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RESEARCH

Ultrasound and MRI-based evaluation of relationships between morphological and mechanical properties of the lower lumbar multifidus muscle in chronic low back pain

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Abstract

Purposes While lumbar multifidus (MF) muscle alterations are linked to low back pain (LBP), the structure-function relationship is not fully understood. This study aims to evaluate the relationship between fatty degeneration of the lumbar MF muscle and its function in individuals with and without LBP.

Methods The study included 25 participants with chronic nonspecific LBP and 25 age- and sex-matched healthy controls. Participants underwent MRI assessment for MF fat infiltration, utilizing IDEAL fat-water images. Ultrasound measures evaluated MF function, including shear-wave elastography (SWE) for stiffness/elasticity and thickness ratio from rest to submaximal contraction. All measurements were acquired at L4/L5 and L5/S1 spinal levels, bilaterally. Bivariate and multivariable linear regression models were used to assess the relationship between morphology and function, while age, sex, body max index (BMI), physical activity levels, and LBP status were considered as covariates.

Results Fifty participants (26 females) were included (mean age: 39.22 ± 11.67). Greater % MF fat at L4/L5 was significantly associated with greater MF SWE ratio ($p = 0.002$). No significant bivariate or multivariable relationships were found between MF fat infiltration and MF thickness ratio. Participants with LBP exhibited lower contraction ratios ($p = 0.017$) and higher SWE during contraction ($p = 0.03$) at L4/L5 compared to controls.

Conclusion This study highlights a positive association between MF fat infiltration and SWE-based stiffness measures at L4/L5, suggesting altered muscle composition may impacts MF function. However, no relationship was found between MF fat infiltration and contraction. Participants with LBP demonstrated distinct deficits in muscle activation, supporting the need for targeted rehabilitation strategies addressing these functional impairments.

Keywords Chronic LBP · Lumbar multifidus muscle · MRI · Ultrasound · Shear wave elastography · Fat infiltration · Muscle stiffness

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Introduction

Low back pain (LBP) is a prevalent musculoskeletal disorder, affecting approximately 80% of individuals in their lifetime [1]. Its high prevalence results in significant socioeconomic costs [2] and increased disability [3]. Though the exact cause remains unclear [4], research shows that LBP is linked to degenerative changes in lumbar multifidus (MF) morphology [5] and function [6]. This includes reduced thickness change during contraction [7], delayed feedforward activation [8, 9], fat infiltration, and atrophy [10]. Given its role in maintaining intervertebral stability, MF dysfunction may contribute to LBP recurrence [7, 9].

Skeletal muscle stiffness arises from both active tension during contraction and passive tension from connective tissue [11]. Since tissue stiffness is altered in pathological conditions, muscle elasticity/stiffness assessments serve as valuable non-invasive tools for diagnosis and management [12]. However, few studies have examined tissue elasticity in musculoskeletal disorders [13]. Shear wave ultrasound elastography (SWE) is an innovative real-time diagnostic imaging technology detecting tissue stiffness variations quantitatively [12, 13], with established reliability and validity to assess lumbar muscles [12, 14, 15].

While previous reports have assessed degenerative changes in morphology and function of the paraspinal muscles in patients with LBP, most studies have examined each aspect separately. Two studies that have assessed the structure-function relationship of the paraspinal muscle in patients with LBP, failed to show a clear association [16, 17], while two other studies did report an association between muscle composition and strength, and postural control, respectively [18, 19]. These discrepancies may be attributed to differences in study design, measurement methods, targeted populations, or the inability of certain imaging modalities to differentiate deep and superficial muscle layers. As such, a more comprehensive approach combining both morphological and functional imaging may help clarify these structure-function relationships. Our present study combined two imaging modalities: magnetic resonance imaging (MRI) for evaluating MF composition (e.g., morphology) and ultrasound for examining MF thickness change and stiffness/elasticity related to functional deficit. Together, they provided a broad assessment of the structure-function relationship of the MF. The aim of the present study was to evaluate the relationship between MF muscle morphology (i.e., fatty infiltration) and function (i.e., contraction/thickness ratio, stiffness/ elasticity) in individuals with and without LBP. A secondary objective was to examine differences in MF muscle function between individuals with and without LBP. We hypothesized that greater MF muscle fatty infiltration would be associated with increased muscle stiffness but reduced contractile function. Additionally, we hypothesized that individuals with LBP would demonstrate reduced contraction capacity and increased muscle stiffness compared to healthy controls.

Material and method

Study design and setting

This observational case-control study was conducted at a site that has been anonymized for confidentiality and was approved by the Central Ethics Research Committee of the Quebec Ministry of Health and Social Services (CCER-15-16-17). Each participant willingly contributed to the study by endorsing an informed consent form. The study's reporting adhered to the guidelines articulated in the STROBE statement.

