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M-mode ultrasound evaluation of lateral abdominal muscle postural response to load: an exploratory study

Maciej Biały[1,2], Wacław Marceli Adamczyk[3], Tomasz Stranc[4], Grzegorz Szlachta[5], Rafał Gnat[5]

[1] *Institute of Physiotherapy and Health Sciences, The Jerzy Kukuczka Academy of Physical Education, Katowice, Poland*
[2] *Functional Diagnostics Laboratory, Sport-Klinika, Scanmed Sport, Żory, Poland*
[3] *Laboratory of Pain Research, Institute of Physiotherapy and Health Sciences, The Jerzy Kukuczka Academy of Physical Education, Katowice, Poland*
[4] *Athletic Performance, Piast Gliwice FC, Gliwice, Poland*
[5] *Motion Analysis Laboratory, Institute of Physiotherapy and Health Sciences, The Jerzy Kukuczka Academy of Physical Education, Katowice, Poland*

Corresponding author: Maciej Biały; e-mail: mbfizjoterapia@gmail.com

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Abstract

Aim: There is a need to evaluate the tissue deformation index of lateral abdominal muscles using M-mode ultrasound in a cohort of healthy subjects to establish a convenient reference point for clinical reasoning in patients. The aim of the study was to assess differences in the tissue deformation index between individual lateral abdominal muscles regardless of body side, compare these differences in the tissue deformation index on the right and left sides of the body, and evaluate side-to-side differences in the tissue deformation index within individual lateral abdominal muscles. **Material and methods:** In a group of 126 healthy volunteers (59 females), the postural response of lateral abdominal muscles to external perturbation in the form of rapid arm abduction with load was recorded on both sides of the body, and the tissue deformation index was calculated. **Results:** The mean values of the tissue deformation index form an increasing gradient from deep to superficial lateral abdominal muscles: 0.06%/ms for the transversus abdominis, 0.084%/ms for the internal oblique and 0.151%/ms for the external oblique (p <0.001). Side-to-side intra-muscle differences were significant only for the transverse abdominis (right: 0.047%/ms; left: 0.070%; p <0.01). **Conclusions:** The tissue deformation index values differ significantly among individual lateral abdominal muscles and form a characteristic gradient: transversus abdominis < internal oblique < external oblique. The transversus abdominis muscle shows significant asymmetry in the tissue deformation index between the left and right sides of the body.

Introduction

Lateral abdominal muscles (LAMs) consist of three morphologically different units: external oblique (EO), internal oblique (IO), and transversus abdominis (TrA)[1]. They are usually divided into deep and superficial layers, however their actions are functionally unified and involved in many physiological activities, such as postural control[2], breathing[3], and activities such as sports[4]. A sedentary lifestyle and the resulting decrease in gravitational loads influence the structure and motor control of the LAMs[5–7]. These changes have been observed in individuals with lumbo-pelvic pain or disability and in subjects exposed to short-term experimental nociceptive stimulation within the lumbar region[8–16]. In such conditions, motor control deficiencies usually occur in the form of the disturbed TrA anticipatory function[10] or/and modification of the lumbar multifidus activation pattern[17]. These adaptations manifest as delayed onset of the TrA activity and atrophy of the multifidus muscle along with its deficient voluntary isometric contraction[10,18,19]. In contrast to deep muscles, impairment of motor control of the superficial layer (e.g., EO) usually involves increased bioelectric activity[12].

A number of studies have investigated LAM motor control by measuring muscle thickness and electrical activity in different populations: healthy adolescents[20], normal subjects[21], individuals with and without low back pain[16,22–24], and athletes[25–28], during various exercises and therapy[29–33]. Significant progress has been made in this research field over the last two decades due to the use of the

