

Article

Ultrasound-Derived External Oblique Muscle Thickness Was Not Associated with Surface EMG Amplitude or Shear Modulus During Progressive Isometric Upper-Limb Loading: An Experimental Study

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Featured Application

The findings support cautious interpretation of ultrasound-derived external oblique muscle thickness in rehabilitation and musculoskeletal assessment, as thickness changes should not be used as a direct surrogate for muscle activity under the tested conditions.

Abstract

The aim of this study was to assess whether external oblique muscle (OE) thickness was associated with surface electromyography (sEMG) amplitude and shear modulus under progressively increasing load and to examine the effect of load on these three measures. Thickness and shear modulus of the OE were assessed using an Aixplorer ultrasound system in shear wave elastography mode, while sEMG amplitude was recorded using the eMotion system. Measurements were obtained in a semi-supine position at rest, in the unloaded starting position, and during isometric upper-limb contractions with external loads corresponding to 3%, 6%, 9%, and 12% of body mass. Forty-two healthy adults (21 women and 21 men; age 23.1 ± 1.4 years) participated in the study. Load effects were assessed using Friedman tests, whereas associations were examined using linear mixed-effects models after natural-log transformation of sEMG amplitude and shear modulus. Progressive loading significantly increased OE sEMG amplitude and shear modulus (both $p < 0.001$). Changes in OE thickness were small despite a significant overall effect of load ($p = 0.04$; Kendall's $W = 0.06$). No significant load $\times$ OE thickness interaction was found for either sEMG amplitude ($p = 0.417$) or shear modulus ($p = 0.740$). In the additive mixed-effects models, load significantly predicted both outcomes ($p < 0.001$ for both), whereas OE thickness was not associated with either sEMG amplitude ($p = 0.814$) or shear modulus ($p = 0.475$). These findings indicate that ultrasound-derived changes in OE thickness should not be interpreted as direct indicators of muscle activity in the semi-supine position and during the isometric upper-limb loading task examined in this study.

Keywords: external oblique muscle; shear wave elastography; muscle thickness; electromyography; muscle activity



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1. Introduction

The assessment of muscle morphology and function is a fundamental component of both clinical practice and scientific research. Ultrasonography (US) is widely used to evaluate muscle morphology because of its non-invasive nature, accessibility, and relatively low cost. In the literature, US is frequently used to assess muscle thickness, including changes during different movements or exercise tasks [1–3]. Such changes in muscle thickness are sometimes interpreted as surrogate markers of muscle activity [1,4–7].

In scientific research, electromyography (EMG) remains the most widely used method for directly assessing muscle activity. The EMG signal results from the stimulation of muscle fibres by the electrical potentials of the nervous system [8]. Consequently, EMG allows the timing of muscle activation, the duration of muscle activity, and the intensity of such activity to be determined. Over the last decade, shear wave elastography (SWE), a non-invasive real-time US method, has been developed to assess muscle shear modulus. Shear modulus measured by SWE is linearly related to active and passive muscle forces [9,10] and is considered a surrogate of muscle elasticity, stiffness, tension, or activity [10–12].

A recent case report evaluated the external oblique muscle (OE) as part of the lateral abdominal wall muscles (LAMs), using EMG, SWE, and B-mode US to assess changes in muscle thickness [13]. The report showed that during isometric contraction, the OE exhibited no increase, or even a decrease, in thickness despite increases in EMG activity and shear modulus [13]. A review by Linek [1] also suggested that changes in LAM thickness should not be interpreted as indicators of muscle activity. In contrast, Shahali et al. [4] indicated that under specific conditions, changes in muscle thickness may serve as a surrogate for muscle activity. Although LAM thickness would be expected to increase during contraction, the specific architecture of the abdominal wall and intra-abdominal pressure may influence thickness measurements [1,14]. Despite this, some studies still interpret changes in LAM thickness in relation to muscle activity [5–7]. Delkhoush et al. [5] and Yodthee et al. [6] used ultrasound-derived thickness changes as indicators of muscle activity or activation across different postures and contraction conditions. Similarly, Kim et al. [7] used muscle thickness ratios to reflect muscle activity during trunk movements.

To the best of our knowledge, aside from the case report mentioned above, the literature contains no experimental studies that assess OE thickness, EMG amplitude, and shear modulus during controlled increases in external load. Therefore, in this study, the OE, as one component of the LAM, was examined using simultaneous EMG, SWE, and US thickness measurements during experimentally controlled, progressively increasing isometric contractions induced by upper-limb loading. The aims of this study were to determine whether OE thickness is associated with EMG amplitude and shear modulus under progressively increasing load, and to examine the effect of load on EMG, shear modulus, and muscle thickness. We hypothesised that OE thickness would not be associated with EMG amplitude or shear modulus during progressively increasing load.