Participants recruitment

Participants were recruited through email advertisements within the nearby university community, a multidisciplinary group developing a province-wide online database of individuals with LBP [20]. Interested individuals were screened for eligibility by a research team member before enrollment. Recruitment began in October 2020, and data collection was completed by February 2022. Both the LBP and control groups were recruited using the same methods and screening process to ensure consistency across groups.

Participants

Based on mean and standard deviation estimates of MF muscle stiffness from a relevant case-control study [21], with values for the LBP group (10.15 ± 4.21 kPa) and the control group (6.84 ± 1.69 kPa), the sample size was calculated at 20 participants per group, aiming to detect an effect size of 1.03, with a significance level of 0.05 and power of 0.90 using the G*Power 3.0 software. To accommodate potential data collection challenges, we aimed to recruit 25 participants for each group. Participants were included in the LBP group if they met all the following inclusion criteria: (1) chronic nonspecific LBP (≥3 months), defined as pain in the region between the lower ribs and gluteal folds, with or without leg pain, (2) between 20 and 65 years of age, (3) a score of 21–40 (moderate disability) or 41–60 (severe disability) on the Oswestry Low Back Pain Disability Questionnaire (ODI), (4) do not engage in any sport or fitness training specifically for the lower back muscles up to 3 months prior to the enrollment in this study, (5) currently seeking care for LBP, (6) speak either French or

English, and (7) no history of lumbar surgery. Participants were excluded if they had: (1) any evidence of nerve root compression or reflex motor sign deficits, (2) previous lumbar spinal surgery, or lumbar vertebral fractures, (2) major lumbar spine structural abnormalities (e.g., spondylolysis, spondylolisthesis, scoliosis > 10°), (3) pregnancy, (4) any history of a sacroiliac joint dysfunction, (5) rheumatologic and neurologic disease, (6) metabolic diseases and malignancies or other major medical conditions, and (7) orthopedic device in the spinal column [20]. The control group consisted of healthy individuals who: (1) reported no episode of LBP lasting more than one week in the past year; (2) had no history of spinal surgery, musculoskeletal, neurological, or rheumatologic disorders; (3) were not engaged in lower back-specific training within the past 3 months; (4) were fluent in French or English; and (5) were age- and sex-matched to participants in the LBP group. Exclusion criteria similar to those for the LBP group were applied to ensure comparability and minimize potential confounding.

Procedure

After confirming eligibility and obtaining consent, we collected demographic and clinical information, and participants completed self-report measures of physical activity. The International Physical Activity Questionnaire (IPAQ)-Short Form was used to determine the degree of physical activity of participants.

MRI assessment of lumbar MF morphology

As seen in Fig. 1, axial fat and water (Lava-Flex, two-echo sequence, TE: 4.5 ms, flip angle: 5°) images were acquired to assess MF fat infiltration at L4/L5 and L5/S1—common spinal pathology sites—bilaterally. MRI scans were obtained using the 3T GE scanner (Milwaukee, WI, USA) with a phased-array body coil (4-mm slice thickness, 180 × 180 mm² field of view, 512 × 512 matrix). Sagittal images were acquired to localize the lumbar levels and guide accurate selection of axial slice positions for subsequent analysis. Multi-planar reconstruction was applied when needed to adjust slice orientation. Muscle composition was analyzed using Horos DICOM software (v4.0.0). MF cross-sectional areas (CSA) were manually delineated on axial fat images at L4/L5 and L5/S1 and then transferred to corresponding water images. A single axial slice per level at mid-disc was selected for each side based on the clearest anatomical visualization of MF muscle margins and alignment with vertebral endplates. This approach was consistent across participants to ensure comparability. MF boundaries were defined using standard anatomical landmarks, including the vertebral lamina medially, the fascia separating MF from erector spinae laterally, and the muscle's outer edge adjacent to the subcutaneous tissue posteriorly. Muscle borders were manually traced on the fat images using Horos DICOM viewer software (v4.0.0), and the same region of interest (ROI) was applied to the corresponding water image, as established by Masi et al. [22]. Each muscle (left and right MF at each level) was outlined once, and bilateral values were averaged to obtain a single CSA value per level. Signal intensities were recorded to calculate the fat signal fraction (%FSF) as: %FSF=((Signalwater+Signalfat)/Signalfat)×100. This method has demonstrated high intra- and inter-rater reliability (Intra-class correlation coefficient(ICC) = 0.91–0.94) [23].

All MF CSA measurements were performed by a blind assessor with 1 year of experience that was previously trained by a senior researcher with over 15 years of experience in lumbar paraspinal muscle imaging analysis.

