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Rehabilitative Ultrasound Imaging of the Abdominal Muscles

Lumbar stabilization training has proven to be a successful treatment option for those with spondylolysis and spondylolisthesis,[80] posterior pelvic pain associated with pregnancy,[102,103] chronic low back pain (LBP),[33] or specific physical signs and symptoms predictive of success.[38] Rehabilitation strategies aiming to restore muscle function in individuals with these types of lumbopelvic dysfunctions have been associated with clinical improvements such as reductions in pain, disability, and recurrence of LBP.[28,33,40,80,103] These exercise programs typically require the assessment and training of the abdominal muscles.

It is important that any clinical rehabilitation or research strategy has reliable and sensitive measures to provide accurate and meaningful information about the specific function targeted by the intervention. This is particularly challenging for the control and coordination of the abdominal muscles, as traditional measures of strength and endurance do not fully explain how a muscle is used during functional tasks.

Ultrasound imaging (USI) and its use in rehabilitation (rehabilitative ultrasound imaging [RUSI])[105] has emerged as a possible solution. RUSI is particularly relevant for assessment and rehabilitation of the abdominal muscles, as it provides one of the only clinical methods to appraise the morphology and behavior of the deepest abdominal muscle, the transversus abdominis (TrA), which is a common target of rehabilitation in contemporary exercise management of certain types of low back and pelvic pain.[63,89] The purpose of this commentary is to review the anatomy of the abdominal muscles as it relates to imaging, to summarize the application of RUSI for assessment and training of these muscles, to consider methodological issues and psychometric properties of contemporary techniques, to highlight intricacies related to interpretation of USI of the abdominal muscles, and to provide guidelines for use and future investigation based on current knowledge.

SYNOPSIS: Rehabilitative ultrasound imaging (RUSI) of the abdominal muscles is increasingly being used in the management of conditions involving musculoskeletal dysfunctions associated with the abdominal muscles, including certain types of low back and pelvic pain. This commentary provides an overview of current concepts and evidence related to RUSI of the abdominal musculature, including issues addressing the potential role of ultrasound imaging in the assessment and training of these muscles. Both quantitative and qualitative aspects associated with clinical and research applications are considered, as are the possible limitations related to the interpretation of measurements made with RUSI. Research to date has utilized a range of methodological approaches, including different transducer placements and imaging techniques. The pros and cons of the various methods are discussed, and guidelines for future investigations are presented. Potential implications and opportunities for clinical use of RUSI to enhance evidence-based practice are outlined, as are suggestions for future research to further clarify the possible role of RUSI in the evaluation and treatment of abdominal muscular morphology and function. *J Orthop Sports Phys Ther 2007;38(8):450-466. doi:10.2519/jospt.2007.2558*

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REGIONAL ANATOMY

Optimal generation and interpretation of sonographic images are dependent on a clear understanding of the underlying anatomy. Many factors, such as muscle shape, size, depth, origin and insertion, and fiber orientation, must be considered. This section describes the applied anatomy of the abdominal wall as it relates to lumbopelvic neuromuscular control and RUSI. For the purpose of this commentary, the abdominal musculature will be divided into the lateral abdominal wall, consisting of the obliquus externus abdominis (OE), obliquus internus abdominis (OI), and the TrA muscles, and the anterior wall, consisting of the rectus abdominis (RA) muscle and associated fascia.

Lateral Abdominal Wall

USI of the lateral abdominal wall (transverse plane) yields an image (**FIGURE 1**) consisting of 3 layers of muscles separated by hyperechoic (whiter) lines relating to the intermuscular fascial layers. From superficial to deep, the fascial lines separate the skin and subcutaneous tissue, OE, OI, TrA muscles, and the abdominal contents.

Although there is individual variability, a normal resting image of the lateral abdominal wall is typically characterized by muscle layers that are tapered in thickness towards their anterior border, of even thickness throughout their middle portion, and curved laterally (**FIGURE 2A**). Thickness of the TrA and OI muscles may increase during expiration, as both are accessory respiratory muscles.[1,21,77,101]