2. Materials and Methods

2.1. Study Design

This was a repeated-measures experimental study conducted under controlled laboratory conditions, with participants in a semi-supine position. Each participant was assessed at rest, in the starting position (PW), and during four loading conditions corresponding to 3%, 6%, 9%, and 12% of body mass. All measurements were performed on the right OE. The conditions were applied in the following order: rest, PW, 3%, 6%, 9%, and 12% of body mass. The loading protocol involved isometric contractions induced by upper-limb loading, with force controlled using a dynamometer. EMG, SWE, and thickness of the OE were recorded simultaneously at each loading level. The rest condition was included for

descriptive purposes only, whereas inferential analyses were limited to the progressively increasing loading conditions from PW to 12% of body mass.

The study was approved by the Bioethics Committee for Scientific Studies at the Academy of Physical Education in Katowice on 5 December 2017 (Decision No. 4/2017). All procedures were performed in accordance with the relevant guidelines and regulations. All participants provided written informed consent.

2.2. Participants

Participants were recruited from the university community on a voluntary basis. The study group comprised primarily healthy university students. Eligibility required adequate ultrasound visualisation of the OE and its fascial borders. Exclusion criteria included any abdominal wall abnormalities identified on ultrasound, subcutaneous adipose tissue that prevented reliable visualisation of the OE, and a history of abdominal or lumbar spine surgery. All participants completed the measurement protocol, which comprised EMG and ultrasound assessment of the OE.

2.3. Instrumentation

US measurements were performed using an Aixplorer system (Supersonic Imagine, Aix-en-Provence, France; Product Version 12.2.0, Software Version 12.2.0.808) equipped with a linear-array transducer (SuperLinear 10–2, Vermon, Tours, France). The shear modulus of the right OE was assessed using SWE, whereas the thickness of the OE was measured from the corresponding B-mode image.

Surface EMG (sEMG) was recorded over the right OE using two channels of the eMotion system (Mega Electronics Ltd., Kuopio, Finland). Bipolar surface electrodes (Bio-Lead-Lok B, Józefów, Poland; diameter 36 mm) were used. EMG signals were notch-filtered at 50 Hz, band-pass-filtered (20–500 Hz), and sampled at 1 kHz. sEMG was selected because it enabled non-invasive, repeated recording simultaneously with ultrasound across all loading conditions.

Force output during isometric contractions was measured using a force gauge (FB1k, AXIS, Gdańsk, Poland) connected to an external S-type load cell (DEE, Keli Sensing Technology, Ningbo, China). Force values were displayed in real time.

2.4. Experimental Procedure

The measurement protocol was adapted from previously described procedures examining the relationship between thickness and shear modulus of the lateral abdominal wall [13].

Before data collection, participants completed a familiarisation phase to ensure correct positioning and handling of the dynamometer and to accurately reproduce the required force levels. Data collected during familiarisation were not included in the analysis. The right OE was identified using B-mode US at the umbilical level, lateral to the rectus abdominis. Its location and fibre direction were marked on the skin. The intended electrode sites were then cleaned with alcohol. Two bipolar sEMG channels were positioned on either side of the marked transducer location. In each channel, the red and yellow electrodes formed the active electrode pair and were aligned with the marked OE fibre direction, whereas the black electrode served as the reference (ground) electrode and was positioned adjacent to the active pair. Adjacent electrodes did not overlap, and their edge-to-edge separation was approximately 3–5 mm. Electrode positions remained unchanged across all conditions and repetitions throughout the measurement session (electrode-skin impedance was not quantified). The transducer was then positioned at the marked location between the two EMG channels, with its longitudinal axis aligned parallel to the OE fibres (Figure 1).