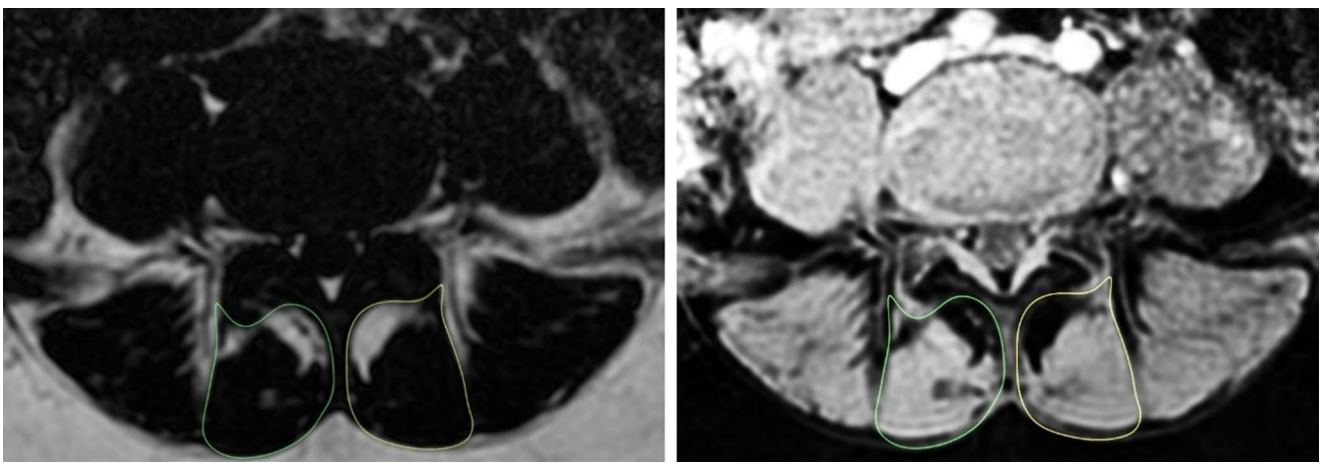

Fig. 1 %FSF method. Example of ROI outlining the MF using fat image (left) and water image (right)

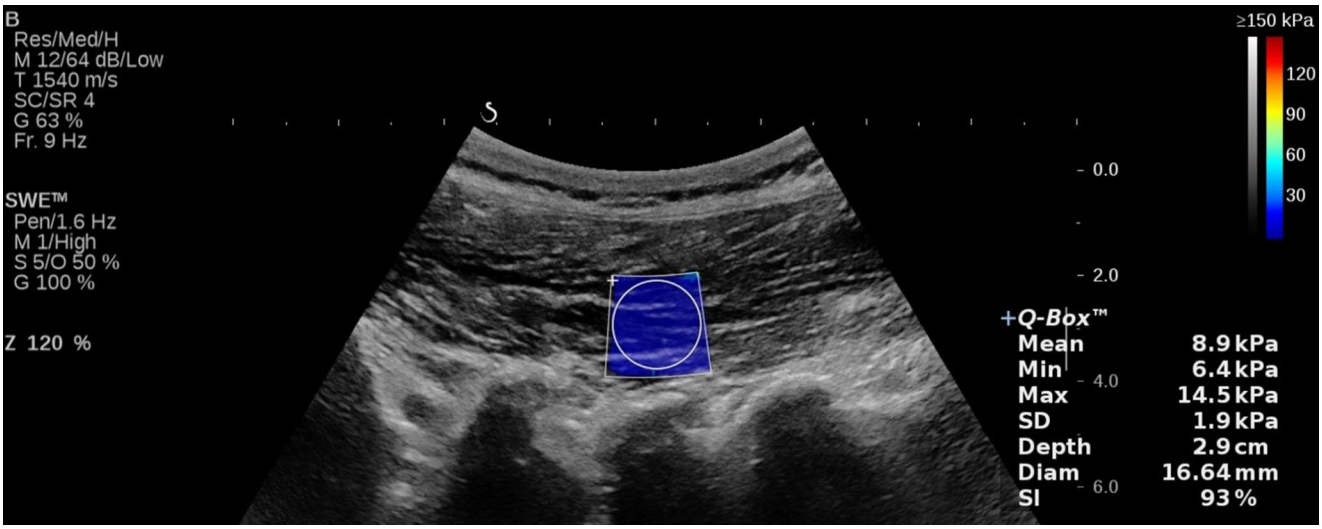

Fig. 2 Representative elastogram from a participant with LBP showing MF stiffness at rest. Based on the Q-Box™ overlay, the displayed mean shear modulus is the value used for analysis