non-invasive and low-cost real-time ultrasound (US) measurement of the LAMs, both in the scientific and clinical settings. Many researchers utilized real-time US in B and M modes to assess changes in LAM thickness between rest and voluntary activation[34–38]; however, thickness change alone does not allow for the measurement of the temporal parameters of muscle activation. Therefore, Mannion *et al*. attempted to use tissue Doppler imaging to assess the time of muscle activation, with results quite similar to electromyography. Nevertheless, their technique did not determine which of the LAMs was activated in the first order[38]. Another US-based approach is tissue velocity imaging, in which the velocity of muscle deformation is assessed[39]; however, the authors reported limited reliability of the measurement. Moreover, US measurement seems to be a reliable and valid tool for assessing skeletal muscle mass. Muscle thickness measured in B-mode US constitutes the most commonly used parameter in this regard due to its relative simplicity and strong correlation with other standard measurements[40]. In our previous reports, we presented an alternative and simple method for assessing LAM activity involving M-mode real-time US imaging, where we recorded the reflex response of the LAMs to postural perturbation in the form of rapid arm movement with an external load and calculated the tissue deformation index (TDI). The TDI combines information on the spatial and time parameters of LAM activation and illustrates the percentage change in the given LAM thickness over time (i.e., the velocity of muscle tissue deformation). We found that TDI values differed significantly among individual LAMs and that three repeated measurements during the procedure seemed sufficient to achieve the acceptable reliability level (intraclass correlation coefficient >0.8)[41].

In light of the mentioned issues, the aim of this study was to evaluate the TDI of the LAMs in a larger population. To avoid pain interference, we decided to recruit only healthy subjects. Our goal was to establish a convenient reference point for clinical reasoning in patients. The detailed objectives were to evaluate: (1) inter-muscle TDI differences for individual LAMs regardless of body side; (2) inter-muscle TDI differences on the right and left sides of the body; and (3) side-to-side intra-muscle TDI differences for individual LAMs. We hypothesized that there are significant differences in TDI values between individual LAMs and between the right and left sides of the body. Our results can further serve as a reference point for clinical conditions.

Material and methods

Out of the 150 volunteers who responded to our announcement, 126 (59 females) were included (mean age: 22.87 ± 2.61 years; body mass: 69.89 ± 12.62 kg; body height: 174.07 ± 10.24 cm; body mass index (BMI): 22.90 ± 2.46). A purposive sampling strategy was applied with the following inclusion criteria: no history of serious pain or injury within the lumbo-pelvic area or lower extremities (requiring medical assistance for at least two weeks); no history of any surgical intervention; no pain or functional limitations within the upper extremities; no pain or other minor inconveniences (e.g., headache, post-exercise fatigue, cold, etc.) on the day of measurement; and no exercise training engaging the lumbar and abdominal musculature (Pilates, Yoga, Tai Chi, Australian approach, etc.) in the two months prior to measurement. All subjects signed their written informed consent. The research was approved by the Ethics Committee of The Jerzy Kukuczka Academy of Physical Education in Katowice, Poland (No. 18/2007).

Two certified physiotherapists, each with two years of professional experience, acted as raters for the procedures. They underwent four weeks of training in US measurement of the LAMs (three 3-hour sessions per week). The training was guided by an experienced specialist not directly involved in the study. After training, the specialist reported that the raters were skilled enough to fulfil their role in the study. Three tasks were randomly assigned to the raters prior to the study: (1) operating the US array; (2) recording US images; and (3) interpreting data from recorded US images. The tasks remained unchanged throughout the procedure and the raters were blinded to the objective of the study. A third person was also involved, whose responsibility was to supervise the procedure, recruit the subjects, check them against the selection criteria, and encode the recorded US images.

A US imaging device equipped with a 75L38EA linear array was used for the measurements. The images were obtained at an imaging frequency of 5 MHz[37,42,43]. First, B-mode US was used to identify the optimal site for LAM imaging. Then, the device was switched to M mode and the final image of the LAMs was recorded (in jpg format). We evaluated the activation of the LAMs in response to postural perturbation in the form of rapid arm abduction with a weight of 3 kg held in the subject's hand[44]. The movement was triggered by an auditory stimulus[43]. The movement of abduction was chosen for two reasons: (1) in previous studies, we found that the images recorded during arm abduction present less graphical distortion[41]; and (2) no rotation moment acts on the trunk during arm abduction (this moment is present during arm flexion/extension and is virtually parallel to the direction of LAM fibers, especially TrA), which might introduce movement-direction-dependent changes in the pattern of activation[45].