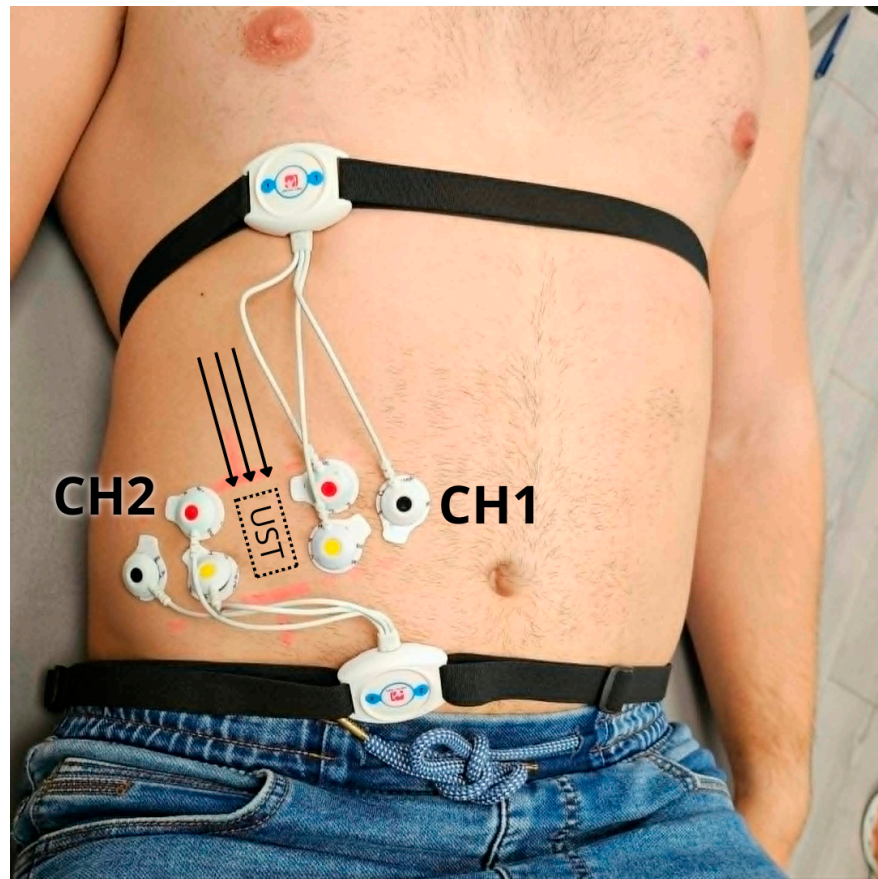


Figure 1. Placement of the ultrasound transducer and sEMG electrodes over the right OE. Black arrows indicate the direction of the OE fibres; the dashed rectangle (UST) marks the transducer position; and CH1 and CH2 denote the two bipolar sEMG channels positioned on either side of the transducer. In each channel, the red and yellow electrodes form the active electrode pair, whereas the black electrode serves as the reference (ground) electrode.

All ultrasound measurements, including SWE acquisitions, were performed by the same investigator, who had completed 30 h of training in the measurement procedure before data collection. For US image acquisition, a generous amount of ultrasound gel and minimal manual transducer pressure were used to minimise tissue compression. The transducer position was adjusted slightly as needed to maintain longitudinal visualisation of the OE and to clearly identify its fascial borders.

During the resting condition, the knees were flexed to 90°, and the upper limbs were positioned alongside the trunk. Participants were instructed to breathe normally, and SWE images were obtained at the end of a quiet expiration. Subsequently, participants maintained the same lower-body position, with the shoulders flexed to 90°, the elbows fully extended, and the hands gripping a handle connected to the dynamometer (PW condition). Participants then performed isometric contractions against force targets of 3%, 6%, 9%, and 12% of body mass. Loads were normalised to body mass to provide reproducible force targets scaled to participant body size. A 3 min rest interval was provided between successive loading conditions. No fixed inter-repetition interval was imposed; the next repetition began once the participant had relaxed and the force output had returned to baseline. During PW and the loading conditions, participants were instructed to breathe normally and to avoid breath-holding or performing the Valsalva manoeuvre. The acceptable force range was set at ± 200 g relative to the target value. Participants continuously monitored force output via real-time visual feedback and were supervised by the investigator, who provided verbal guidance when necessary (Figure 2).

Once the target force was reached and the SWE image had stabilised for approximately 3–4 s, activation of the foot switch initiated a 1 s EMG recording. At the end of this period, the EMG recording was terminated, and the US image was captured simultaneously. Three repetitions were performed at rest, in the PW condition, and at each load level. The investigator performing the SWE acquisition did not have access to the recorded EMG amplitude values.

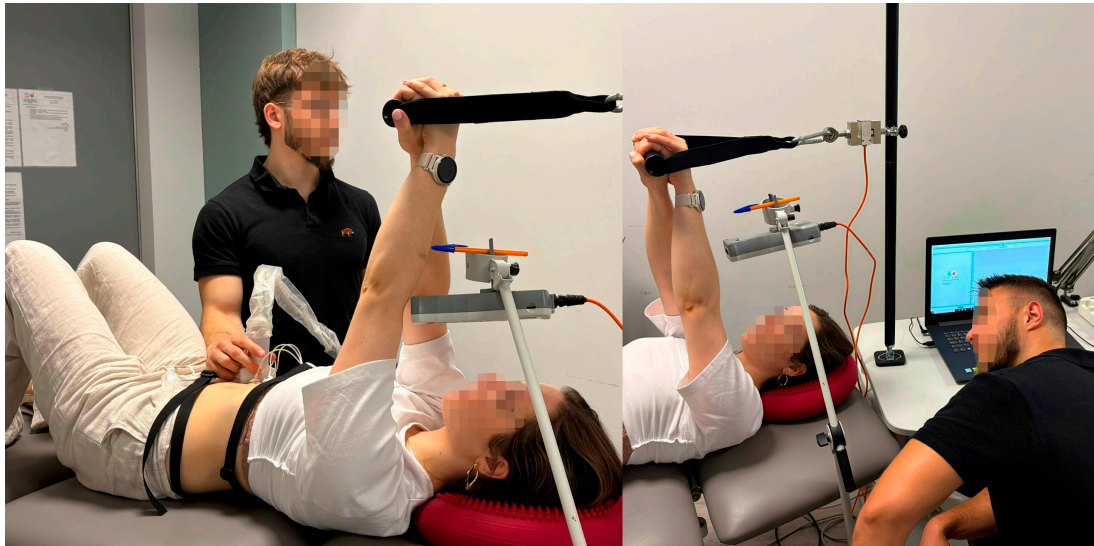


Figure 2. Experimental setup and participant positioning during simultaneous ultrasonographic and sEMG assessment of the right external oblique muscle under progressive isometric upper-limb loading.