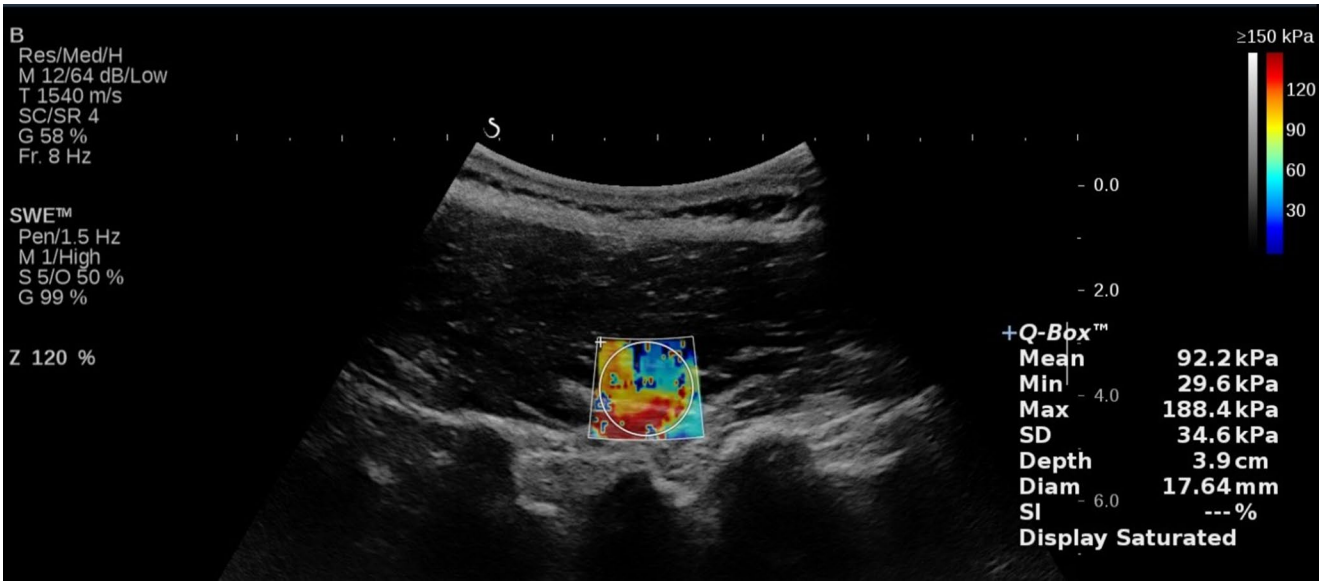

Fig. 3 Representative elastogram from a participant with LBP showing MF stiffness during a contraction. Based on the Q-Box™ overlay, the displayed mean shear modulus is the value used for analysis

Ultrasound measures of lumbar MF function

Ultrasound examination of the L4/L5 and L5-S1 levels were acquired the same day. The Aixplorer ultrasound unit (Supersonic Imagine, Aix-en-Provence, France) with SWE and SL10-2 curvilinear transducer with 5 MHz frequency was used to measure MF shear elastic modulus (i.e., index of muscle stiffness and elasticity) at rest and during submaximal contraction (Figs. 2 and 3). MF % thickness ratio (i.e., contraction) was computed using the following equation: %thickness ratio= ((thickness contracted–thickness rest)/thickness rest) x100 [24]. A previous studies have shown that this method of measuring MF thickness using ultrasound is both reliable and valid [24].

The procedures for ultrasound MF muscle measurements at rest and during submaximal contraction have been described in detail elsewhere [25]. Briefly, measurements were taken with participants in a prone position, using standardized probe placement and minimal pressure to ensure consistency. The thickness and SWE measurements were recorded three times per side and spinal level, with the average used for analysis. To quantify the increase in shear elastic modulus during contraction, the contraction ratio was calculated by dividing the mean shear modulus during

Table 1 Demographic and clinical characteristics of participants

Characteristic	All ($n=50$) Mean (SD) or Frequency (%)	Controls ($n=25$) Mean (SD) or Frequency (%)	LBP ($n=25$) Mean (SD) or Frequency (%)	*P*-value
Age (years)	39.22 (11.67)	38.56 (11.43)	39.88 (12.11)	0.694
BMI (kg/m2)	24.18 (3.88)	23.64 (3.63)	24.74 (4.13)	0.323
Sex				
Male	24 (48%)	12 (%)	12 (%)	1.000
Female	26 (52%)	13 (%)	13 (%)	
IPAQ score				
Low	38%	40%	36%	0.753
Moderate	30%	28%	32%	
High	32%	32%	32%	
ODI (%)	---	---	26.68 (9.23)	---

BMI: Body mass index, SD: standard deviation, IPAQ: international physical activity questionnaire, ODI: Oswestry disability index

The mean age for all participants was 39.22 ± 11.67 years, with 26 females (52%). MF function and %FSF measurements are reported in Table 2

contraction by the meanshear modulus at rest (absolute values), as described by Botanlioglu et al. (2013) [26].

The ultrasound images were then transferred to a desktop computer and analysed offline using the HOROS imaging analysis software. The examiner was blinded to the participant's demographic identification and MRI analysis. All ultrasound measurements were performed by an examiner with over 5 years of experience in musculoskeletal ultrasound.

Statistical analysis

Descriptive statistics were calculated for demographic characteristics and MF measurements. The relationship between MF fat infiltration and MF function (thickness ratio and stiffness/elasticity) was analyzed using bivariate and multivariable analyses. Separate linear regression models were used for each muscle site to assess multivariable relationships, considering covariates such as age, sex, BMI, group assignment (LBP vs. controls), and physical activity.

