The relationship between clinical examination measures and ultrasound measures of fascia thickness surrounding trunk muscles or lumbar multifidus fatty infiltrations: An exploratory study.

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ABSTRACT

Patients with chronic low back pain (CLBP) exhibit remodeling of the lumbar soft tissues such as muscle fatty infiltrations (MFI) and fibrosis of the lumbar multifidus (LuM) muscles, thickness changes of the thoracolumbar fascia (TLF) and perimuscular connective tissues (PMCT) surrounding the abdominal lateral wall muscles. Rehabilitative ultrasound imaging (RUSI) parameters such as thickness and echogenicity are sensitive to this remodeling. This experimental laboratory study aimed to explore whether these RUSI parameters (LuM echogenicity and fascia thicknesses), hereafter called dependent variables (DV) were linked to independent variables (IV) such as (1) other RUSI parameters (trunk muscle thickness and activation) and (2) physical and psychological measures.

RUSI measures, as well as a clinical examination comprising physical tests and psychological questionnaires, were collected from 70 participants with LBP. The following RUSI dependent variables (RUSI-DV), measures of passive tissues were performed bilaterally: (1) LuM echogenicity (MFI/fibrosis) at three vertebral levels (L3/L4, L4/L5 and L5/S1); (2) TLF posterior layer thickness, and (3) PMCT thickness of the fasciae between subcutaneous tissue thickness (STT) and external oblique ($PMCT_{STT/EO}$), between external and internal oblique ($PMCT_{EO/IO}$), between IO and transversus abdominis ($PMCT_{IO/TrA}$) and between TrA and intra-abdominal content ($PMCT_{TrA/IA}$). RUSI measures of trunk muscle's function (thickness and activation), also called measures of active muscle tissues, were considered as independent variables (RUSI-IV), along with physical tests related to lumbar stability (n = 6), motor control deficits (n = 7), trunk muscle endurance (n = 4), physical performance (n = 4), lumbar posture (n = 2), and range of motion (ROM) tests (n = 6). Psychosocial measures included pain catastrophizing, fear-avoidance beliefs, psychological distress, illness perceptions and concepts related to adherence to a home-based exercise program (physical activity level, self-efficacy, social support, outcome expectations). Six multivariate regression models (forward stepwise selection) were generated, using RUSI-DV measures as dependent variables and RUSI-IV/physical/psychosocial measures as independent variables (predictors).

The six multivariate models included three to five predictors, explaining 63% of total LuM echogenicity variance, between 41 and 46% of trunk superficial fasciae variance (TLF, $PMCT_{STT/EO}$) and between 28 and 37% of deeper abdominal wall fasciae variance ($PMCT_{EO/IO}$,

$PMCT_{IO/TrA}$ and $PMCT_{TrA/IA}$). These variables were from RUSI-IV (LuM thickness at rest, activation of IO and TrA), body composition (percent fat) and clinical physical examination (lumbar and pelvis flexion ROM, aberrant movements, passive and active straight-leg raise, loaded-reach test) from the biological domain, as well as from the lifestyle (physical activity level during sports), psychological (psychological distress – cognitive subscale, fear-avoidance beliefs during physical activities, self-efficacy to exercise) and social (family support to exercise) domains.

Biological, psychological, social and lifestyle factors each accounted for substantial variance in RUSI-passive parameters. These findings are in keeping with a conceptual link between tissue remodelling and factors such as local and systemic inflammation. Possible explanations are discussed, in keeping with the hypothesis-generating nature of this study (exploratory). However, to impact clinical practice, further research is needed to determine if the most plausible predictors of trunk fasciae thickness and LuM fatty infiltrations have an effect on these parameters.

Keywords: (5): Multifidus fatty infiltration; perimuscular connective tissues; fascia; low back pain; rehabilitative ultrasound imaging; modifiable factors; physical and psychological clinical examination.

1. INTRODUCTION

A reliable pathoanatomical diagnosis (injured ligament, disc, muscle, etc.) is currently not possible in more than 90% of patients with LBP (Koes et al., 2006). However, inflammatory-related biomarkers substantiate the presence of an initial injury, regardless of the tissue origin. These biomarkers include muscle fatty infiltrations (MFI), fibrosis of the lumbar multifidus (LuM) muscles (Hodges and Danneels, 2019), and remodeling of fasciae surrounding the LuM (Langevin et al., 2009) and abdominal muscles (Whittaker et al., 2013). While more specific and precise imaging approaches exist to measure these changes, along with more invasive methods, it appears that some rehabilitative ultrasound imaging (RUSI) parameters may be sensitive enough to detect these remodeling processes (Langevin et al., 2009, Whittaker et al., 2013, Young et al., 2015).

RUSI echogenicity is affected by MFI (Reimers et al., 1993) and fibrous content (Arts et al., 2012, Pillen et al., 2009). As for all imaging techniques, however, it cannot differentiate between the two. RUSI can also measure the thickness of the thoracolumbar fascia (TLF) and perimuscular connective tissues (PMCT), or fasciae, surrounding the muscles of the lateral abdominal wall: external oblique (EO), internal oblique (IO), transversus abdominis (TrA). Our research group has initiated a series of studies to substantiate the usefulness of these RUSI parameters.

In the initial study, we tested 30 healthy and 34 participants with chronic low back pain (CLBP) in order to make between-group comparisons and determine the sensitivity of the RUSI measures to known determinants such as age, sex, vertebral level and body fat (Lariviere et al., 2020a). The corresponding results, in addition to the aforementioned findings from other groups, prompted testing of the reliability of these relatively “new” RUSI parameters (Lariviere et al., 2021a). Other reliability studies support the intra- and interrater reliability of these RUSI parameters, including LuM echogenicity (Farragher et al., 2021, Resende et al., 2021) and TLF (Almazan-Polo et al., 2020) and lateral abdominal wall fasciae (Pirri et al., 2019) thicknesses.

To further explore the relevance of these RUSI parameters, we investigated their main known determinants: age, sex, the presence of LBP, body size/composition characteristics (height, weight, trunk length, subcutaneous tissue thickness over the abdominal and LuM muscles), trunk muscle function or activation (RUSI measures of percent thickness change of LuM, EO, IO, and TrA muscles during a standardized effort), and physical activity level during sport and leisure activities (self-report questionnaire) (Lariviere et al., 2021b). Using multivariate regression, with expected

interactions, the link between trunk muscle thickness and activation, abdominal PMCT and TLF thicknesses, and LuM fatty infiltrations (ultrasound image echogenicity) was tested. We demonstrated that determinants such as subcutaneous adipose tissue deposits explain more of the variance in lumbar soft tissue remodelling than body size characteristics, age, sex, or pain status. Modifiable factors, such as physical activity level and trunk muscle thickness and function were also involved, suggesting that rehabilitation can potentially impact tissue remodeling.

Different rehabilitation treatments may help remodeling the LuM, TLF and lateral abdominal wall PMCT. The aim of the present study was to explore the baseline link between the corresponding RUSI measures and some modifiable physical, psychological, social and lifestyle variables that can be assessed during the clinical exam in participants with CLBP. In other words, if these modifiable variables from different domains are correlated to RUSI measures, they may become the target of different clinical interventions. These clinical exam measures were collected in our previous sample of participants with CLBP (Lariviere et al., 2021a). The sample size has been further increased to allow multivariate analyses.

2. METHODS

2.1 Design of the study and sample size justification

This is an experimental and cross-sectional correlational study conducted in a laboratory setting. This study is part of a larger study (Larivière et al., 2022b) which aimed to derive clinical prediction rules of success (n = 110 participants) following an 8-week lumbar stabilization exercise program (LSEP). Briefly, physical tests from clinical examination and questionnaires were administered before and after the LSEP in all 110 participants, while laboratory-based neuromuscular tests (including the RUSI tests performed first) were performed in a subsample of participants (n = 70, as described in the next section) on another day in the same week. These laboratory-based neuromuscular tests aimed at assessing the action mechanisms that would explain why some patients have success and others not. It was estimated that approximately 30 participants in each subgroup of patients would be sufficient to conduct two-way ANOVAs (2 SUBGROUPS × 2 TIMES), requiring to recruit up to 73 participants, considering other issues, as detailed elsewhere (Larivière et al., 2022a). The current study used data collected at baseline only as there was no treatment (or time) effect on any RUSI parameters of interest (LuM echogenicity, TLF and abdominal PMCT thicknesses). As further explained in the statistical analyses section, this correlational study, using multivariate analyses, limited the number of independent variables introduced in the different regression models to account for the limited sample size.