2.5. Signal Processing and Data Reduction

Shear modulus was calculated after data collection using the Q-Box™ tool integrated into the ultrasound system. The rectangular SWE field represented the acquisition area used to generate the colour-coded elastogram and extended beyond the OE borders. For each image, three equal-sized circular Q-Boxes were used. Their diameter was adjusted to the OE thickness visible in the image to ensure that all measurement areas remained entirely within the fascial borders of the muscle (Figure 3A). The shear modulus for each image was calculated as the mean of the three Q-Box measurements [15].

US images were accepted if the OE fascial borders were clearly visible, the SWE colour map adequately covered the analysed muscle region, and no evident artefacts were present. Images that did not meet these criteria were immediately reacquired. The final dataset comprised three accepted images per participant and condition. US images were also exported in DICOM format.

OE thickness was measured using RadiAnt DICOM Viewer 2026.1 software (Medixant, Poznań, Poland). For each image, three measurements were taken between the superficial and deep fascial borders of the OE, and the mean was used for further analysis (Figure 3B). For both shear modulus and OE thickness, the participant-level value for each condition was calculated as the mean of the three accepted images. All SWE images were acquired and analysed by the same investigator, whereas OE thickness was measured by a different investigator.

EMG data were processed using MegaWin 3.0 software (Mega Electronics Ltd., Kuopio, Finland). For each 1 s recording, the MegaWin Averaging function calculated the mean absolute value of the filtered EMG samples within the selected window, providing the average rectified EMG amplitude expressed in μV . The mean of the two channel-specific values was used as the repetition-level EMG amplitude. The participant-level EMG value

for each condition was then calculated as the mean of the three repetitions. EMG amplitude was not normalised to MVC.

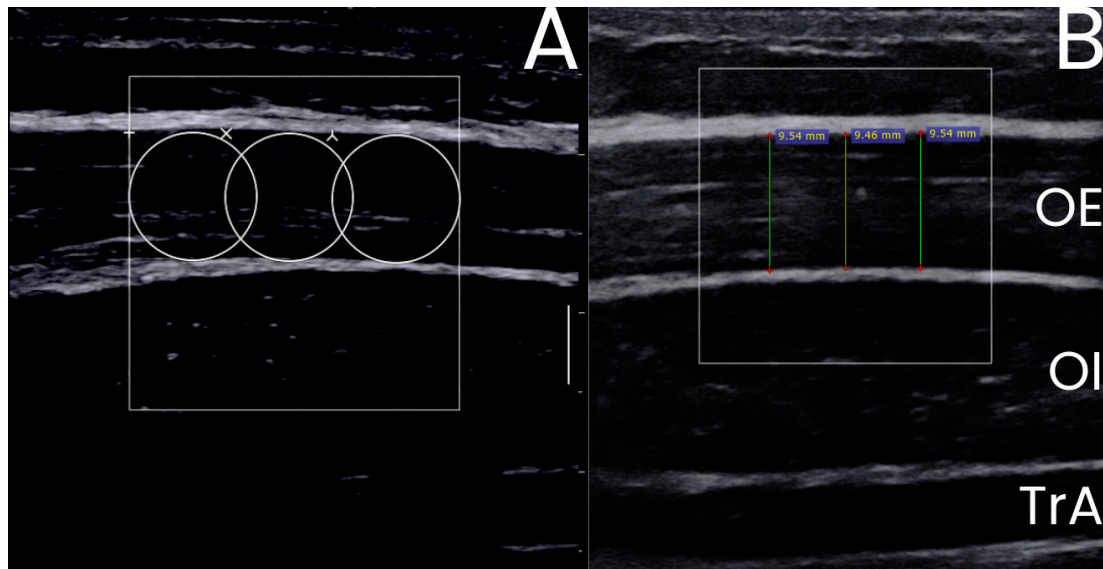


Figure 3. Representative ultrasound images showing measurements of right OE shear modulus (A) and thickness (B). OE, external oblique; OI, internal oblique; TrA, transversus abdominis.

2.6. Statistical Analysis

The analysis was based on repeated-measures data collected under five loading conditions (PW, 3%, 6%, 9%, and 12% of body mass). EMG amplitude, shear modulus, and thickness of the OE were assessed at each load level. Normality of distribution was evaluated using the Shapiro–Wilk test. OE thickness showed an approximately normal distribution, whereas EMG amplitude and shear modulus deviated from normality.