The subjects assumed an erect position with feet 23 cm apart, sight fixed on a point marked on the wall and arms at their sides. With the US array positioned horizontally, Rater 1 identified the optimal location for LAM imaging on one (randomized) side of the body. Starting from the navel, the array was gradually moved in the lateral direction until the desired image of the three layers of the LAMs appeared on the screen[37]. The optimal array location was marked on the skin using a piece of elastic kinesio tape with an opening matching the array shape (Fig. 1). In this way, the array's position can be reproduced easily, if necessary. Subsequently, the US device was switched to M mode. The subjects held the 3-kg weight in their hand (contralateral to the location of the US array, due to technical reasons[39]) and performed three preparatory repetitions of rapid arm abduction up to 90°, triggered by an auditory stimulus in their earphones. The stimulus was synchronized with the start of M-mode image registration. The auditory stimulus appeared 2–6 s (in random order) after the subject indicated readiness. Six repetitions of arm abduction were performed and six M-mode US images were gathered. This constituted Series 1 of the measurements. An identical series (Series 2) was started after a 5-minute rest period in order to perform measurements on the opposite side LAMs. The procedure for LAM measurement and its reliability have been reported previously[41] and all measurements were conducted in a laboratory setting under standardized environmental conditions.

A total of 12 US images of the LAMs were gathered from each subject (two series of six recordings). These were checked for image quality by the third person. The two poorest images from Series 1 and 2 were excluded; thus, a total of eight images from each subject were ulti-

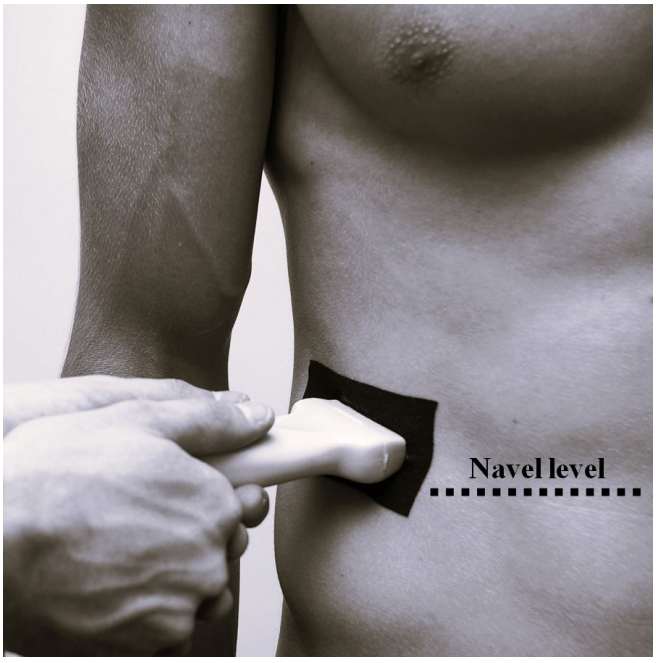

Fig. 1. *The probe location on the lateral abdominal wall was marked with a piece of kinesio tape, featuring an opening that matches the shape of the array. With the US array positioned horizontally, Rater 1 identified the optimal location for LAM imaging on one (randomized) side of the body. Starting from the navel, he gradually moved the array in the lateral direction until the desired image of the three layers of the LAMs appeared on the screen. The array's location was then marked using elastic kinesio tape with an opening matching the array's shape*