2.2 Participants

Subjects between 18 and 65 years old were recruited through newspaper advertisements and from physiotherapy clinics in Montreal, Quebec, Canada. A preliminary (phase 1) study was conducted from July 2012 to August 2016, and a final (phase 2) study was conducted from July 2018 to October 2020.

The subjects' characteristics are described in Table 1. Participants with LBP had lumbar or lumbosacral pain for at least four weeks, with or without radicular pain, and a score on the Oswestry Disability Index (ODI) of at least 12 percent. Exclusion criteria were: pelvic or spinal column surgery; systemic or degenerative disease; scoliosis; known specific lumbar pathology; initiation of an exercise program in the last three months; pregnancy; or one positive neurological sign in two of three test categories: (a) reduced Achilles and patellar tendon reflexes; (b) reduced

strength in lumbosacral myotomes; (c) reduced sensation in lumbosacral dermatomes. As large amounts of subcutaneous tissue and fat can affect many of the neuromuscular tests, including the RUSI assessment, participants had to have a body mass index (BMI) ≤ 30 kg/m^2. This study was approved by the Centre for Interdisciplinary Research in Rehabilitation of Greater Montreal's ethics review board (CRIR-738-0512 and CRIR-1315-0318 for preliminary and final studies, respectively).

2.3 Clinical examination

To derive the clinical prediction rules (Larivière et al., 2022b) while reducing the likelihood of spurious findings (selection of a given predictor by chance), the potential predictors were selected according to (1) a sound theoretical rationale using well-known theoretical models and (2) the psychometric properties of the tests and questionnaires, more specifically with regard to interrater reliability for the physical tests. These modifiable variables cover different domains, namely biology (physical tests; RUSI muscle function variables as described in the next section), psychology (e.g., pain catastrophizing, psychological distress), social (family and friend support to exercise) and lifestyle (physical activity level) domains. Consequently, these modifiable variables appear well-suited to test the biopsychosocial conceptual model of Klyne et al. (2021). To avoid muscle fatigue during clinical examination, physical tests were separated by questionnaires. Tests are briefly (and broadly) identified below but are detailed and linked to relevant theoretical models in the **Supplementary material file**. The corresponding acronyms are described in the table of abbreviations.

The physical examination was conducted by a research-trained physical therapist (M.Sc.). Some anthropometric measures were carried out first to describe the participants (Table 1). The selected tests have acceptable interrater reliability [kappa > 0.6; intraclass correlation coefficients - ICC > 0.70; (Denteneer et al., 2017)], as detailed in the **Supplementary material file**. They also can be theoretically related to lumbar segmental instability (LSI) or motor control impairments (MCI) (Denteneer et al., 2017, Ferrari et al., 2015, Alqarni et al., 2011). Different dimensions were covered, namely LSI tests (n = 4), MCI tests (n = 7), posture and range of motion (ROM) tests (n = 6), trunk muscle endurance (TME) tests (n = 4) and physical performance tests (PPT) (n = 4). With respect to MCI tests, because the skills required to evaluate signs (alignment, movements) are relatively complicated and have debatable reliability, only symptoms caused by these tests

were examined (Van Dillen et al., 1998). For measures taken bilaterally (e.g., right and left lateral trunk flexion; left and right lower extremity measurements), only the measurements most associated with impairments were retained, namely the minimal ROM (exception: lateral trunk flexion) and TME scores, as well as the maximal scores during PPT (more time to produce movements) and MCI (symptom change: increase: 1, decrease: -1, the same: 0) tests.

The questionnaires included the brief STarT Back screening tool (Hill et al., 2008), variables from the fear-avoidance model (pain intensity, disability, pain catastrophizing, fear-avoidance beliefs, psychological distress, physical activity level), and variables theoretically related to home-exercise adherence (Hall et al., 2010, Jack et al., 2010, Beinart et al., 2013, Thompson et al., 2015) (pain during activity/exercise, self-efficacy for exercise, family or friend support to exercise and illness perception).

2.4 RUSI assessment

This section outlines methods published about (1) RUSI measures of active muscle tissues (RUSI-muscle), namely LuM, EO, IO and TrA thicknesses at rest and thickness percent change (or muscle activation) during standardized contractions (Lariviere et al., 2018a, Lariviere et al., 2018b) as well as (2) RUSI measures of passive tissues (RUSI-passive), namely LuM echogenicity, TLF and PMCT thicknesses (Lariviere et al., 2020a). For their definitions, please refer to the table of abbreviations. The different categories of RUSI parameters will play a different role in the statistical analyses described in the next section. RUSI-muscle parameters, namely muscle thickness at rest (R_{LuM}, R_{EO}, R_{IO}, R_{TrA}) and percent change of thickness, or activation, during the standardized tasks ($\%C_{LuM}$, $\%C_{EO}$, $\%C_{IO}$, $\%C_{TrA}$), were independent variables (IVs). RUSI-passive parameters ($ECHO_{LuM}$, TLF_{L45}, $PMCT_{EO/IO}$, $PMCT_{IO/TrA}$, $PMCT_{TrA/IA}$, $PMCT_{STT/EO}$), were dependent variables (DVs). The reader is referred to a review of validation studies (Koppenhaver et al., 2009) showing that the change of muscle thickness, as measured with RUSI, is correlated to the gold standard for measuring muscle activation (electromyography) during submaximal isometric contractions of different trunk muscles and as such, can be considered as a valid measure of muscle activation.

A laboratory session was performed with the following steps: (1) the participant was positioned on an exam table and a RUSI transducer was placed on the skin, as described below; (2) two

familiarization trials were completed, and (3) for each side (left before right), three 10-s videos were recorded, with about one minute of rest between trials.

A Phillips HD11 1.0.6 (Philips Medical Systems, Bothell, WA) ultrasound machine was used to image the lumbar spine structures (Figure 1) in a parasagittal plane using a 5-2 MHz curvilinear array transducer (model C5-2; 75° field of view; 6.5 cm footprint), while the PMCT of abdominal wall in the longitudinal plane was imaged (Figure 2) using a 12-5 MHz 50-mm linear array transducer (Model L12-5).

Images were collected on an exam table, with the subjects keeping their head straight and both legs extended, in supine (ventrolateral abdominal wall) and prone (dorsal soft tissues). A 10-s image recording was started at the end of an exhalation phase, starting 3 s before (at rest) and during an isometric standardized tasks to induce muscle activation (Lariviere et al., 2018a, Lariviere et al., 2018b). For each side of the dorsal trunk and of the ventrolateral abdomen, three 10-s ultrasound video clips were collected, with approximately one minute of rest between trials.

LuM echogenicity measures quantifying LuM muscle fatty infiltrations and fibrosis required that all settings of the ultrasound scanner were unchanged (gain: 70; depth: 8 cm) across participants and trials (Molinari et al., 2015). Echogenicity (ECHO) parameters were calibrated for the subcutaneous tissue thickness (in mm) overlying the LuM (STTL45; Figure 1), following this equation (Young et al., 2015):

$$ECHOcorrected = ECHO + (STT_{L45} \times 4.05278)$$

This calibration equation has been shown to increase the association between ECHO and intramuscular percent fat as determined using magnetic resonance imaging (Young et al., 2015).

2.5 Statistical analyses

All statistical analyses were done with NCSS 2019 software (version 19.0.3 for Windows), using a significance level (alpha) of 0.05. Some variables showed abnormal distributions, so all continuous variables were transformed (Van Albada and Robinson, 2007) to obtain normal distributions.

To reduce the number of independent (IV) and dependent variables (DV) in multivariate analyses, new RUSI variables were generated through principal component analysis (PCA), using a scale-

invariant correlation matrix as well as Varimax rotation. Using PC scores also likely filters-out some noise from the RUSI measures. The six ECHO parameters (3 vertebral levels × 2 sides) were aggregated in a single variable ($ECHO_{LuM}$), generating their common factor scores. The same was performed for the six LuM muscle thickness parameters (leading to the variables R_{LuM} and $\%C_{LuM}$) as well as all remaining RUSI measures collected bilaterally. Except for three RUSI parameters (detailed below), these factor scores showed high correlations with the individual RUSI parameters (r range: 0.80 to 0.98; $P < 0.001$) and, consequently, captured the same constructs. The corresponding correlations were slightly lower for $PMCT_{IO/TrA}$ bilaterally (r: 0.73 to 0.82; $P < 0.001$) and $PMCT_{TrA/IA}$ bilaterally (r: 0.61 to 0.76; $P < 0.001$), but not satisfactory for $\%C_{TrA}$ bilaterally (r: 0.20 to 0.54; P: 0.125 to < 0.001). The latter may relate to $\%C_{TrA}$ (left side) not being a reliable measure (Lariviere et al., 2019). Preliminary analyses showed that approximately the same IVs predicted ECHO variables at different vertebral levels, justifying merging the data from vertebral levels through PCA. Merging RUSI LuM of the three vertebral levels (R_{LuM}, $\%C_{LuM}$) also more consistently involved R_{LuM} as a predictor of different DVs, although less so after considering covariates in the multivariate models.