Considering the repeated-measures design and the distributional properties of the data, the effect of load on EMG, shear modulus, and thickness of the OE was analysed using the non-parametric Friedman test. Effect sizes were measured using Kendall's coefficient of concordance (W) and categorised as negligible (<0.10), small ($0.10-<0.30$), moderate ($0.30-<0.50$), and large (≥ 0.50). When significant effects were found, post hoc pairwise comparisons were performed using the post hoc multiple comparisons following the Friedman test ($\alpha = 0.05$). Friedman tests and post hoc comparisons were conducted in Statistica 13 (StatSoft, Kraków, Poland).

Intra-session variability across the three repeated measurements was assessed separately for OE thickness and OE shear modulus at each loading condition. For each participant, the standard deviation (SD) of the three repetitions was calculated. A pooled within-subject SD was then computed as the square root of the mean of the individual within-participant variances. The pooled coefficient of variation (CV) was calculated as the pooled within-subject SD divided by the group mean and multiplied by 100. All calculations were performed in Microsoft Excel.

To examine associations among variables while accounting for repeated observations within participants, linear mixed-effects models were used. Load was treated as a continuous predictor, coded as 0, 3, 6, 9, and 12, with the PW condition set to 0 and subsequent values representing external load as a percentage of body mass. The models included participant-specific random intercepts and random slopes for load to account for between-participant variability in responses to progressive loading. Random slopes were specified as uncorrelated with the random intercept. Continuous predictors were mean-centred in the mixed-effects models.

Model assumptions were assessed using Q-Q plots of residuals and residual-versus-predicted plots. Models fitted to the untransformed EMG amplitude and shear modulus showed departures from residual normality and homoscedasticity. Therefore, both outcomes were natural-log transformed before the final mixed-effects analyses. Residual diagnostics were reassessed after transformation and showed marked improvement.

Observations with the largest positive or negative residuals, as identified in the diagnostic plots, were cross-checked against the source data. All measurements were valid and retained in the analyses. The following models were estimated:

- $\ln(\text{EMG amplitude}) \sim \text{load} + \text{OE thickness} + (1 \mid \text{participant}) + (0 + \text{load} \mid \text{participant})$;
- $\ln(\text{Shear modulus}) \sim \text{load} + \text{OE thickness} + (1 \mid \text{participant}) + (0 + \text{load} \mid \text{participant})$.

For each outcome, a load $\times$ OE thickness interaction was tested to assess whether the association between OE thickness and the outcome varied with load. Models with the interaction were fitted using maximum likelihood (ML). If the interaction was not statistically significant, the more parsimonious additive model was retained; otherwise, the interaction model was retained. The selected models were then refitted using restricted maximum likelihood (REML).

Denominator degrees of freedom for fixed effects were computed using the Satterthwaite approximation. Unstandardised regression coefficients (B), standard errors (SE), 95% Wald confidence intervals (CIs), F statistics, and *p* values were reported. Marginal and conditional R^2 values and random-effects variance components were also reported to characterise model fit and between-participant variability. Mixed-effects analyses were conducted in jamovi (version 2.7) using the GAMLj module (version 3.7.0).

Statistical significance was set at $\alpha = 0.05$. The rest condition was included for descriptive purposes only and was excluded from inferential analyses, which were limited to the progressively increasing loading conditions (PW-12%).

2.7. Use of Artificial Intelligence (AI)-Assisted Technologies

ChatGPT-5.6 (OpenAI, San Francisco, CA, USA) and Grammarly v1.2.294.1953 (Grammarly Inc., San Francisco, CA, USA) were used to assist with language editing, text organisation, consistency checks, statistical reporting, and the preparation of responses to reviewer comments. All statistical analyses were conducted by the authors using the specified statistical software. All methodological decisions, interpretation of the findings, verification of references, and final manuscript revisions were critically reviewed and approved by the authors, who take full responsibility for the manuscript's content. No AI-generated images were used.

3. Results

3.1. Participants' Characteristics

The study involved 42 participants (21 females and 21 males). Mean age was 23.12 ± 1.42 years, mean body height 173.81 ± 7.41 cm, mean body mass 71.45 ± 10.76 kg, and mean body mass index 23.57 ± 2.55 kg/m². Descriptive statistics of EMG amplitude, shear modulus, and OE thickness across loading conditions are presented in Table 1.

Table 1. Descriptive values of EMG amplitude, shear modulus, and OE thickness across loading conditions.