Intra-rater reliability of MRI and ultrasound measurements was investigated using a subset of participants ($n=10$), using ICC(3,1) two-way random-effect model, single measure and absolute agreement. Initially, variables with notable bivariate associations ($p<0.10$) were included as covariates [17]. IPAQ was included a priori as a potential confounder due to literature suggesting that physical activity may influence both muscle morphology and function, warranting its inclusion despite non-significant bivariate associations. In the second step, MF fat infiltration was introduced [17]. This selection strategy assessed whether MF function was linked to fat infiltration after accounting for covariates. Adjusted R-squared values were iteratively computed to reflect variance explained while adjusting for the number of predictors. Model assumptions were verified and tenable. Differences in muscle morphology and function between LBP and controls were examined using independent samples tests, evaluating both between-group (LBP vs. controls) and within-group (morphology vs. function) factors. A p-value < 0.05 was considered statistically significant.

Table 2 MF% FSF measurements, thickness ratio and shear elastic modulus

Variables	All ($n=50$) Mean (SD)	Controls ($n=25$) Mean (SD)	LBP ($n=25$) Mean (SD)	*P*-value	effect sizes (Cohen's d)
MF % FSF					
L4/L5	19.92(6.99)	18.98(6)	20.85(7.88)	0.35	0.27
L5/S1	22.2 (9.3)	21.55(9.6)	22.64(8.96)	0.68	0.12
MF Th ratio					
L4/L5	20.07(8.09)	22.62(8.52)	17.28(6.72)	0.018	0.7
L5/S1	12.68(7.67)	12.93(8.52)	12.41(6.69)	0.811	0.07
MF SWE rest (kPa)					
L4/L5	12.94(4.21)	13.38(4.07)	12.5(4.37)	0.465	0.21
L5/S1	13.21(3.85)	13.23(4.04)	13.19(3.74)	0.971	0.01
MF SWE contraction ratio					
L4/L5	0.31(0.18)	0.36(0.22)	0.25(0.1)	0.027	0.64
L5/S1	0.35(0.35)	0.44(0.47)	0.26(0.1)	0.067	0.53

FSF: Fat signal fraction, LBP: low back pain, MF: multifidus, SD: standard deviation, SWE: shear wave elastography, Th: thickness

Results

Data from all 50 recruited participants (25 per group) was included for analysis. Age, BMI, sex, and physical activity levels were comparable between individuals with LBP and healthy controls. Demographic and clinical characteristics are presented in Table 1. Intra-rater reliability for MRI and ultrasound measurements was excellent. For MF CSA

measurements, ICC values ranged from 0.91 to 0.94. For ultrasound-based measurements, including shear modulus and thickness ratio, ICC values ranged from 0.89 to 0.94.

Bivariate regression analysis for lumbar MF muscle parameters and covariates (age, sex, BMI, group status, physical activity) are presented in Table 3. An association was observed between lumbar MF %FSF and age and sex at both L4/L5 and L5/S1 levels, while both MF thickness ratio and MF SWE contraction ratio were associated with BMI and LBP status at L4/L5.

Multivariable regression analyses assessing the associations between MF %FSF and functional measures-including SWE at rest, SWE contraction ratio, and MF thickness ratio-at both L4–L5 and L5–S1 are presented in Tables 4 and 5. Significant associations were observed for SWE-based measures at L4–L5 (Table 4), while no significant associations were found for MF thickness ratio at either level (Table 5).

Between-group comparisons of muscle function revealed significant differences in the lumbar MF thickness ratio ($p=0.017$) and SWE contraction ratio ($p=0.041$), both at the L4–L5 level, with smaller ratios observed in the LBP group compared to healthy controls (Table 6). Additionally, the LBP group demonstrated significantly greater shear elastic modulus during contraction at both L4–L5 ($p=0.03$) and L5–S1 ($p=0.017$). No other significant group differences were observed (Table 6).

Discussion

Relationship between MF fat infiltration and muscle function (MF thickness ratio)

Contrary to our hypothesis, no association was found between MF fat infiltration and MF thickness ratio. Similar findings have been reported in the literature, including Le Cara et al. [17], who found no association between MF fat infiltration and thickness change. Possible explanations include cohort characteristics, measurement limitations, and the complex nature of LBP [17].

The function of the MF may differ between its deep and superficial layers. MacDonald et al. [27] reported activation impairments in deep MF fibers in recurrent LBP patients, suggesting functional differences between layers. While ultrasound is a valid tool to assess MF function, its ability to distinguish deep and superficial muscle layers remains uncertain [28], highlighting the need for further investigation. Our study assessed MF function during a submaximal contraction. Since fat infiltration is more prominent in deep MF, compensatory activation of superficial regions may have influenced the results [29]. Future studies should explore direct measures of deep MF activation, along with muscle strength and endurance assessments, to better identify LBP-related morphological and functional impairments.