Before performing forward stepwise regression models, a preliminary step was conducted to identify potential covariates. Consensus-based recommendations of confounding variables of MFI (RUSI ECHO variable here) are age, sex, body composition, physical activity and pain duration (Hodges et al., 2021). Only age and sex were retained as covariates whereas body composition and physical activity (PAL-sport and PAL-leisure here) were considered as modifiable IVs, in line with the aim of the present study. Body composition was represented by the percent body fat (%Fat) as it is more specific to body fatness than the body mass index (BMI); their Pearson's correlation was only 0.50, $P < 0.001$, revealing that they do not measure exactly the same concept. Pain duration did not meet the definition of a covariate as it must be associated with the IV and with the DV, but cannot be affected (i.e. caused) by the IV (Shrier and Platt, 2008), which was potentially the case for some IVs (e.g., muscle thickness). Potential covariates of fascia thickness included age, sex, and weight (Lariviere et al., 2021b). For each dependent variable, age, sex, and weight were introduced in a multivariate regression model to identify which ones were influential, as detailed in Table 2. Only the statistically significant covariates were entered in the respective multivariate regression model to compute the residuals, the latter being considered as DVs in the next step (forward stepwise procedure).

Given that this study is exploratory, Pearson's correlations ≥ 0.25 ($P < 0.05$) were reported to get an overall appraisal of the relationships between the different DVs (RUSI-passive parameters) and IVs (RUSI-muscle parameters, clinical examination variables). The complete list of IVs and DVs is provided in the table of abbreviations.

As a final step, each dependent variable (PCA-based RUSI-passive parameters) was regressed using a forward stepwise procedure called "subset selection in multiple regression", with the option "hierarchical forward selection with switching" in NCSS. Only one-way models were explored. This statistical procedure does not use stopping rules based on *P* values to select the final number of predictors, so we started with a given number of predictors and verified if they were all significant. Sample size issues guided the number of IVs included in each regression model to avoid over-fitting data with the use of noisy parameters, using the "events-per-variable" rule of thumb that requires at least 10 subjects per predictor in the model (Prescott, 2019). Although the initial sample size was 70 participants, some RUSI variables were missing for some subjects, leading to 54 participants having a full set of data for multivariate analyses. A maximum of five IVs were consequently initially included in the models. Then, if the corresponding ANOVA results indicated that at least one parameter was not statistically significant ($P \geq 0.05$), the multiple regression analysis was repeated with one less IV until all IVs were statistically significant. The presence of multicollinearity was determined with a variance inflator factor (VIF) greater than 10. Residuals were inspected to make sure they were normally distributed and did not suggest the presence of non-linearity or outliers.

3. RESULTS

Considering the number of DVs and IVs, two strategies were used to present and interpret the findings in a structured manner. The DVs were separated in three categories (1. LuM echogenicity; 2. thoracolumbar fascia; 3. abdominal wall fasciae) while the IVs were separated in four domains (1. biological; 2. psychological; 3. social; 4. lifestyle).

Pearson's correlation between RUSI-passive parameters (DVs) and the IVs are presented in Table 3. Several significant correlations (≥ 0.25 or ≤ -0.25; $P < 0.05$) were found, but all except one were small, ranging between .25 and .42, the exception ($r = .58$) linking lumbar flexion ROM (LumbFlx-ROM) to $ECHO_{LuM}$. While variables from the biological, psychological and lifestyle domains were represented, the social domain was not. However, all IVs were considered in multivariate analyses as interactions may highlight the contributions of IVs not identified in Table 3. Interestingly, none of the RUSI-passive parameters (DVs) were significantly correlated with disability (ODI) or pain intensity (NPRS), which are common clinical descriptors for LBP.

Preliminary multivariate analyses often revealed multicollinearity problems with MCI tests (binary variables; not ROM continuous variables) so they were excluded from the final multivariate analyses. Every multivariate model showed normally distributed residuals and a VIF lower than 2.2, definitively excluding any multicollinearity issues.

The multivariate models are detailed in Table 4. As summarized in Table 5, various biological, psychological, social and lifestyle variables accounted for up to 63% of total $ECHO_{LuM}$ variance, 41% of TLF_{L45} variance and between 28 and 46% of abdominal wall fasciae variance ($PMCT_{STT/EO}$, $PMCT_{EO/IO}$, $PMCT_{IO/TrA}$ and $PMCT_{TrA/IA}$). As detailed in Table 4, these IVs included RUSI-muscle parameters (R_{LuM}, $\%C_{IO}$, $\%C_{TrA}$), body composition (%Fat), clinical physical examination (lumbar and pelvis flexion ROM, aberrant movements, measures from passive and active straight-leg raise, NPPT-Reach), physical activity level (PAL-sport) and psychosocial (PDIcog, FABQ-AP, BarriersSES, family social support to exercise) measures. Each of these relationships will be elaborated on in more detail in the Discussion where we provide a plausible interpretation and also generate additional hypotheses.

4. DISCUSSION

Variables from different domains (biological, psychological, social and lifestyle) accounted for a substantial proportion of variance of RUSI-passive parameters (muscle echogenicity, fascial thickness) that are known to be impacted by structural remodeling. These preliminary findings may have implications for rehabilitation. Interestingly, a conceptual model of factors that can potentially impact such tissue remodeling has recently been proposed to explain connective tissue remodeling, namely intra and extra-muscular fascia fibrosis (Klyne et al., 2021). The model explains the role of local and systemic inflammatory processes and their reciprocal influence, which in turn are impacted by local (e.g., tissue damage / pathology) and systemic (e.g., psychosocial and lifestyle) factors. This biopsychosocial conceptual model may at least partly apply to MFI as inflammatory processes impact connective tissues (e.g., fasciae) and MFI simultaneously (Zugel et al., 2018). It also implies the coordinated involvement of different rehabilitation disciplines such as neuroscience (neurally mediated effects on pain processes), physical therapy/rehabilitation (behavior and muscle activity), orthopedics (tissue structure), and rheumatology (inflammatory processes), as suggested by Langevin (2021). The present findings provide some preliminary support to the idea that tissue remodelling may be influenced by this complex interaction. However, the multivariate models generated are difficult to explain and, as such, the present results should be viewed as a hypothesis generation exercise.

Multiple regression statistical modeling is a delicate task (Heinze et al., 2018). Even if distributions normality, multicollinearity and residual issues have been scrutinized and potential covariates (age, sex, weight) have been accounted for, alternative models can always be generated. This research domain is relatively new, so a sound foundation of a theoretical model, allowing to infer cause and effect, as well as potential covariates (Shrier and Platt, 2008), is lacking. This motivated the present exploratory study (or hypothesis-generating study). The reader is invited to closely examine Pearson's correlations between IVs and DVs (Table 3) to identify other potential predictors. In one case ($PMCT_{TrA/IA}$), it can even be observed that none of the correlated IVs were retained in the final multiple regression model (Table 4). All except one variable accounted for at least 5% of the dependent variable variance (≥ 5% VAF), which may represent a minimal threshold for clinical significance, considering that inherent measurement errors (noise) have likely lowered their predictive value. Fortunately, as discussed below, even if several potential predictors were

available, some variables were selected in several models (e.g., R_{LuM}, PAL-sport, SSES-FamPa), which suggest that these variables may give some insights with regard to rehabilitation interventions.

4.1. LuM echogenicity

Five parameters accounted for 63% of echogenicity ($ECHO_{LuM}$) variance, three from the biological (R_{LuM}, LumbFlx-ROM, PelvisFlx-ROM), one from the psychological (PDIcog) and one (PAL-sport) from the lifestyle domain.