Loading Conditions		EMG Amplitude [μV]	Shear Modulus [kPa]	Thickness [mm]
Rest	mean $\pm$ SD	16.23 ± 9.00	15.52 ± 3.95	8.46 ± 2.35
	median [Q1–Q3]	14.08 [8.54–24.46]	14.96 [12.72–18.14]	8.39 [7.25–9.31]

Table 1. *Cont.*

Loading Conditions		EMG Amplitude [μ V]	Shear Modulus [kPa]	Thickness [mm]
PW	mean $\pm$ SD	17.38 $\pm$ 9.38	16.15 $\pm$ 4.09	8.28 $\pm$ 2.23
	median [Q1–Q3]	15.58 [8.71–25.79]	15.85 [12.76–18.83]	7.90 [7.07–9.08]
3%	mean $\pm$ SD	20.29 $\pm$ 12.04	18.71 $\pm$ 7.62	8.07 $\pm$ 2.18
	median [Q1–Q3]	18.16 [10.17–28.75]	16.65 [15.16–20.36]	7.66 [6.79–9.11]
6%	mean $\pm$ SD	23.33 $\pm$ 14.51	21.62 $\pm$ 12.79	8.05 $\pm$ 2.22
	median [Q1–Q3]	20.75 [11.5–31.92]	19.07 [15.38–23.42]	7.65 [6.62–9.08]
9%	mean $\pm$ SD	26.97 $\pm$ 18.30	26.60 $\pm$ 18.94	8.19 $\pm$ 2.14
	median [Q1–Q3]	22.08 [13.46–35.46]	22.41 [16.68–28.56]	7.94 [6.94–9.20]
12%	mean $\pm$ SD	32.43 $\pm$ 24.80	32.72 $\pm$ 23.51	8.32 $\pm$ 2.32
	median [Q1–Q3]	24.33 [16.00–35.38]	25.12 [17.53–38.46]	8.01 [6.67–9.54]

Data are presented as mean $\pm$ SD and median [Q1–Q3]. Q1, first quartile; Q3, third quartile.

Intra-session variability of OE thickness was low across loading conditions, with pooled CVs of 4.71%, 4.57%, 4.19%, 3.66%, and 5.48% for PW, 3%, 6%, 9%, and 12%, respectively. Corresponding pooled CVs for OE shear modulus were 8.83%, 18.62%, 15.29%, 21.72%, and 26.57%.

3.2. Effect of Load on EMG Amplitude, Shear Modulus, and Muscle Thickness

The Friedman test revealed a significant effect of load on OE thickness, shear modulus, and EMG amplitude. However, the magnitude of the effect differed across variables: it was negligible for OE thickness and moderate for both shear modulus and EMG amplitude (Table 2). Post hoc pairwise comparisons showed that EMG amplitude and shear modulus increased progressively with load, with significant differences observed between higher load levels and PW, as well as between selected intermediate and maximal load conditions. In contrast, although a statistically significant main effect was found for OE thickness, pairwise comparisons did not demonstrate a consistent load-dependent pattern, and the observed changes were small in magnitude (Figure 4).

Table 2. Effect of load on EMG amplitude, shear modulus, and muscle thickness.

Variable	χ^2 (df = 4)	<i>p</i> Value	Kendall's W
OE thickness	9.83	0.04	0.06
Shear modulus	70.23	<0.001	0.42
EMG amplitude	76.38	<0.001	0.45

χ^2 , Friedman test statistic; df, degrees of freedom; W, Kendall's coefficient of concordance.

3.3. Association Between OE Thickness and EMG Amplitude Under Increasing Load

The load $\times$ OE thickness interaction was not significant ($F(1, 52.3) = 0.67$, $p = 0.417$); therefore, the additive model was retained. In the final model, load was significantly associated with $\ln(\text{EMG amplitude})$, whereas OE thickness was not. Detailed model estimates and characteristics are shown in Table 3.

Table 3. Linear mixed-effects model examining the association between OE thickness and log-transformed EMG amplitude under increasing load.

Dependent Variable	Predictor	B	SE	95% CI	F (df1, df2)	<i>p</i>
$\ln(\text{EMG amplitude})$	Load	0.046	0.006	0.034–0.058	$F(1, 41.1) = 54.14$	<0.001
	OE thickness	0.006	0.027	−0.046–0.059	$F(1, 167.7) = 0.06$	0.814
Model characteristics					Value	

Table 3. Cont.

Dependent Variable	Predictor	B	SE	95% CI	F (df1, df2)	p
Marginal R ²					0.087	
Conditional R ²					0.957	
Random-intercept variance					0.386	
Random load-slope variance					0.0014	
Residual variance					0.0193	

B = unstandardised regression coefficient; SE = standard error; CI = confidence interval; df = degrees of freedom. EMG amplitude was natural-log transformed before mixed-effects modelling. The model included participant-specific random intercepts and random slopes for load. Marginal R² represents the variance explained by fixed effects, whereas conditional R² represents the variance explained by both fixed and random effects.