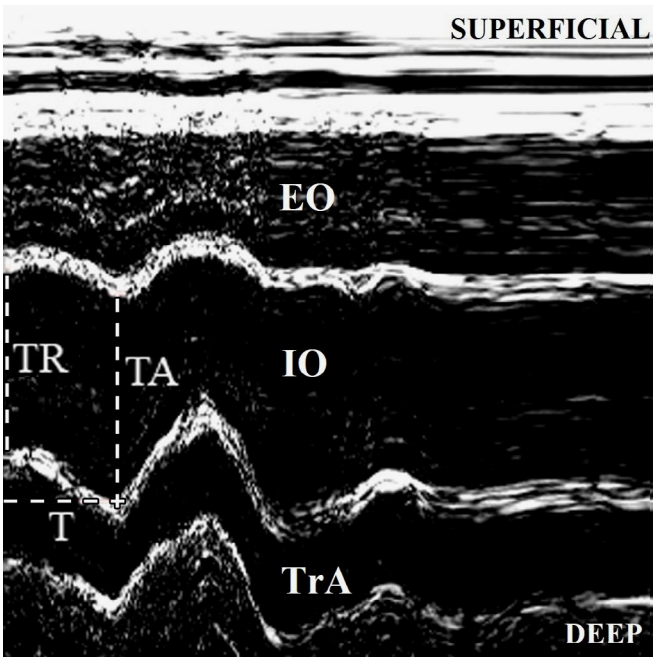

Fig. 2. *The image was enhanced with contrast correction (+75%) using Photoshop software. For illustration, measurements were conducted on the internal oblique (IO) muscle. Muscle thickness at rest was assessed along the TR line, between the inner borders of the intermuscular fascia. Thickness at maximal activation was measured along the TA line, at the point of deepest excursion of the fascia beneath the muscle. The time to maximal activation was measured along the T line, between the TR and TA lines. The measurement protocol was consistent for both the external oblique (EO) and transversus abdominis (TrA) muscles*

mately subjected to analysis. To reduce bias, the names of the selected images were encoded and the images were transferred to a computer to be analyzed using Photoshop 8.0 (Adobe, San José, USA). The contrast (+75%) and zoom (×10) of the images were adjusted and, using the Photoshop tools, the following measurements were performed for each of the LAMs (TrA, IO and EO): muscle thickness at rest, muscle thickness at the point of maximal activation (both along the *y*-axis of the image), and time to achieve maximal activation (along the *x*-axis of the image). Both image axes were scaled to provide accurate information on the time and spatial parameters (Fig. 2).

Based on the outcomes of the three mentioned measurements, the TDI was calculated for each individual LAM according to the following formula:[41]

$$TDI = [(TA/TR \times 100\%) - 100\%] \times T^{-1}$$

where:
TDI = tissue deformation index (%/ms);
TR = muscle thickness at rest (mm);
TA = muscle thickness at maximal activation (mm);
T = time to achieve maximal activation (ms).

Having chosen four US images of best quality, we calculated four TDIs for each individual LAM. These four values were subsequently averaged and their mean value was subjected to statistical analysis.

Statistical analysis was performed using Statistica 10 software (StatSoft Inc., Tulsa, OK, USA). To verify distributions, normality analysis was carried out using the Shapiro-Wilk test. To detect side-to-side differences for individual LAMs, the Mann-Whitney U test was used. Kruskal-Wallis ANOVA was conducted to test differences between individual LAMs, irrespective of body side (both sides of the body pulled together) and with division into right and left side muscles, along with its corresponding post-hoc test (multiple comparisons for Kruskal-Wallis ANOVA); $p < 0.05$ was considered significant.

Results

Regardless of body side, the differences between TrA (mean 0.058%/ms), IO (0.084%/ms) and EO (0.151%/ms) were statistically significant ($H = 141.32$; $p < 0.001$) (Fig. 3). Similarly, significant differences were observed on the right side (TrA: 0.047%/ms; IO: 0.081%/ms; EO: 0.154%/ms; $H = 87.51$, $p < 0.001$) (Fig. 4, right section) and left side (TrA: 0.070%/ms; IO: 0.087%/ms; EO: 0.149%/ms; $H = 55.59$, $p < 0.05$) (Fig. 3, left section) of the body, with one exception: left TrA and left IO ($p > 0.05$). Intra-muscle differences of the TDI between the same LAMs (TrA, IO and EO) on the right and left body sides were statistically significant only for TrA (right TrA: 0.047%/ms; left TrA: 0.070%/ms; Mann-Whitney U test: $Z = 3.21$, $p < 0.01$) (Fig. 5, left section). The results for IO and EO were not significant: (right IO: 0.081%/ms; left IO: 0.087%/ms; Mann-Whitney U test: $Z = 1.14$, $p > 0.05$) (Fig. 5, middle section); (right EO: 0.154%/ms; left EO: 0.149%/ms; Mann-Whitney U test: $Z = -0.41$, $p > 0.05$) (Fig. 5, right section). Within the overall number of recorded TDI measurements, 93% were positive, which signifies an