Interestingly, overall trunk flexion ROM is linked to $ECHO_{LuM}$, as LumbFlx-ROM (17% VAF) and PelvisFlx-ROM (12% VAF), two uncorrelated variables ($r = 0.09$; $P = 0.418$), were included in the model. $ECHO_{LuM}$ cannot differentiate MFI from fibrosis but considering the positive relationship between $ECHO_{LuM}$ and lumbar ROM (from Table 4 regression coefficients and Table 3 correlations) only an increased LuM MFI (not increased fibrosis) would be associated with an increased lumbar flexion ROM. Fibrosis would have produced the opposite relationship, as it has been shown to increase muscle stiffness (Brown et al., 2011). More LuM MFI would theoretically decrease muscle stiffness and increase lumbar ROM. This explanation might appear counter-intuitive at first sight as patients with LBP generally show a decreased lumbar flexion ROM relative to healthy controls (Laird et al., 2019, Wong and Lee, 2004, Lariviere et al., 2000, Shahvarpour et al., 2017). However, central mechanisms such as modified motor control, disuse/unloading or inflammation (Hodges et al., 2021), inducing MFI in the subacute and chronic phases (Hodges and Danneels, 2019), may produce increased lumbar ROM if the patients are free of guarding behaviors at the time of clinical examination.

Why was pelvis flexion ROM also involved in the present regression model? Again, only LuM MFI (not fibrosis) would explain the positive relationship with $ECHO_{LuM}$, as an increased MFI in the posterior vertebral muscles (erector spinae + LuM) has been associated with pelvic retroversion (Elysee et al., 2021, Lee et al., 2022, Zhang et al., 2021). However, MFI in LuM was not enough to induce a change in pelvic inclination in 93 healthy controls (Menezes-Reis et al., 2018), which was later confirmed in a study showing a relationship with the erector spinae MFI but not LuM MFI in participants with spinal deformity (Miura et al., 2021). This could suggest that the participants of the present study may also have erector spinae MFI. This question needs further investigation, specifically in participants with CLBP without spinal deformity. Such an initial

retroversion posture of the pelvis, explained by an inability of the lumbar extensors to maintain lordosis and its associated pelvic anteversion (Takaki et al., 2016, Beneck et al., 2016), allows for a greater ROM of the pelvis during flexion (pelvis may finish at the same maximal flexion angle but starts more backward when the trunk is at vertical, leading to an increased ROM).

LuM thickness at rest (R_{LuM}) was the best predictor (19% VAF) of $ECHO_{LuM}$, the positive regression coefficient suggesting that R_{LuM} increases as $ECHO_{LuM}$ increases. An inverse compensatory relationship between stiffness of the spine and stiffness of its surrounding muscles has been shown (Gsell et al., 2017). This means that if LuM MFI decreases lumbar stiffness, it might be compensated for -by an increase in muscle stiffness (or muscle volume), as measured by R_{LuM}.

PDIcog or cognitive problems (concentration, memory, making decision), as measured with the PDI (psychological distress inventory), accounted for 8% of $ECHO_{LuM}$ variance. Taking for granted that it is more likely that PDIcog impacts $ECHO_{LuM}$ rather than the opposite, the negative regression coefficient would suggest that more cognitive problems would decrease $ECHO_{LuM}$ (less MFI or fibrosis), which is difficult to explain. Research on back pain and even more broadly on musculoskeletal disorders do not measure this concept. Interestingly, decline in working memory is detrimental to motor control, possibly increasing the likelihood of injuries (Avedesian et al., 2022). However, the present findings (negative regression coefficient) do not support this hypothesis.

Finally, PAL-sport accounted for 7% of $ECHO_{LuM}$ variance, the negative regression coefficient suggesting that less physical activity during sports would increase $ECHO_{LuM}$ (more MFI or fibrosis). A lower level of physical activity has already been associated with LuM MFI after adjusting for confounding variables (Teichtahl et al., 2015). However, as a rehabilitation professional, the question that needs to be addressed is which type of exercise (general vs LuM isolated exercises) is more likely to reduce LuM MFI. With regard to general exercises (aerobic, resistance or combined training), one systematic review and meta-analysis was conducted in adults with different chronic diseases, affecting different muscles (Tuñón-Suárez et al., 2021). The authors concluded that aerobic and combined training of moderate intensity reduce MFI and that this effect is associated with exercise-induced body weight and fat mass losses. In other words, at least a part of LuM MFI is related to body composition, which in turn can be modified through

aerobic exercises. It has been suggested, as a concluding remark of another review also looking at different chronic diseases (affecting different muscles), that at least 12 weeks of exercise would be required to decrease MFI (Addison et al., 2014). However, LuM MFI due to factors other than disuse/unloading or inflammatory mechanisms, namely modified motor control, may be addressed better by LuM activation using isolated exercises (Hodges et al., 2021). Some training modalities show promise: (1) lumbar stabilization exercises including isolated motor control training, (2) isolated lumbar strengthening exercises using a device restraining pelvis motion and allowing the positioning of lower limbs to lengthen hip extensor muscles (Steele et al., 2015), which favors the activation and fatigue of lumbar extensors comparatively to hip extensor muscles (da Silva et al., 2009, Lariviere et al., 2010) and (3) the Functional Re-adaptive Exercise Device (FRED), which is similar to an elliptical trainer but offers little resistance to lower limb movement, which induces tonic LuM activation (Weber et al., 2017, Caplan et al., 2014, Debuse et al., 2013). To the authors' knowledge, only case or uncontrolled preliminary studies, with few participants, have been conducted to study the effect of motor control exercises (Woodham et al., 2014) and isolated lumbar strengthening (Mooney et al., 1997, Berry et al., 2019) on LuM MFI, with inconsistent findings. Interestingly, the FRED has been shown to increase LuM cross-sectional area in a proof-of-concept study but, unfortunately, MFI was not assessed (Lindsay et al., 2020). Another study warranting attention showed decreased LuM MFI following a 16-week free-weight-based resistance training program where emphasis was placed on maintaining a neutral lumbopelvic position during each exercise (Welch et al., 2015), which may provide some isolated activation of the LuM. Future sufficiently powered randomized controlled trials (Fortin et al., 2021) should clarify whether such isolated exercise modalities can reduce LuM MFI.

4.2. Thoracolumbar fascia thickness

Four parameters accounted for 41% of TLF_{L45} variance, three from the biological (%Fat, $\%C_{IO}$, Abe-Mvt) and one from the psychological (FABQ-AP) domain.

A body composition parameter (%Fat) was the best predictor (14% VAF), which concurs with our previous study (Lariviere et al., 2021b), showing that the RUSI measure of subcutaneous tissue thickness overlying this fascia explained 15% of TLF_{L45} variance. It appears that fatty infiltrations can invade the TLF, making its architecture look more disorganized (De Coninck, 2018, Langevin et al., 2009) and the TLF thicker (Bishop et al., 2016, Langevin et al., 2009). This might be due to

local injury of the TLF (Bishop et al., 2016), triggering inflammation in the fasciae and its remodeling (Zugel et al., 2018), as this is the case for MFI (Hodges et al., 2021). If so, aerobic exercises may help, as this is the case for MFI (Tuñón-Suárez et al., 2021). From a mechanical perspective, having fatty infiltration of the TLF may alter its elastic modulus, or ability to extend under a certain load, and thus have an important role in local load allocation (Newell and Driscoll, 2021a, Newell and Driscoll, 2021b). In Zugel et al. (2018)'s consensus statement on PMCT research, researchers emphasized the need "to gain a deeper understanding of the mechanisms underlying the impact of treatments on fibrosis and fatty changes in fascial tissues", referring to exercise, physical therapies, or pharmacological approaches.

The activation of the internal oblique ($\%C_{IO}$) further explained 11% of TLF_{L45} variance. The co-dependent mechanism described by Vleeming et al. (2014) may be involved, which require a balanced tension between paraspinals by way of pressurization and deep abdominal muscles (IO and TrA), applying forces to the TLF through their aponeurotic portions. These muscle forces are converted to a bio-chemical response likely generating TLF and abdominal PMCT remodeling (Driscoll and Blyum, 2011). More specifically, the posterior portion of the TLF measured here is tensioned partially by LuM expansion (contraction) and by contracting deep abdominal muscles, which apply forces to the posterior TLF through their aponeurotic portions. When this mechanical homeostasis is disturbed by improper trunk muscle activation imbalance (Driscoll and Blyum, 2011), motor control exercises (Richardson et al., 2004) may potentially help.