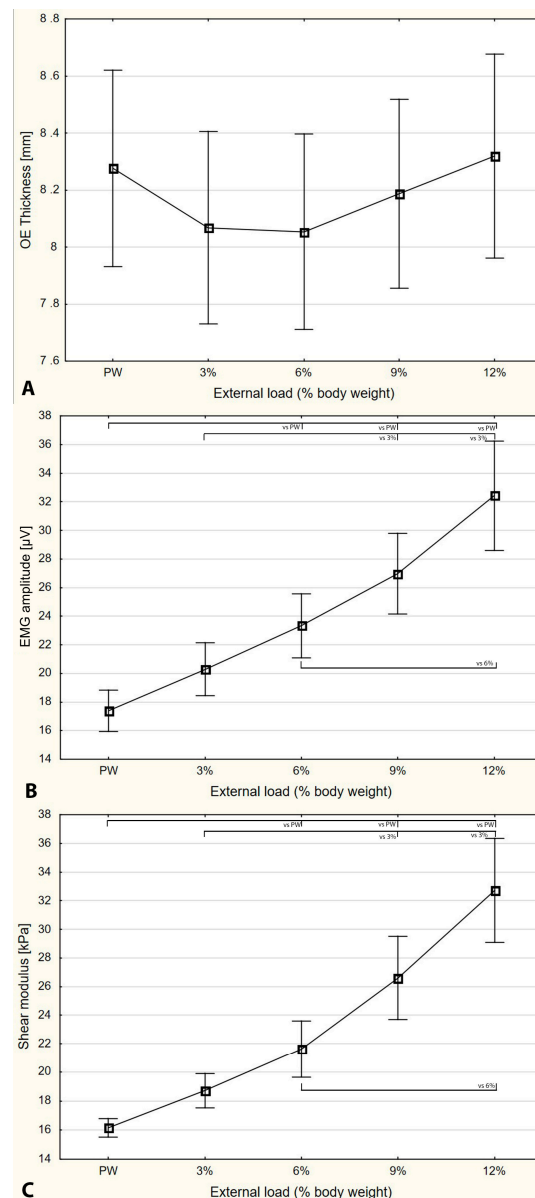


Figure 4. Effects of progressively increasing external load on external oblique muscle (OE) thickness (A), EMG amplitude (B), and shear modulus (C). Data are presented as mean $\pm$ SEM across PW and 3–12% body-mass loading conditions. Significant pairwise differences, identified by the Friedman ANOVA post hoc test ($\alpha = 0.05$), are indicated in the panels. The truncated Y-axis in panel A is used to visualise the small absolute changes in OE thickness, for which the overall effect size was negligible (Kendall's $W = 0.06$).

3.4. Association Between OE Thickness and Shear Modulus Under Increasing Load

The load $\times$ OE thickness interaction was not significant ($F(1, 53.2) = 0.11, p = 0.740$); therefore, the additive model was retained. In the final model, load was significantly associated with $\ln(\text{shear modulus})$, whereas OE thickness was not. Detailed model estimates and characteristics are shown in Table 4.

Table 4. Linear mixed-effects model examining the association between OE thickness and log-transformed shear modulus under increasing load.

Dependent Variable	Predictor	B	SE	95% CI	F (df1, df2)	p
$\ln(\text{Shear modulus})$	Load	0.046	0.007	0.032–0.059	$F(1, 41.0) = 44.77$	<0.001
	OE thickness	−0.015	0.021	−0.056–0.026	$F(1, 86.9) = 0.51$	0.475
Model characteristics					Value	
Marginal R^2					0.208	
Conditional R^2					0.885	
Random-intercept variance					0.127	
Random load-slope variance					0.0017	
Residual variance					0.0217	

B = unstandardised regression coefficient; SE = standard error; CI = confidence interval; df = degrees of freedom; shear modulus was natural-log transformed before mixed-effects modelling. The model included participant-specific random intercepts and random slopes for load. Marginal R^2 represents the variance explained by fixed effects, whereas conditional R^2 represents the variance explained by both fixed and random effects.

4. Discussion

This study examined the effects of load on EMG amplitude, shear modulus, and thickness of the OE, and assessed whether OE thickness was associated with EMG amplitude and shear modulus under progressively increasing load. EMG amplitude and shear modulus increased with load, whereas OE thickness changed only slightly and showed no consistent load-dependent pattern. In the mixed-effects models, OE thickness was not associated with either EMG amplitude or shear modulus after accounting for load. These findings supported the hypothesis that changes in OE thickness would not reflect the muscle's electrical and mechanical responses to progressive loading, and suggested that ultrasound-derived changes in OE thickness should not be interpreted as a direct indicator of OE activity in the tested position and loading task.

The interpretation that LAM thickness reflects muscle activity remains widely used in the literature. Delkhoush et al. [5] assessed abdominal muscle activity in both stable (prone and supine lying) and unstable positions (quadruped, Swiss ball sitting, and tilt board standing) using only ultrasound-derived muscle thickness measurements. Similarly, Yodthee et al. [6] investigated transversus abdominis activation by analysing only US-measured muscle thickness. Kim et al. [7] further examined changes in abdominal muscle activity during variations in curl-up and leg-raise exercises, using muscle thickness ratios derived from US. In contrast, studies directly comparing ultrasound-derived changes in abdominal muscle architecture or thickness with EMG have reported weak, inconsistent, or participant-, muscle-, task-, and contraction-intensity-dependent relationships [16–21]. In a critical review, Linek [1] emphasised that changes in LAM thickness should not be interpreted as evidence of muscle activation and recommended using neutral terminology, such as “changes in thickness” or “morphological changes”, to avoid overinterpretation. In the present study, the experimental setup enabled assessment of changes in OE thickness as upper-limb loading increased. As a result, the thickness of the OE showed no consistent load-dependent pattern and was unrelated to simultaneously collected EMG or SWE data.

