlata et al., 2019	Unspecified	recumbent position	66	Inadequat	+	+					Very low, (+)
			Orde et al., 2016	Experienced	semi-recumbent position, head up45	10	Doubtful			+			+	Very low, (+)
			Baldwin et al., 2011	Unspecified	semi-recumbent position	10	Doubtful					+		Very low, (+)
	Diaphragm-Unspecifying side	Thickness	*Harperet al., 2013*	Novice	supine	12	Adequate			+	+			Very low, (+)
			Cappellini et al., 2021	Experienced	semi-recumbent position, head up45	10	Adequate		-					Very low, (-)
	Diaphragm-Left	Excursion	*Boussuges et al., 2009*	Experienced	standing	180	Doubtful			+			+	Low, (+)
	Diaphragm-Right	Excursion	*Scarlata et al., 2018*	Experienced	spine	42	Doubtful	+			+/-			Within-day intra-rater very low, (+)
			Orde et al., 2016	Experienced	semi-recumbent position, head up45	10	Doubtful			+			+	Very low, (+)
			Boussuges et al., 2009	Experienced	standing	180	Doubtful			+			+	Low, (+)
	Diaphragm-Unspecifying side	Excursion	*Blaney et al., 1998*	Experienced	sitting	12	Inadequat					+		Very low, (+)
	Diaphragm-Right	Stiffness	*Xu et al., 2021*	Experienced	supine	15	Very good	+						Low, (+)
			Flattres et al., 2020	Experienced	supine	15	Doubtful					+		Very low, (+)
			Flattres et al., 2020	Novice	supine	15	Doubtful					+		Very low, (+)
			Flattres et al., 2020	Experienced +novice	supine	15	Doubtful						+	Very low, (+)
		Strain rate	*Orde et al., 2016*	Experienced	semi-recumbent position, head up45	10	Doubtful			+			+	Very low, (+)
		Motion velocity	*Soilemezi et al., 2020*	Experienced	supine with back elevated at 30 degree	20	Doubtful					+	+	Very low, (+)
	Intercostal muscle-Right	Thickness	*Dres et al., 2020*	Experienced	supine	23	Doubtful		+					Very low, (+)
		Stiffness	*Pietton et al., 2021*	Experienced	supine	16	Doubtful		+					Very low, (+)
	TrA-Left	Thickness	*Amerijckx et al. 2020*	Experienced	standing	67	Doubtful	+	+/-					Within-day intra-rater very low, (+)
	IO-Left	Thickness	*Amerijckx et al. 2020*	Experienced	standing	67	Doubtful	+	+/-					Within-day intra-rater very low, (+)
LBP	Diaphragm-Left	Thickness	*Nassiri et al., 2019*	Experienced	Hook lying, pillow under knees, arms on sides	10	Doubtful	+		+				Very low, (+)
			Ziaeifar et al., 2021	Experienced	spine, knees bend 30 degree, arms cross over the chest	17	Adequate	+						Very low, (+)
			Marugan et al., 2021	Experienced	supine without pillow	37	Very good	+	+	+	+			Low, (+)
	Diaphragm-Right	Thickness	*Nassiri et al., 2019*	Experienced	Hook lying, pillow under knees, arms on sides	10	Doubtful	+		+				Very low, (+)
			Ziaeifar et al., 2021	Experienced	spine, knees bend 30 degree	17	Adequate	+						Very low, (+)
			Marugan et al., 2021	Experienced	supine	37	Very good	+	+	+	+			Low, (+)
	Diaphragm-Right	Excursion	*Nassiri et al., 2019*	Experienced	Hook lying, pillow under knees, arms on sides	10	Doubtful	+		+				Very low, (+)
			Mohan et al., 2017	Experienced	head elevated to 30 degree	9	Doubtful			+				Very low, (+)
AIS	Diaphragm-Left	Excursion	*Noh et al., 2016*	Experienced	supine	32	Doubtful	+	+					Very low, (+)
	Diaphragm-Right	Excursion	*Noh et al., 2016*	Experienced	supine	32	Doubtful	+	+					Very low, (+)
	Intercostal muscle	Stiffness	*Pietton et al., 2021*	Experienced	supine	16	Doubtful		+					Very low, (+)
COPD	Intercostal muscle	Thickness	*Wallbridge et al., 2018*	Experienced	supine	20	Doubtful	+	+/-					Within-day intra-rater very low, (+)

Abbreviations: TrA= Transverse abdominals; IO= internus obliquus; LBP = low back pain; AIS= adolescent idiopathic scoliosis; COPD= chronic obstructive pulmonary disease; Not sure=not sure time interval

Supplementary File 2.8 Quality assessments and level of evidence – Validity

SUPPLEMENTARY FILE 2.8 Quality assessments and level of evidence – Validity

Polupation	Targeted Muscle	Convergent	Discriminative /known-groups	Study	Sample Size	Quality rating(COSMIN)	Results rating	Level of Evidence
Healthy	Diaphragm-Right	Excursion & Radiographic Image		*Noh et al., 2014*	14	Very good	+	n=14, low (+)
		Excursion & FEV1, FVC		*Boussuges et al., 2009*	180	Very good	+	n=180, high (+)
		Stiffness & Pdi		*Bachasson et al., 2019*	15	Very good	+	n=15, low (+)
		Strain rate & Pdi		*Oppersma et al., 2017*	15	Very good	+	n=15, low (+)
AIS	Diaphragm-Bilateral		Excursion：AIS Left & right side	*Noh et al., 2016*	32/32	Adequate	+	n=32, very low (+)
	Intercostal muscle-Right		Stiffness: AIS & Healthy	*Pietton et al., 2021*	16/19	Doubtful	-	n=16, very low (-)
COPD	Diaphragm-Right	Stiffness & FEV1,FVC		*Xu et al., 2021*	43	Very good	+	n=43, low (+)
			Stiffness : COPD & Healthy	*Xu et al., 2021*	43/34	Doubtful	+	n=43, very low (+)
	Intercostal muscle	Thickness & FEV1		*Wallbridge et al., 2018*	20	Adequate	+	n=20, very low (+)

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