The presence of aberrant movements was linked with an increased TLF thickness, explaining 8% of its variance. Whether aberrant movements are the cause or the effect of TLF thickness increase is unknown, which makes difficult to identify the most effective interventions. Aberrant movements are lumbopelvic coordination patterns that deviate from the typical/normal pattern. They are associated with low back disorders (Delitto et al., 1995) and more specifically, with patients thought to have movement coordination impairment, segmental hypermobility or clinical lumbar instability (Cook et al., 2006, Delitto et al., 2012, Rabin et al., 2013). Aberrant movements are associated with decreased control of lumbar segment mobility in the mid-range portion of the lumbar ROM, as demonstrated by a fluoroscopic study of flexion and extension movements in the sagittal plane (Teyhen et al., 2007). Furthermore, it was suggested that a synergistic pressurization of the intra-abdominal cavity and intra-muscular cavity, bounded by the posterior and midline TLF

and controlled by way of TrA/Obliques and spinal erectors and multifidus respectively, is important for adequately conveyed tension to the TLF without undesired translation of the lateral rathe (El-Monajjed and Driscoll, 2020, El-Monajjed and Driscoll, 2021). Aberrant movements would be non-synergistic, so to speak, and thus, one would lose the stabilizing mechanism and perhaps depend more on the passive tension in the TLF, which, in itself, is already important in healthy people (El Bojairami and Driscoll, 2022). Depending more on the passive tension of TFL would lead to an increase in thickness over time.

Finally, fear-avoidance beliefs about physical activity (FABQ-PA) explained 8% of TLF_{L45} variance. According to the fear-avoidance model (FAM), pain-related fears (fears of pain or movement) would affect participation in physical activities and, as such, would indirectly lead to disuse and disability (Vlaeyen and Linton, 2000). However, as introduced in Larsson et al. (2016), the link between pain-related fears and physical activity level is controversial in cross-sectional studies. The only longitudinal study, conducted in older adults with chronic pain, showed that kinesiophobia predicted physical activity at a 12-month follow-up, controlling for age and physical activity confounders at baseline; pain intensity did not enter in the regression model (Larsson et al., 2016). However, what about the effects on fasciae? Interestingly, inactivity triggers systemic and local inflammation, which in turn increases fascia fibrosis (Klyne et al., 2021). Although fibrosis might not change TLF_{L45} thickness, fatty infiltration generally accompany fibrosis, at least in back muscles (Hodges and Danneels, 2019, Zugel et al., 2018), which in turn may increase TLF thickness as shown in patients with CLBP (Langevin et al., 2009) and animal models simulating a TLF injury (Bishop et al., 2016).

4.3. Thickness of perimuscular connective tissues (fasciae) surrounding the lateral abdominal wall muscles

Across the four investigated fasciae surrounding the lateral abdominal wall muscles, three to five parameters accounted for 28 to 46% of their variance. As for LuM echogenicity and TLF thickness, biological, psychological and lifestyle domains were represented. Interestingly, the social domain was also consistently represented (in three out of four regression models).

Structural remodeling of PMCT (including the TLF) due to CLBP may lead to increased fascia thickness due to fatty infiltrations, which apparently affect more superficial fasciae such as TLF_{L45}

and $PMCT_{STT/EO}$ and to a much lesser extent $PMCT_{EO/IO}$, but not deeper fascia such as $PMCT_{IO/TrA}$ and $PMCT_{TrA/IA}$ (Lariviere et al., 2021b). The reader is asked not to confuse our way of classifying superficial and deep fasciae (in relation to the depth of the surrounded muscles), with the more classical way of classifying fasciae (Pirri et al., 2020). In fact, Pirri et al. (2020) describe the different layers of tissue separating the epidermis from the muscle (1. epidermis; 2. dermis; 3. superficial adipose tissue and retinacula cutis superficialis; 4. superficial fascia; 5. deep adipose tissue and retinacula cuti profunda; 6. deep fascia; 7. muscle), which also included a superficial and a deep fascia layer. Interestingly, their example was about tissues overlying a superficial muscle, which also included two layers of adipose tissues. However, it may also lead to decreased fascia thickness (less collagen material) due to overall disuse/unloading, or reflex inhibition of specific muscles (e.g., TrA), as observed for $PMCT_{IO/TrA}$ and $PMCT_{TrA/IA}$ of participants with CLBP comparatively to healthy controls (Lariviere et al., 2020a). The net effect of CLBP (increased vs. decreased thickness) might consequently be easier to predict for deeper fasciae than for superficial fasciae. Arguably, both those scenarios could reduce the stiffness and the passive modulus of these tissues. The regression coefficients in the different models will help understand how each predictor can affect PMCT thickness, as discussed below.

Overall, several influential IVs were concepts closely related to physical activity, namely social support from the family to exercise, barriers to self-efficacy for exercise and the physical activity level during sport activities. Social support from the family to exercise was involved in three regression models out of four with regard to PMCT surrounding the lateral abdominal wall muscles, namely for $PMCT_{STT/EO}$ (IV = SSES-FamPa for family participation; 20% VAF), $PMCT_{IO/TrA}$ (IV = SSES-FamRP for family rewards and punishments; 5% VAF) and $PMCT_{TrA/IA}$ (IV = SSES-FamRP; 9% VAF). This argues against a purely spurious finding. Moreover, the physical activity level (PAL-sport) was introduced in two of these models ($PMCT_{STT/EO}$; $PMCT_{IO/TrA}$), revealing that social support to exercise explained an independent portion of the DV variance. Most interestingly, these two IVs (SSES-FamPa; SSES-FamRP) were measured with the social support for exercise survey, tapping concepts from the social domain. The fact that this social construct was more predictive (19-20 %VAF) than physical activity level (5-9 %VAF) in these models was unexpected, which may question the validity (sensitivity) of the measures of physical activity level. Notwithstanding, the regression coefficients were positive in all cases, suggesting that decreased (or increased) family social support to exercise is associated with

decreased (or increased) fasciae thickness, as the opposite interpretation (fascia thickness impacting social support) is unlikely. Self-efficacy in overcoming barriers to exercise (BarriersSES), which is a concept from the psychological domain, accounted for 12% of $PMCT_{STT/EO}$ variance. The regression coefficient is also positive, suggesting that decreased self-efficacy to overcome barriers to exercise is associated with decreased fasciae thickness, as the opposite interpretation (fascia thickness impacting self-efficacy to overcome these barriers) is unlikely. In summary, increasing family social support (Collado-Mateo et al., 2021) and self-efficacy (McAuley et al., 2011, Areerak et al., 2021, Collado-Mateo et al., 2021) to engage into exercise can theoretically increase the physical activity level, which in turn may increase $PMCT_{STT/EO}$, $PMCT_{IO/TrA}$ and $PMCT_{TrA/IA}$ thickness. A path-analysis, testing a theoretically driven model involving moderator and mediator variables, might help further understanding these relationships. These findings concur with the overloading (or disuse) hypothesis, chronic overloading leading to increased thickness and chronic unloading leading to decreased thickness (Driscoll and Blyum, 2011).

The physical activity level during sport activities (PAL-sport) was selected in two regression models, namely for $PMCT_{STT/EO}$ (9% VAF) and $PMCT_{IO/TrA}$ (19% VAF), which tap into concepts of the lifestyle domain. The regression coefficients suggest a negative correlation whereby a decrease of PAL-sport would be associated with an increase in fascia thickness. As discussed earlier, this might be due to fatty infiltrations into the more superficial fasciae ($PMCT_{STT/EO}$), but this would not explain the relationship with $PMCT_{IO/TrA}$ thickness.

LuM thickness at rest (R_{LuM}) was selected in two regression models, namely for $PMCT_{IO/TrA}$ (10% VAF) and $PMCT_{TrA/IA}$ (9% VAF), the positive regression coefficients suggesting that the PMCT thickness surrounding the TrA increases as R_{LuM} increases. The likely explanation arises from the biological (or biomechanical) domain. Effectively, as for the link between the activation of the internal oblique ($\%C_{IO}$) and TLF_{L45} (11% VAF), or between the activation of the TrA ($\%C_{TrA}$) and $PMCT_{EO/IO}$ (4% VAF), the above-mentioned mechanism (Vleeming et al., 2014), involving a balanced tension between paraspinal and deep abdominal muscles (IO and TrA), applies here. These muscle forces (e.g., LuM) are applied to the aponeurotic portions of the antagonist trunk muscles (e.g., IO, TrA), inducing remodeling of the corresponding PMCT. Epimuscular myofascial shear force transmission between neighboring muscles (e.g., between IO and TrA) can

also contribute to PMCT remodeling (e.g., $PMCT_{IO/TrA}$) (Huijing, 2009, Yoshitake et al., 2018). In line with these explanations, please note that between one and three trunk muscle thickness measures (R_{LuM}, R_{EO}, R_{IO}, R_{TrA}) were significantly correlated with the thickness of PMCT surrounding the lateral abdominal wall muscles (Table 3).