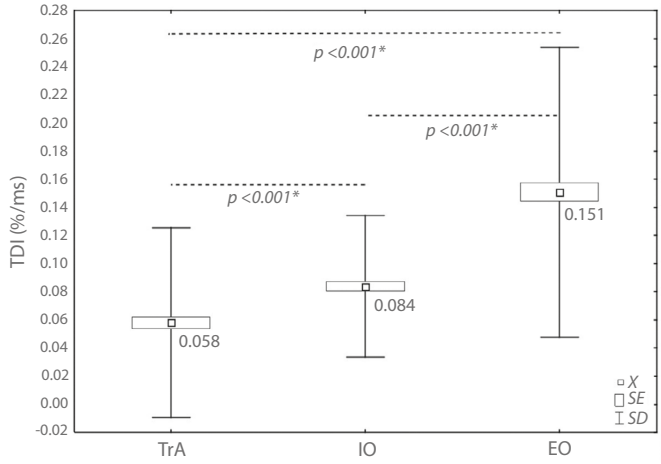

Fig. 3. *Mean values of the tissue deformation index (TDI) for lateral abdominal muscles (TrA – transversus abdominis; IO – internal oblique; EO – external oblique) regardless of body side. Squares denote the mean value (X); frames represent the standard error (SE); whiskers denote the standard deviation (SD); *statistically significant*

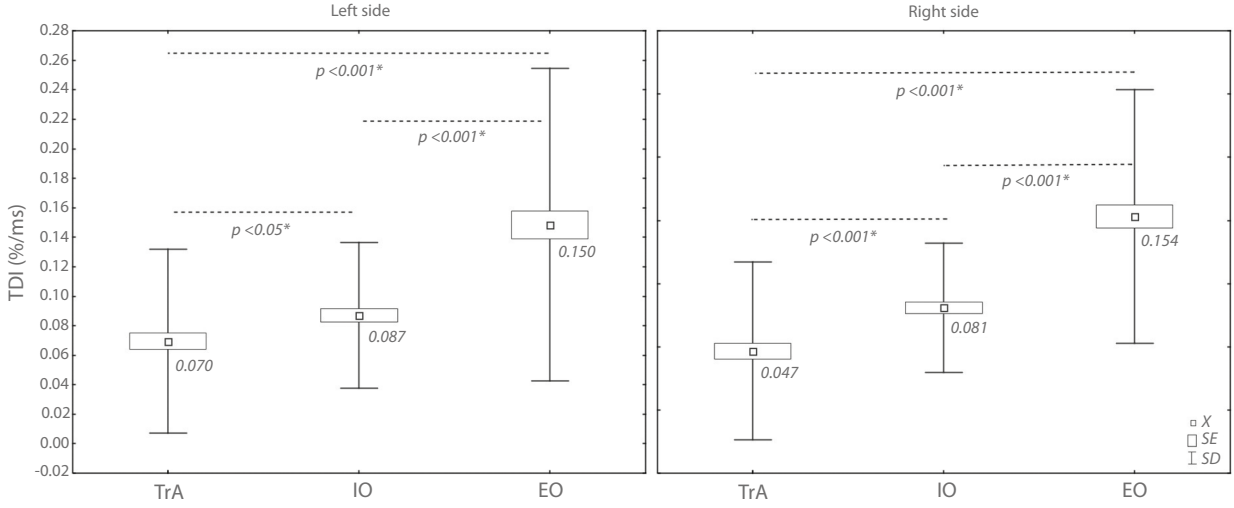

Fig. 4. *Mean tissue deformation index (TDI) values for lateral abdominal muscles (TrA – transversus abdominis; IO – internal oblique; EO – external oblique) on the left and right sides of the body. Squares denote the mean value (X); frames represent the standard error (SE); whiskers denote the standard deviation (SD); *statistically significant*