Table 3 Bivariate associations of lumbar MF infiltration and MF function with age, sex, body mass index, group status, and physical activity ($n=50$)

	Age		Sex		BMI		LBP status		Physical activity	
	Coeff (95%CI)	*P*	Coeff (95%CI)	*P*	Coeff (95%CI)	*P*	Coeff (95%CI)	*P*	Coeff (95%CI)	*P*
MF % FSF										
L4/L5	0.37 [0.23,0.5]	<0.001*	5.73 [2.07, 9.4]	0.003*	-0.01 [-0.54,0.50]	0.94	1.86 [-2.12, 5.84]	0.35	2.05 [-0.33, 4.44]	0.09
L5/S1	0.36 [0.16,0.56]	<0.00*	8.26 [3.4,12.98]	<0.001*	-0.37 [-1.05,0.29]	0.26	1.08 [-4.19, 6.37]	0.68	2.35 [-0.85, 5.56]	0.14
MF Th ratio										
L4/L5	-0.06 [-0.26,0.13]	0.49	0.65 [-3.98, 5.28]	0.77	-0.81 [-1.36, -0.26]	0.005*	-5.34 [-9.71, -0.97]	0.01*	0.09 [-2.79, 2.98]	0.94
L5/S1	0.02 [-0.16, 0.21]	0.78	0.29 [-4.07, 4.65]	0.89	-0.48 [-1.03, 0.06]	0.08	-0.51[-4.88, 3.84]	0.81	-1 [-3.72, 1.71]	0.46
MF SWE rest (kPa)										
L4/L5	-0.05 [-0.16,0.04]	0.27	1.71 [-0.66,4.07]	0.15	0.07 [-0.23, 0.39]	0.61	-0.87 [-3.28,1.52]	0.46	0.04 [-1.44, 1.53]	0.95
L5/S1	-0.05 [-0.15,0.03]	0.21	0.23 [-1.98, 2.45]	0.83	0.15 [-0.12, 0.44]	0.26	0.04 [-2.17, 2.26]	0.96	0.61 [-1.96,0.74]	0.36
MF SWE contraction ratio										
L4/L5	0.00 [-0.005, 0.004]	0.93	-0.023 [-0.12,0.08]	0.66	0.01 [0.004, 0.029]	0.01*	0.1[0.03, 0.005]	0.04*	0.01 [-0.05, 0.07]	0.81
L5/S1	0.003 [-0.005,0.01]	0.43	-0.08 [-0.28,0.12]	0.42	0.03 [0.005, 0.05]	0.01*	-0.18[-0.37,0.01]	0.07	0.03 [-0.09, 016]	0.58

BMI: Body mass index, CI: confidence interval, Coeff: coefficient, FSF: fat signal fraction, kPa: kilo pascal, MF: multifidus, SWE: shear wave elastography, Th: thickness. * = significant outcome

Table 4 Results of multivariable regression analyses between MF %FSF and function (SWE contraction ratio and SWE rest) while controlling for covariates identified in the bivariate analyses. ($N=50$)

Analysis	Variables	Adjusted R2	R2 Change significance	Coeff (95% CI)	*P*-value
Outcome variable	LM SWE cont. ratio at L4/L5				
Model 1 (covariates)	L4/L5 MF % FSF	0.242	0.321	0.016 [0.006, 0.025]	0.002*
	Age			-0.007 [-0.012, -0.001]	0.014*
	Sex			-0.048 [-0.163, 0.067]	0.405
	BMI			0.021 [0.007, 0.034]	0.004*
	IPAQ			-0.006 [-0.064, 0.052]	0.833
Outcome variable	LM SWE cont. ratio at L5/S1				
Model 2 (covariates)	L5/S1% MF FSF	0.12	0.23	0.007 [-0.007,0.021]	0.335
	Age			-0.002 [-0.012, 0.009]	0.76
	Sex			-0.027 [-0.266,0.213]	0.824
	BMI			0.037 [0.008, 0.067]	0.015*
	IPAQ			0.032 [-0.091, 0.155]	0.604
	LBP status			-0.223 [-0.42, -0.026]	0.027*
Outcome variable	LM SWE rest L4/L5(kPa)				
Model 3 (covariates)	L4/L5% MF FSF	0.047	0.126	0.242 [0.01, 0.494]	0.049*
	Age			-0.129 [-0.263, 0.005]	0.058
	Sex			0.286 [-2.454, 3.027]	0.834
	IPAQ			-0.111 [-1.606, 1.384]	0.882
Outcome variable	LM SWE rest L5/S1(kPa)				
Model 4 (covariates)	L5/S1% MF FSF	-0.046	0.041	-0.058 [-0.218, 0.102]	0.471
	Age			-0.021 [-0.134, 0.092]	0.713
	Sex			0.593 [-2.016, 3.202]	0.649
	IPAQ			-0.431 [-1.858, 0.996]	0.546