Clinical tests involving straight-leg raise (SLR) were included in two regression models. Passive SLR ROM at pain threshold (16% VAF) was predictive of $PMCT_{EO/IO}$, while the active SLR difficulty was predictive of both $PMCT_{EO/IO}$ (8% VAF) and $PMCT_{TrA/IA}$ (7% VAF). The corresponding regression coefficients were all negative, suggesting that pain-related limitations or execution of the SLR task were associated with increased fasciae thicknesses. Regrettably, the authors are unable to provide credible interpretations of these findings.

The lumbar flexion ROM accounted for 5% of $PMCT_{STT/EO}$ variance, the positive regression coefficient suggesting that an increased lumbar flexion ROM might be facilitated by an increased $PMCT_{STT/EO}$ thickness, given that the latter is explained by an increased fatty infiltration (and lower tissue stiffness) into this superficial fascia. The alternative cause-and-effect relationship (increased fascial thickness caused by greater lumbar flexion ROM) seems unlikely.

The maximal forward loaded reach test (NPPT-Reach) accounted for 6% of $PMCT_{TrA/IA}$ variance and moreover, just failed to reach statistical significance ($P = 0.064$) to enter in $PMCT_{IO/TrA}$'s regression model. The negative regression coefficients both suggest that an increased (or decreased) forward loaded reach is associated with a decreased (or increased) $PMCT_{TrA/IA}$ (and possibly $PMCT_{IO/TrA}$) thickness. Interestingly, this test was selected in the clinical prediction rules predicting the treatment success after a lumbar stabilization exercise program at the end of the 8-week treatment as well as at the six-month follow-up (Larivière et al., 2022b). In healthy participants (no LBP), moving the load forward induces an automatic co-contraction of back and abdominal muscles (Larivière et al., 2019), which would contribute to preserving lumbar stability (Ghezelbash et al., 2022). This is especially true for deeper abdominals (IO and TrA), comparatively to EO, as substantiated in a surface electromyographic (EMG) study (Larivière et al., 2019). The positioning of the EMG electrodes in this latter study allows measuring the combined activity of IO and TrA (Marshall and Murphy, 2003, McGill et al., 1996). These biomechanical studies suggest that the increased IO and TrA activation may induce the surrounding PMCT remodeling if chronically overloaded (increased thickness) (Driscoll and

Blyum, 2011), which is not in line with the negative association substantiated in the multivariate regression models. However, participants with CLBP may behave otherwise, preferentially using superficial abdominals (EO) because of reflex inhibition of deep abdominals (IO and TrA). Furthermore, selective inherent load bearing may become biases if such irregularities exist and further contribute to this potential detrimental cycle to tissue health (Newell and Driscoll, 2021a, Newell and Driscoll, 2021b).

4.4. Limitations

The present study has several limitations. First, a cross-sectional design cannot establish cause-effect relationships. Second, the sample size limited the number of predictors to be considered in the multiple regression models and more importantly, did not allow considering interaction terms (at least two-way interactions). Finally, measuring some concepts differently or considering other concepts would likely change these multivariate regression models. Effectively, a more direct measure of PAL (e.g., using accelerometers) or measurement of aerobic capacity might produce different findings regarding the role played by physical activity. The measurement of muscle strength, in addition to muscle endurance, might also be relevant. %Change RUSI parameters ($\%C_{L5S1}$, $\%C_{L45}$, $\%C_{L34}$, $\%C_{EO}$, $\%C_{IO}$, $\%C_{TrA}$) are not as reliable as thickness at rest RUSI parameters (R_{L5S1}, R_{L45}, R_{L34}, R_{EO}, R_{IO}, R_{TrA}) (Lariviere et al., 2018a, Lariviere et al., 2019) or RUSI passive parameters (Lariviere et al., 2021a) used as DVs in the present study, as discussed in these papers. This may have affected their predictive capacity, reducing their likelihood to enter in the different regression models. RUSI measures of fasciae thickness represent a simple assessment, limiting the possible interpretations of the findings. A combination of complementary measures of different fascia properties (e.g., stiffness, gliding between layers) are needed for a more comprehensive assessment (Zugel et al., 2018). Differentiating between fibrosis and fatty infiltration is also an important issue. In the mean time, to help understand the clinical implications of MFI and fibrosis, future studies may also need to combine echogenicity with measures of muscle stiffness, either with the use of shear wave elastography or another procedure involving palpation, ideally with some form of objective quantification (Jacobson and Driscoll, 2021, Jacobson and Driscoll, 2022), to produce a clinically interpretable stiffness-echogenicity matrix (Stecco et al., 2019).

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AUTHOR CONTRIBUTIONS

All authors have made substantial contributions to all of the following: (1) the conception and design of the study, or acquisition of data, or analysis and interpretation of data, (2) drafting the article or revising it critically for important intellectual content, (3) final approval of the version to be submitted.

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Table of abbreviations (see Figure 1 and 2 as well as the supplementary material for more detailed description of the corresponding variables)

Abbreviation	Type of variable*	Definition
$\%C_{LuM}$, $\%C_{EO}$, $\%C_{IO}$, $\%C_{TrA}$	IVs	Percentage of change (%C) in thickness of the LuM, EO, IO and TrA muscles between rest and contraction (standardized task)
Abe-Mvt	IV	Aberrant movements during trunk flexion and extension
ActRelPain	IV	Activity related pain
ASLR-Act/5-max (/5), ASLR-Pain-max (0 or 1)	IVs	Perceived effort (score between 0 and 5) and presence of pain (0 or 1) during the active straight-leg raise (ASLR); the maximal (max) score between sides is retained.
BarriersSES	IV	Barriers Self-Efficacy Scale
Beighton	IV	Generalized ligamentous laxity (Beighton scale)
$ECHO_{LuM}$	DV	Echogenicity of the lumbar multifidus at the three vertebral levels
EO		External oblique
FABQ-PA	IV	Fear-avoidance beliefs questionnaire – physical activity subscale
IO		Internal oblique
L5S1, L45, L34		Lumbar vertebral levels and sacrum (S1)
LuM		Lumbar multifidus
LumbFlx-ROM	IV	Lumbar flexion ROM
LumbLatFlx-ROM-Min	IV	Lumbar lateral flexion ROM (minimum score across sides)
MCI tests	IVs	Different tests assessed motor control impairments (MCI), as described in the supplementary material, but created multicollinearity problems in the regression models (thus eliminated).
NPRS		Numeric pain rating scale
ODI		Oswestry disability index
PCS	IV	Pain catastrophizing scale
PAL-leisure, PAL-sport	IV	Physical activity level during leisure and sport activities, respectively
PDItot, PDIanx, PDIdep, PDIsom, PDIang, PDIcog	IVs	Psychological Distress Inventory (PDI) total score and scores corresponding to its five subscales: anxiety, depression, somatization, anger, and cognitive problems, respectively
PelvisFlx-ROM	IV	Pelvis flexion ROM
PLE	IV	Passive lumbar extension test (lumbar segmental instability)
$PMCT_{EO/IO}$, $PMCT_{IO/TrA}$, $PMCT_{TrA/IA}$, $PMCT_{STT/EO}$	DVs	Perimuscular connective tissues, between EO and IO, between IO and TrA, between TrA and the intra-abdominal content, between STT_{ABD} and EO, respectively

Abbreviation	Type of variable*	Definition
PPT-SitStand, PPT-Flexion, NPPT-Reach, PPT-Rollover-max	IVs	Physical performance tests (PPT) measuring the time to produce 5 sit-to-stand-to-sit (SitStand) or trunk flexion/extension (Flexion) cycles, or measuring time to roll over 360° in both directions (Rollover) or measuring the distance of a loaded reach (Reach).
ProneIT	IV	Prone instability test (lumbar segmental instability)
PSLR-Pain ROM-min, PSLR-Max ROM-min	IVs	ROM at the onset of pain (Pain) and at maximal elevation (Max) during the passive straight-leg raise (PSLR); the minimal (min) score between sides is retained.
ROM		Range of motion
R_{LuM}, R_{EO}, R_{IO}, R_{TrA}	IVs	Thickness at rest (R) of the LuM at three vertebral levels (L5/S1, L45 and L34) and of EO, IO and TrA abdominal muscles
RUSI		Rehabilitative ultrasound imaging
SSES-FamRP, SSES-FamPa, SSES-FriendPa	IVs	Social support for exercise scale, comprising three subscales: family rewards and punishments (FamRP), family participation (FamPa) and friend participation (FriendPa)
STarT Back	IV	Subgroups for Targeted Treatment (STarT) Back Screening Tool
STT_{ABD}		Subcutaneous tissue thickness cover the abdominal lateral wall
STT_{L45}		Subcutaneous tissue thickness at L45
TLF_{L45}	DV	Thickness of the thoracolumbar fascia at L45
TME-Abdominals, TME-Back, TME-Side-min	IVs	Trunk muscle endurance (TME) tests of the abdominal muscles, back muscles as well as trunk muscles generating side bending moments
TrA		Transversus abdominis

* Type of variable (IV: independent variable or candidate predictor; DV: dependent variable) in the multivariate regression analyses (details in section Statistical analyses)

Table 1. Demographic, anthropometric and clinical characteristics [Mean (SD)] of the 70 participants with LBP.