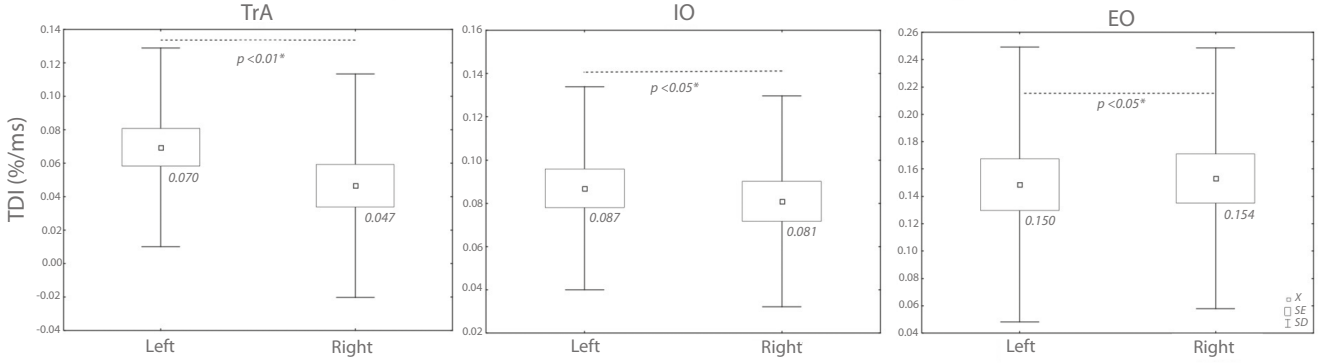

Fig. 5. *Average intra-muscle tissue deformation index (TDI) values for the lateral abdominal muscles (TrA – transversus abdominis; IO – internal oblique; EO – external oblique) on the left and right sides of the body. Squares denote the mean value (X); frames represent the standard error (SE); whiskers denote the standard deviation (SD); *statistically significant*

increase in muscle thickness over time, whereas 7% were negative, indicating a decrease in muscle thickness over time. As far as individual muscles are concerned, the largest number of negative values was recorded for TrA: 17% (42 images). Detailed results of the TDI values are presented in Tab. 1.

Tab. 1. Tissue deformation index (TDI: divided into positive and negative values) for individual lateral abdominal muscles with respect to body side

TDI	*N*	Mean	SD	–95%	+95%CII
TrA, R	126	0.047	0.057	0.051	0.071
>0	94	0.073	0.061	0.061	0.085
<0	32	0.028	0.024	0.020	0.037
TrA, L	125	0.070	0.057	0.063	0.084
>0	115	0.078	0.058	0.067	0.089
<0*	10	0.026	0.021	0.011	0.041
IO, R	126	0.081	0.051	0.071	0.090
>0	125	0.082	0.051	0.072	0.091
<0*	1	0.003	–	–	–
IO, L	126	0.087	0.049	0.078	0.095
>0	125	0.087	0.050	0.087	0.096
<0*	1	0.035	–	–	–
EO, R	126	0.154	0.098	0.136	0.171
>0	123	0.158	0.098	0.140	0.175
<0*	3	0.024	0.018	0.068	0.020
EO, L	126	0.150	0.103	0.133	0.168
>0	123	0.153	0.103	0.135	0.172
<0*	3	0.039	0.020	0.089	0.011

TrA – transversus abdominis; IO – internal oblique; EO – external oblique; R – right side of the body; L – left side of the body; >0 – positive values; <0 – negative values; SD – standard deviation; CI – confidence interval

Discussion

This study is the first to investigate TDI values in a large cohort of 126 healthy subjects with a mean age of 22.87 ± 2.61 years. The differences in TDI values among the LAMs demonstrate a similar deformation pattern to that reported previously[41], which suggests that these values might be considered a reference points for assessing LAM abnormalities in various dysfunctions of the lumbo-pelvic region (e.g., low back pain). The main findings indicate that, despite the fact that the LAMs are often perceived as a single functional unit, they show different deformation patterns during postural disturbances induced by rapid arm abduction with load. We observed significant differences in TDI values for TrA, IO and EO irrespective of body side and with division into left and right side muscles. Moreover, the results of this study confirmed our previous findings, demonstrating the existence of a characteristic LAM TDI gradient (TrA < IO < EO) which can be explained by the LAM morphology. The superficial EO is mainly composed of fast-twitch muscle fibers[46], which matches the highest velocity of its deformation (TDI = 0.151%/ms). In contrast, the deepest TrA, which has a greater proportion of slow-twitch fibers, yielded the lowest TDI value (0.053%/ms). The recorded TDI gradient was observed on both body sides and was statistically significant between individual LAMs (p <0.001 in all cases except the left side TrA and IO, where p >0.05), which may reflect the morphometric variability of the LAMs[47].