However, a systematic review suggests that the relationship between muscle thickness and muscle activation is condition-dependent [4]. This relationship appears stronger when the target muscle acts as a prime mover or during standardised, muscle-specific contractions [20,22–24]. Nevertheless, even during OE-specific isometric trunk contractions, the relationship between changes in OE thickness and EMG amplitude has varied considerably across participants and tasks [19,21]. In our protocol, the OE did not act as a prime mover but was recruited as part of the trunk-stabilisation response during isometric upper-limb loading in a semi-supine position. Therefore, the absence of an association between OE thickness and EMG amplitude should be interpreted as task-specific rather than as evidence that OE thickness cannot reflect activation under any conditions. A potential biomechanical explanation is provided by the composite-laminate model of the abdominal wall, in which the OE, internal oblique, and transversus abdominis, along with their fascial layers, are mechanically coupled [17]. Contraction of adjacent muscles, tension transmitted through the fascial layers, and changes in intra-abdominal pressure may constrain OE shortening or modify its thickness independently of its electrical activation [1,17]. Taken together, the findings of the present study provide experimental support for concerns about using OE thickness as a direct proxy for muscle activity, specifically under the tested conditions [1,4]. Although this was not experimentally tested in the present study, we hypothesise that, owing to the mechanical coupling among the layers of the LAM [17], the same interpretative limitation may also apply to thickness changes in other LAMs. This hypothesis requires direct investigation. Clinically, under the tested conditions, ultrasound-derived OE thickness should be regarded as a morphological parameter and should not be used alone as a direct indicator of functional muscle activation, because sEMG amplitude and shear modulus increased despite minimal changes in thickness.

Several limitations should be acknowledged. First, sEMG recordings may have been affected by cross-talk from adjacent abdominal muscles, particularly the internal oblique [25,26]. Electrode-skin impedance was not quantified, and EMG amplitude was not normalised to MVC. Although electrode positions remained unchanged and the repeated-measures design reduced the influence of these factors on within-participant comparisons across loading conditions, they still limit between-participant comparisons and the interpretation of EMG amplitude relative to individual maximal activation. Future studies should determine whether these findings are reproduced using MVC-relative loading. Future validation studies could use intramuscular (fine-wire) EMG to provide a more muscle-specific assessment of OE activation. Second, the testing task did not preferentially recruit the OE as a prime mover and likely involved load sharing among the abdominal and other trunk muscles, which were not simultaneously assessed. Third, only the right OE was examined; therefore, the findings should not be directly extrapolated to all lateral abdominal muscles. Fourth, loading conditions were normalised to body mass rather than expressed relative to MVC. Although this provided objectively defined, directly verifiable force targets scaled to body size, the applied loads may have reflected different relative exercise intensities among participants, thereby contributing to interindividual variability in EMG amplitude and shear modulus and limiting comparisons with studies using MVC-based loading. Fifth, shear modulus represents a local mechanical response that may be influenced by active contraction, passive tension, muscle geometry, and force transmission, and should not be interpreted as a direct measure of neural activation [9,10,27]. Although a generous amount of ultrasound gel and minimal manual transducer pressure were used, transducer pressure was not objectively quantified. Sixth, although the 1 s EMG recording and US image capture were synchronised under stabilised isometric conditions, the protocol was not designed to examine fine temporal relationships or electromechanical delay between electrical activation and mechanical or morphological responses. Seventh, the sample

consisted exclusively of young and healthy individuals, which limits the generalisability of the findings to other populations. Furthermore, the protocol was based on a controlled laboratory task involving progressive isometric loading, and the findings may not directly translate to other functional or dynamic conditions. Finally, the statistical analyses were based on linear modelling approaches and therefore captured only linear associations between variables, whereas potential curvilinear or other non-linear relationships were not examined.

5. Conclusions

The present findings indicate that ultrasound-derived changes in OE thickness should not be interpreted as direct indicators of OE activity during the semi-supine, progressive isometric upper-limb loading task tested. OE thickness showed no consistent load-dependent pattern and was not associated with either EMG amplitude or shear modulus after accounting for load. Although only the OE was examined, mechanical coupling among the layers of the LAM suggests that similarly cautious interpretation may be warranted for thickness changes in other LAM layers; however, this possibility was not tested and requires direct investigation.

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Data Availability Statement: The anonymised data supporting the findings of this study are available from the corresponding author upon request.

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Abbreviations

The following abbreviations are used in this manuscript:

OE	external oblique
US	ultrasonography
sEMG	surface electromyography
EMG	electromyography
SWE	shear wave elastography
LAM	lateral abdominal wall muscles
PW	starting position
UST	ultrasound transducer
OI	internal oblique
TrA	transversus abdominis
MVC	maximal voluntary contraction

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