	Men (*n* = 30)	Females (*n* = 40)
Variable	Mean (SD)	Mean (SD)
Age (years)	44.4 (12.6)	42.1 (13.1)
Height (cm)	175.3 (6.7)	164.7 (6.6)
Weight (kg)	79.5 (13.0)	67.7 (9.3)
BMI (kg/m^2)	25.8 (3.4)	24.9 (2.9)
%Fat	22.7 (5.9)	32.4 (4.8)
PAL-sport (/5)	2.7 (0.8)	2.6 (0.9)
PAL-leisure (/5)	2.7 (0.7)	2.8 (0.8)
NPRS (/10)	5.1 (1.4)	4.7 (1.1)
ODI (%)	25.5 (8.4)	26.6 (9.8)
$FABQ_{PA}$ (/24)	15.6 (5.1)	12.9 (5.6)
PCS (/52)	23.9 (10.7)	17.6 (11.1)
STarT Back (/9)	4.5 (2.0)	3.6 (2.0)
Duration LBP*	/	/

BMI: body mass index; %Fat: percentage of body fat (Durnin and Womersley, 1974); PAL-sport and PAL-leisure: Physical activity level – sport and leisure subscales (Baecke et al., 1982); NPRS: numeric pain rating scale (Childs et al., 2005); ODI: Oswestry Disability Index (Fairbank et al., 1980); $FABQ_{PA}$: Fear-avoidance beliefs questionnaire - physical activity subscale (Waddell et al., 1993); PCS: pain catastrophizing scale (Sullivan et al., 1995); STarT Back: Subgroups for Targeted Treatment (STarT) Back Screening Tool (Hill et al., 2008). For the duration of the self-reported LBP, 95.7% (67/70) of participants had chronic pain (3 months or more), distributed as follows (Deyo et al., 2015): less than one month (n = 0; 0%), 1–3 months (n = 2; 2.9%), 3–6 months (n = 1; 1.4%), 6–12 months (n = 8; 11.4%), (5) 1–5 years (n = 25; 35.7%), (6) >5 years (n = 34; 48.6%).

Table 2. Effect (P values) of potential covariates of each dependent variable*

Dependent variable	**Age**	**Sex**	**Weight**
$ECHO_{LuM}$	0.324	< **0.001**	/
TLF_{L45}	0.336	0.245	< **0.001**
$PMCT_{STT/EO}$	0.091	< **0.001**	< **0.001**
$PMCT_{EO/IO}$	0.241	0.497	< **0.001**
$PMCT_{IO/TrA}$	0.444	0.271	0.079
$PMCT_{TrA/IA}$	0.121	0.594	0.465

* For each dependent variable, age, sex, and weight were introduced in a multivariate regression model to identify which ones were influential. Only the statistically significant covariates identified in this table were then entered in the respective multivariate regression model to compute the residuals, the latter being considered as DVs in the forward stepwise procedure.

Table 3. Pearson correlations ≥ 0.25 or ≤ -0.25 ($P < 0.05$) between dependent variables (adjusted for covariates) and independent variables*

$ECHO_{LuM}$ †	TLF_{L45} †	$PMCT_{STT/EO}$†	$PMCT_{EO/IO}$ †	$PMCT_{IO/TrA}$	$PMCT_{TrA/IA}$
LumbFlx-ROM (.58)	MCI-HipIR-Pas-ROM (-.38)	LumbFlx-ROM (.35)	PSLR-Pain-ROM (-.31)	PAL-sport (-.35)	R_{EO} (.35)
R_{LuM} (.42)	FABQ-AP (.37)	R_{LuM} (.27)	R_{TrA} (.29)	R_{LuM} (.28)	R_{TrA} (.29)
$\%C_{LuM}$ (-.35)	$\%C_{IO}$ (.35)	R_{EO} (.26)		R_{TrA} (.27)	R_{IO} (.25)
%Fat (.34)	%Fat (.34)				
TME-Abdo (-.34)	MCI-HipER-Pas-ROM (-.33)				
Lordosis (.33)	PCS (.27)				
	TME-Side (-.26)				
	STarT Back (.26)				
	PPT-SitStand (.25)				

*Binary variables are not part of this table as Pearson correlations are for continuous variables

† Adjusted (residuals) for the statistically significant covariates identified in Table 2 (depends on the dependent variable).

Table 4. Multivariate stepwise (forward) regression models

Dependent variable	Selected variables in the final regression model*	R^2	Adj R^2	*Regression coefficient*	*%VAF*
$ECHO_{LuM}$ adjusted for sex (residuals)		0.63	0.59		
	• R_{LuM}: Thickness of the lumbar multifidus			0.3779	19
	• LumbFlx-ROM: Lumbar flexion ROM			0.3778	17
	• PelvisFlx-ROM: Pelvis flexion ROM			0.2861	12
	• PDIcog: Psychological distress inventory – cognitive subscale			-0.1891	8
	• PAL-sport: Physical activity level – sport activities			-0.2142	7
TLF_{L45} adjusted for weight (residuals)		0.41	0.36		
	• %Fat: percentage of fat			0.4051	14
	• $\%C_{IO}$: Activation of the internal obliques			0.2671	11
	• FABQ-PA: Fear-avoidance beliefs questionnaire – physical activity			0.3304	8
	• Abe-Mvt = 1: Presence of aberrant movements			0.5650	8
$PMCT_{STT/EO}$ adjusted for sex and weight (residuals)		0.46	0.42		
	• SSES-FamPa: Social support for exercise - family participation			0.3278	20
	• BarriersSES: Barriers self-efficacy to exercise			0.3026	12
	• PAL-sport: Physical activity level – sport activities			-0.2221	9
	• LumbFlx-ROM: Lumbar flexion ROM			0.1948	5
$PMCT_{EO/IO}$ adjusted for weight (residuals)		0.28	0.24		
	• PSLR-Pain ROM-min: Passive SLR ROM at pain threshold (min)			-0.5650	16
	• ASLR-Act/5-max: Active SLR difficulty (max)			-0.2375	8
	• $\%C_{TrA}$: Activation of the transversus abdominis			0.2176	4
$PMCT_{IO/TrA}$		0.34	0.30		
	• PAL-sport: Physical activity level – sport activities			-0.5359	19
	• R_{LuM}: Thickness of the lumbar multifidus			0.3840	10
	• SSES-FamRP: Social support exercise - family rewards/punishments			0.1872	5
$PMCT_{TrA/IA}$		0.37	0.30		
	• SSES-FamRP: Social support exercise - family rewards/punishments			0.1517	9
	• R_{LuM}: Thickness of the lumbar multifidus			0.2337	9
	• ASLR-Act/5-max: Active SLR difficulty			-0.1276	7
	• PDIcog: Psychological distress inventory – cognitive subscale			0.1471	6
	• NPPT-Reach: Maximal forward loaded reach			-0.2044	6

* The independent variables were ordered according to the percent of variance accounted for (%VAF) as detailed in the last column
%VAF: percent variance accounted for R^2 by individual independent variables. Main abbreviations (see abbreviation table for details): $ECHO_{LuM}$: LuM echogenicity; PMCT: perimuscular connective tissues; STT: subcutaneous tissue thickness; TLF: thoracolumbar fascia.