The TrA muscle was the only one among all the LAMs that showed a significant intra-muscle TDI difference between body sides (right TrA: 0.047%/ms; left TrA: 0.070%/ms). This asymmetry in thickness change over time was not detected in the case of IO and EO. Despite significant differences in the mean TDI for TrA, its standard deviations on the right and left body sides overlap to a significant degree (Fig. 5 and Tab. 1). Therefore, the results for TrA and its side-to-side asymmetry are questionable. Richardson *et al.* reported that symmetrical activation of the LAMs, particularly TrA, during postural perturbation is necessary for optimal stabilization of the lumbo-pelvic complex[47]. Conversely, Gray *et al.* found LAM thickness asymmetry in asymptomatic athletes but in symptomatic subjects they recorded LAM thickness symmetry[48]. Our results do not provide additional clarity on this dilemma.

Additionally, we noted another characteristic of TrA that distinguishes it from other LAMs. A total of 251 TrA muscles were analyzed (one excluded due to a lack of a recorded image) on the right and left sides of the body, 42 of which showed a different postural response to upper extremity movement. In most cases (83%), TrA increased its thickness, which was indicated by a positive TDI value, whereas in 42 cases (17%) the TDI was negative, indicating a decrease in thickness as compared to the initial status. This variety of TrA reactions justifies the use of the adjective "variable" as the most appropriate to describe its typical physiological activation. This variability might also account for the previously reported, though questionable, side-to-side TDI differences for TrA. It is also reflected in the timing of TrA activation. Hodges *et al.* were the first to note that TrA may act in a different, anticipatory manner, engaging what is known as the feed-forward mechanism of activation[9]. Jacobs *et al.* noticed that healthy individuals demonstrate increased variability in the activation time of deep LAMs compared to individuals with low back pain[18]. Lehman *et al.* reported delayed TrA activation in a group of healthy individuals on the side where the upper extremity movements were performed[49]. Marshall and Murphy observed this phenomenon in 20% of their subjects[50]. Similarly, Alison *et al.* outlined that TrA anticipatory activation occurs only on the body side contralateral to the upper extremity performing movements[44]. The variability in TrA behavior may suggest that the control mechanism of this muscle is flexible and shows diversity depending on the specific motor requirements (e.g., symmetric/asymmetric moments of internal/external forces acting statically/dynamically or in combination with e.g. pain within the lumbo-pelvic region). Perhaps traces of such plasticity should be sought in the central nervous system. Gnat *et al.* provided interesting insights in this regard by using functional magnetic resonance imaging to analyze brain activity during conscious stimulation of both the deep layer (e.g., TrA) and the superficial layer abdominal muscles. A significantly greater range of changes in brain activity was observed during deep layer activity[51]. The results of this experiment confirm that TrA engages the brain in a more complex way. Therefore, it can be claimed that TrA activation is more demanding and more difficult to coordinate, making it more susceptible to various types of disorders. Perhaps the next step that should be taken to confirm the variability of TrA behavior is to individually determine its variability for each subject.

There are several limitations to the presented study. First of all, our results are confined to a healthy and potentially young cohort and yet they seem to be clinically useful because they offer a good reference for symptomatic populations. Subjective and arbitrary adjustments of image contrast during image analysis may introduce errors. When used inappropriately, such adjustments may alter perceived muscle boundaries. These procedures were, however, tested in previous studies[40]. Furthermore, we did not implement standardized control of the US array position and pressure, which posed challenges during rapid arm abduction. Nevertheless, in our opinion, this limitation can be minimized thorough appropriate training of the raters.

Conclusions

We observed significant differentiation of the TDI among the individual LAMs, which may be expressed by the following TDI gradient: TrA < IO < EO. This pattern of TDI values is characteristic regardless of body side. The TrA muscle showed differences between the left and right sides of the body, with simultaneous high variability in TDI outcomes (the highest number of negative TDI values). The more superficial muscles, IO and EO, showed no side-to-side differences in the TDI. The results were obtained using a very simple US device, avoiding the limitations inherently linked to the electromyographic measurement. Recorded differences in the TDI values may be used as a convenient reference point for clinical reasoning in patient populations with different lumbo-pelvic disorders.

Conflict of interest

The authors do not report any financial or personal connections with other persons or organizations which might negatively affect the contents of this publication and/or claim authorship rights to this publication.

Author contributions

Original concept of study: MB, WMA, RG. Writing of manuscript: MB, GS, RG. Analysis and interpretation of data: TS, GS, RG. Final acceptation of manuscript: MB, WMA, TS, GS, RG. Collection, recording and/or compilation of data: MB, WMA, TS, RG. Critical review of manuscript: MB, WMA, TS, GS, RG.

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