BMI: Body mass index, CI: confidence interval, Coeff: coefficient, FSF: fat signal fraction, kPa: kilo pascal, MF: multifidus, SWE: shear wave elastography, Th: thickness. * = significant outcome

Table 5 Results of multivariable regression analyses between MF %FSF and function (MF Th ratio) while controlling for covariates identified in the bivariate analyses. ($N=50$)

Analysis	Variables	Adjusted R2	R2 Change significance	Coeff (95%CI)	*P*-value
Outcome variable	MF Th ratio at L4/L5				
Model 1 (covariates)	L4/L5 MF % FSF	0.161	0.266	0.261 [-0.201, 0.723]	0.261
	Age			-0.052 [-0.307,0.203]	0.683
	Sex			-3.682 [-9.1, 1.736]	0.178
	BMI			-0.859 [-1.504, -0.213]	0.01*
	LBP status			-4.616 [-8.992, -0.024]	0.039*
	IPAQ level			0.032 [-2.698, 2.761]	0.981
Outcome variable	MF Th ratio at L5/S1				
Model 2 (covariates)	L5/S1% MF FSF	0.032	0.133	0.182 [-0.131,0.495]	0.247
	Age			0.053 [-0.18,0.286]	0.649
	Sex			-3.3 [-8.66, 2.061]	0.221
	BMI			-0.618 [-1.273,0.036]	0.063
	IPAQ level			-1.479 [-4.237,1.278]	0.285

BMI: Body mass index, CI: confidence interval, Coeff: coefficient, FSF: fat signal fraction, MF: multifidus, SWE: shear wave elastography, Th: thickness. * = significant outcome

Relationship between MF fat infiltration and muscle function (MF SWE)

Although we hypothesized that morphological and mechanical properties of the MF muscle would be associated with chronic LBP at both the L4/L5 and L5/S1 levels, our findings only partially support this hypothesis, revealing a positive association between MF fat infiltration and both resting SWE and the contraction ratio measures of the MF muscle SWE at L4/L5. This suggests that greater fat infiltration is associated with increased passive and active MF muscle stiffness. Clinically, this may indicate that higher fat levels and connective tissue in the MF muscle contribute

Table 6 Between groups comparison for lumbar MF function

Variables	Controls mean (SD)	LBP mean (SD)	*P*-value
MF Th ratio			
L4L5	22.62 (8.52)	17.28 (6.72)	0.017*
L5S1	12.93 (8.52)	12.41 (6.69)	0.812
MF SWE rest (kPa)			
L4L5	13.38 (4.07)	12.5 (4.37)	0.467
L5S1	13.19 (3.74)	13.23 (4.04)	0.967
MF SWE contraction (kPa)			
L4L5	43.28 (13.94)	52.11 (13.89)	0.03*
L5S1	42.78 (16.17)	53.91 (15.65)	0.017*
MF SWE contraction ratio			
L4L5	0.36 (0.22)	0.25 (0.1)	0.041*
L5S1	0.44 (0.47)	0.26 (0.1)	0.073

kPa: kilo pascal, MF: multifidus, SD: standard deviation, SWE: shear wave elastography, Th: thickness

to stiffness-related issues, potentially affecting movement, flexibility, and stability.

Significant associations were observed at L4/L5, but not at L5/S1. One possible explanation for this discrepancy lies in the biomechanical and anatomical differences between these spinal levels. The L4/L5 segment typically undergoes greater motion and mechanical loading during daily activities, which may result in more pronounced changes in muscle structure and stiffness. Conversely, the L5/S1 level may be more susceptible to degenerative changes or anatomical variations, such as lumbosacral transitional vertebrae, potentially obscuring associations with muscle properties. These factors could help explain why associations were more apparent at L4/L5 and absent at L5/S1.

Low back pain has been linked to MF fatty degeneration, with affected individuals showing MF atrophy, intramuscular fat invasion, and reduced function [16]. While some studies found no association between MF fat infiltration and thickness change during contraction [17, 24], they did not report contraction-specific data, limiting direct comparisons with our findings. Other measures, such as stiffness, strength, and endurance, could provide stronger associations. Indeed, SWE is a valuable tool to assess muscle function, as shear modulus changes proportionally to muscle force [21]. Increased stiffness in LBP patients may result from muscle spasm induced by pain and stress on intervertebral structures [21]. Chronic overuse of stiffened MF muscles could impair circulation and contribute to secondary LBP [1, 21, 30]. Animal studies further suggest that fat and connective tissue contribute to increased shear modulus in LBP patients [31]., aligning with our findings.

Differences in MF SWE between group

Participants with LBP exhibited a significantly lower contraction ratio at L4–L5, which may reflect reduced muscular stiffness increase during contraction [16]. Since the contraction ratio precisely reflects stiffness variations and force generation [21], it serves as a useful metric for comparing muscular stiffness across conditions. This finding aligns with previous research showing segment-specific changes in lumbar MF in LBP patients [21].