Table 5. Overview of major findings emerging from the multivariate analyses

RUSI-passive parameters (dependent variables)	Independent Variable Domains that explained variance				Total variance explained
	Biological	Psychological	Social	Lifestyle	
LuM echogenicity	√	√		√	63%
Thoracolumbar fascia	√	√			41%
Abdominal wall fasciae (n = 4)	√	√	√	√	28 to 46%

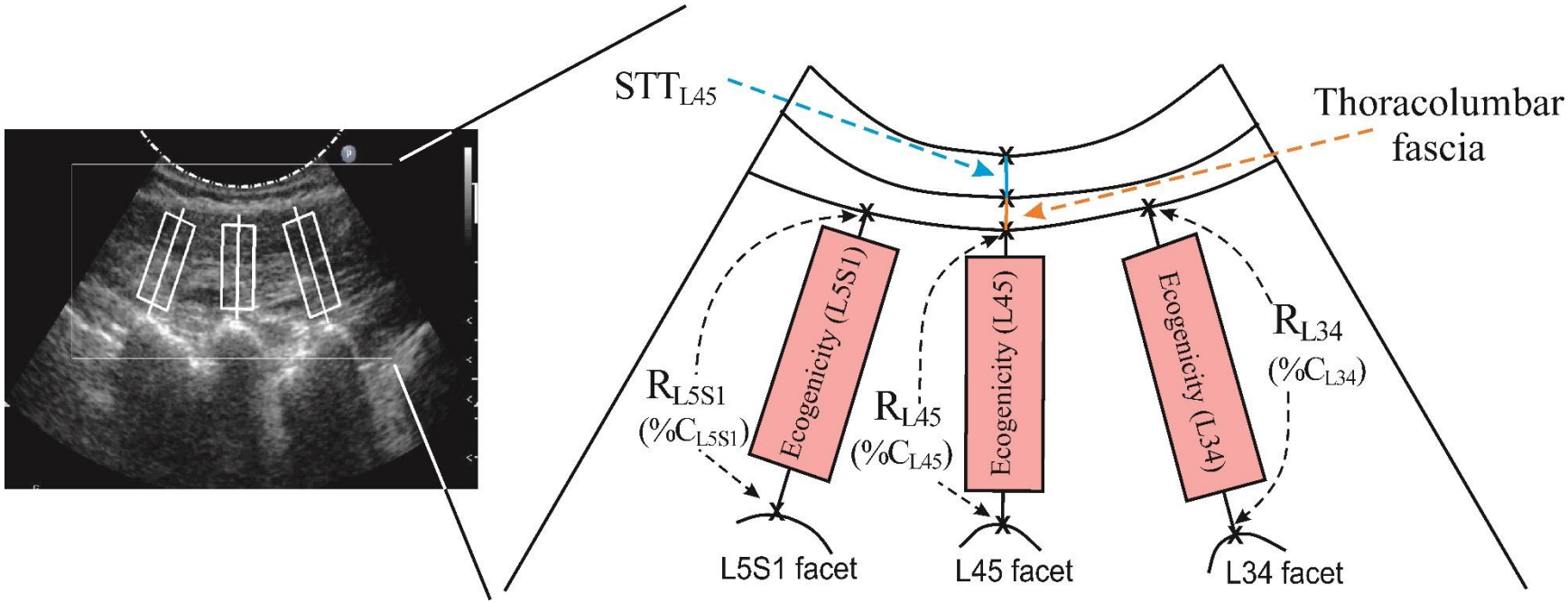

Figure 1. From Lariviere et al. (2020b). RUSI measures (thickness) of the LuM at rest (e.g., R_{L5S1}) and during the contraction (in parentheses; e.g., $\%C_{L5S1}$) as previously defined (Lariviere et al., 2018a), as well as the new measures for the current study (STT_{L45} thickness; thoracolumbar fascia thickness, LuM echogenicity at the L5S1, L45 and L34 facets) that were only performed at rest. The images were processed using a custom Matlab program (The Mathworks, Natick, MA) allowing for calibration of the image and accounting for transducer curvature (note that the LuM thickness measures are not identified with vertical lines but follow the image curvature). LuM echogenicity was measured inside the regions of interest identified with shaded rectangles (width: 1 cm; height: 80% of LuM thickness) positionned in the middle of the marks used to define LuM thickness at rest (Lariviere et al., 2018a); the grey-scale analysis to compute echogenicity is detailed elsewhere (Nadeau et al., 2016). STT_{L45}: subcutaneous tissue thickness at the L45 vertebral level (in blue); thoracolumbar fascia: posterior layer of the thoracolumbar fascia thickness at the L45 vertebral level (in orange); R and %C: lumbar multifidus thickness at rest and as a percent change during contraction.

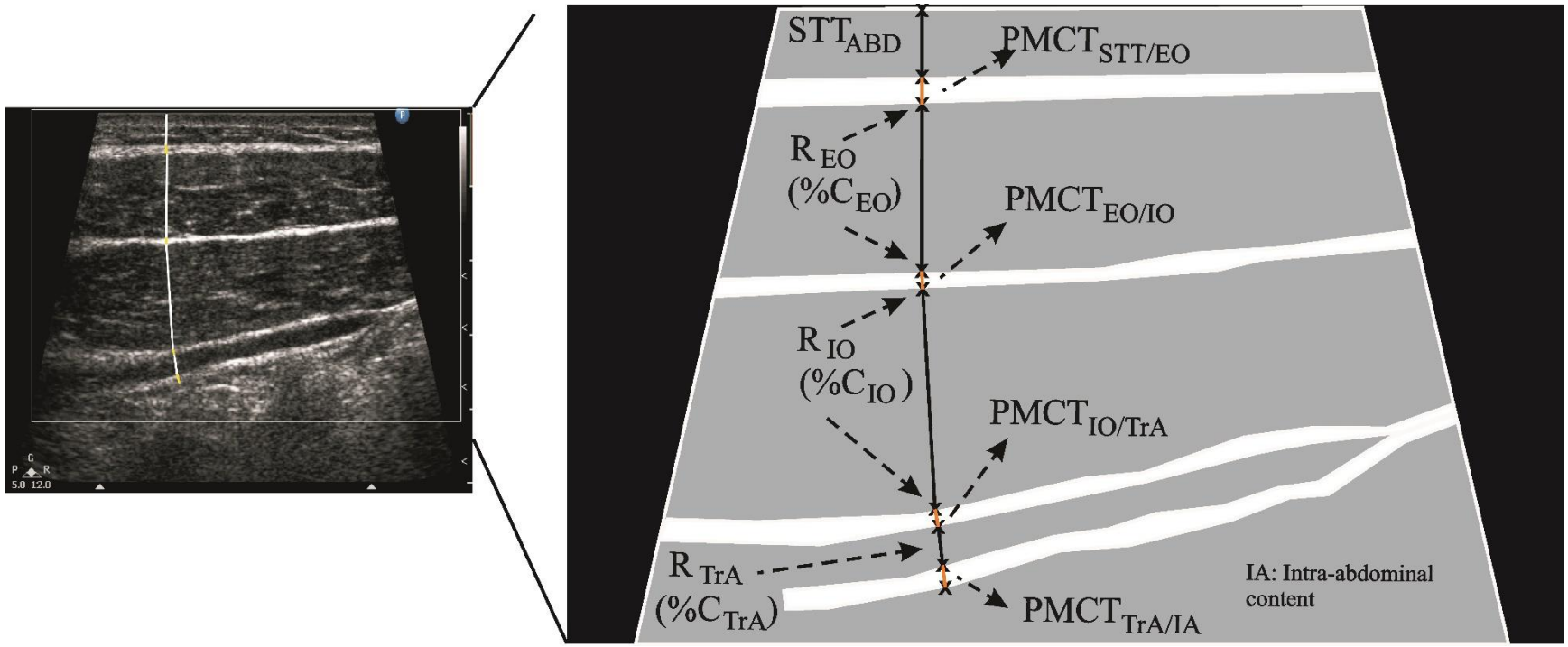

Figure 2. From Lariviere et al. (2020b). RUSI measures of the lateral abdominal wall muscles at rest (e.g., R_{EO}) and during the contraction (in parentheses; e.g., $\%C_{EO}$) as previously defined (Lariviere et al., 2018b), as well as new measures for the current study (STT_{ABD}, PMCT) that were only performed at rest. Images were processed using a custom Matlab program (The Mathworks, Natick, MA), allowing calibration of the image and automatic placement of dashed vertical lines (75% of image width from the image border corresponding to the lateral side of the participant) serving as a reference for thickness measures (inner borders) for each muscle. When one muscle was oblique (ie, not horizontal) in the image, the corresponding thickness measure was adjusted perpendicular to the longitudinal axis of the muscle (see IO and TrA muscles). Muscle thickness = distance between inside edges of each muscle border; PMCT thicknesses = distance between outside edges of each connective tissue represented in white (thickness measures in orange on the right). Inside edges of muscles correspond to outside edges of PMCT planes, allowing to compute PMCT thicknesses using the pixels already identified for muscle thicknesses. STT_{ABD}: subcutaneous tissue thickness over lateral abdominal wall. PMCT: perimuscular connective tissue between STT_{ABD} and EO (ST/EO), between EO and IO (EO/IO), between IO and TrA (IO/TrA) and between TrA and intra-abdominal area (TrA/IA) are illustrated. R and %C: EO, IO and TrA thickness at rest and as a percent change during contraction (Lariviere et al., 2018b).