Murillo et al. [21] also reported increased passive stiffness in the superficial MF and reduced stiffening during isometric trunk extension in LBP patients. Differences in shear elastic modulus between LBP and asymptomatic individuals likely reflect variations in muscle composition, as passive stiffness is influenced by more than just contractile tissue [15]. Consistent with our results, studies have also found reduced active stiffness in deeper neck muscles during isometric extension in individuals with neck pain [32] and decreased MF activation during trunk extension in those with LBP [33, 34].

The lower contraction-induced stiffness in LBP patients may be due to fibrotic collagen proliferation and increased connective tissue, leading to reduced contractile tissue and impaired muscle function [21].While this study contributes to existing evidence, no significant difference in SWE at rest was observed between participants with and without LBP. Further research is needed to clarify these findings and refine clinical implications. In contrast, Masaki et al. [30] reported greater MF shear elastic modulus at rest in LBP patients, whereas Chan et al. [35] found no group differences at the same spinal level. Differences in study populations may explain these discrepancies, as Masaki et al. [30] included only young and middle-aged medical workers, whereas our sample ranged from 21 to 61 years with diverse occupations. Additionally, unlike our study, Masaki et al. [30] did not match groups for age and sex. The discrepancy between our findings and those of Masaki et al. [29], who reported higher MF stiffness at rest in individuals with LBP, may stem from methodological differences. Masaki et al. used a linear transducer operating at 10 MHz in a sitting posture, while our study used a curvilinear probe at 5 MHz with participants in the prone position. Probe frequency and positioning can substantially influence SWE values due to differences in depth penetration, muscle tension, and contact pressure. Furthermore, their sample consisted of young and middle-aged healthcare workers, a more homogeneous occupational group as compared to our general population, which included adults from 21 to 61 years old with varied activity levels. Similarly, Chan et al. [34] used dynamic positional changes to assess stiffness, whereas our study assessed stiffness at rest and during static contraction. These differences in protocol design, probe selection, and postural context likely contributed to the divergence in findings.

Despite expectations that LBP patients would engage in less physical activity, no significant differences in BMI or

IPAQ scores were found between groups. This could be due to sample homogeneity and self-report biases in IPAQ data. Future studies should use objective activity measures and larger cohorts to better assess these relationships.

This study has several limitations. First, lumbar MF assessment was limited to the L4/L5 and L5/S1 levels, which are clinically relevant in LBP, but the anatomy at L5/S1 can vary due to transitional lumbosacral anatomy, potentially affecting measurements. Second, while individuals with lower back-specific training were excluded, broader exercise habits and activity levels were only controlled via self-reported IPAQ data. Third, the study did not include non-BMI-related body composition measurements, such as bioelectrical impedance analysis or DEXA, which could offer further understanding of how body composition influences MF function and fat infiltration. Fourth, while the sample size was determined using prior data, the variability in MF measurements and the multifactorial nature of LBP may raise concerns about sufficient power to detect subtle relationships. Future studies should include larger and more diverse samples. Fifth, biomechanical factors like posture, movement patterns, and occupational demands were not considered, although they are known to affect lumbar MF function and stiffness. Including these variables in future studies will help provide a more comprehensive understanding of the structure-function relationship in the MF and its role in LBP. Finally, our regression models included group status as a covariate but did not test for interaction terms (e.g., FSF × group), assuming homogeneity of associations across individuals with and without LBP. Conducting a stratified analyses could have offered additional insights. Given known pathophysiological differences between these populations, stratified analyses or interaction testing might have yielded additional insights. Future studies should explore these interactions to better understand group-specific relationships between MF composition and function.

Conclusion

This study identified a limited association between lumbar MF fat infiltration and muscle function. While MF thickness ratio was not related to fat content, SWE-based measures of stiffness at L4/L5 were positively associated with fat infiltration, suggesting potential alterations in muscle mechanical properties. Individuals with chronic low back pain exhibited a smaller increase in muscle stiffness during contraction at L4/L5, which may reflect reduced activation capacity. These findings support the utility of SWE as a complementary tool to traditional morphological assessments and highlight segment-specific changes in MF properties in chronic low back pain. Furthermore, rehabilitation strategies that target both the structural integrity and neuromuscular function of the MF muscle (e.g., motor control training, targeted strengthening, or neuromuscular stimulation) may be warranted and should be explored in future research.

Author contributions N.N. participated in the research design, planned the statistical analyses, recruited the participants, collected the data, analyzed the results, and wrote the manuscript. S.M. and C.B. participated in the MRI and ultrasound lumbar muscle measurements. B.R. contributed to the recruitment and data collection. J.CA., H.R., and M.R. contributed to the conception, design, and editing of the manuscript. M.F. contributed significantly to the conception, design, data collection, analysis, revision, and editing of the manuscript. All authors read and approved the final manuscript.

Data availability All extracted data are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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