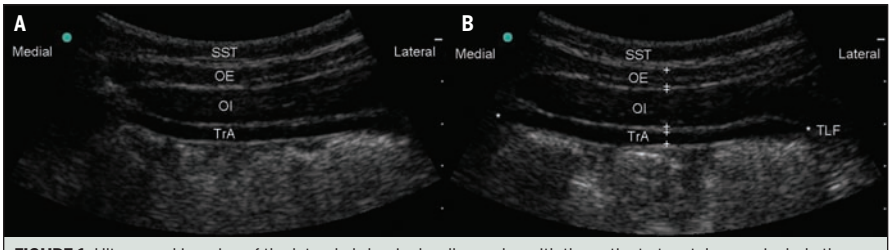

FIGURE 1. Ultrasound imaging of the lateral abdominal wall muscles with the patient at rest. Images include the transversus abdominis (TrA), obliquus internus abdominis (OI), and obliquus externus abdominis (OE) muscles, along with superficial soft tissue (SST) and the thoracolumbar fascia (TLF). (A) Demonstrates a more anteriorly positioned transducer, in which the center of the transducer is along the anterior axillary line. This position allows for visualization of the anterior reach of the lateral abdominal wall. The OE, OI, TrA, and SST are visible. (B) Demonstrates the entire length of the TrA muscle. Represents the anterior and posterior reach of the TrA muscle. The OE, OI, TrA, TLF, and SST are visible. Thickness measurements are marked in alignment with the center of the image.

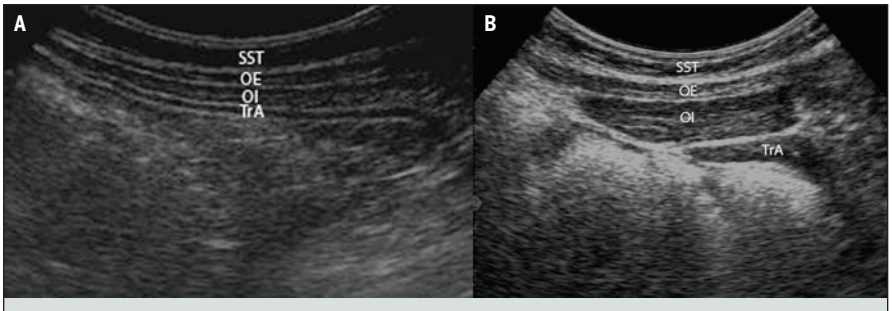

FIGURE 2. Ultrasound imaging of the lateral abdominal wall at baseline, annotating resting activity. Images include the transversus abdominis (TrA), obliquus internus abdominis (OI), and obliquus externus abdominis (OE) muscles, and superficial soft tissue (SST). (A) Ultrasound image of the left lateral abdominal wall, in which normal resting activity is assumed. In the region between the inferior aspect of the rib cage and the superior aspect of the iliac crest, the OI muscle is the thickest, followed by OE, and then TrA muscles.[85,110] (B) An image of the left anterolateral abdominal wall with the patient at rest demonstrating a possible increase in baseline activity of both TrA and OI muscles, as visualized by an increase in baseline muscle thickness while the patient is at rest. This may be visualized as the muscle layer being more equal in depth throughout its length, with the appearance that it is being held in a static or fixed "corset" shape throughout its lateral reach.

Muscle Fascicle Orientation and Attachments The fibers of the OE arise from the outer surface of the lower 8 ribs and terminate into the linea alba and anterior half or third of the iliac crest.[78,121] Some authors describe a posterior attachment into the thoracolumbar fascia (TLF) at the upper lumbar levels,[4] while others describe a free posterior border.[121] The OI muscle arises from the anterior two thirds of the iliac crest and the lateral half or third of the inguinal ligament, and attaches to the lower 3 or 4 costal cartilages, the linea alba, and the pubic crest.[78,121] Variable attachments of OI fascicles to the TLF from the lower lumbar vertebrae have also been described.[4,8,78] The TrA muscle originates from the inner surface of the lower 6 costal cartilages, from the TLF, the anterior two thirds of the iliac crest, and the lateral third of the inguinal ligament, and inserts into the linea alba anteriorly and pelvis.[78,121]

The lateral abdominal wall muscles can be divided into 3 regions (**FIGURE 3**): the upper (above the 11th costal cartilage), middle (between the 11th costal cartilage and the iliac crest), and lower (below the iliac crest) section.[110] Regional differences

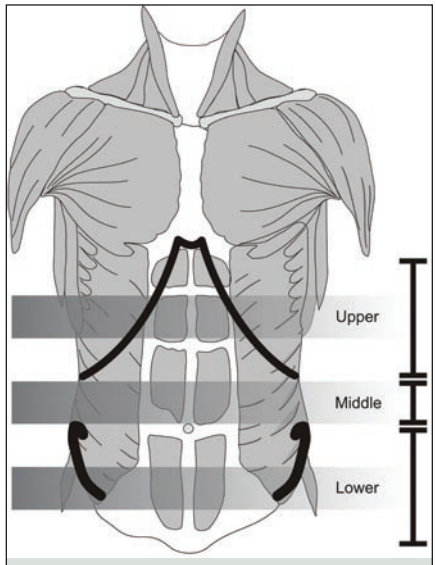

FIGURE 3. Anterior view of the regions of the abdominal wall. The upper region is above the 11th costal cartilage, the middle region is between the 11th costal cartilage and the iliac crest; the lower region is below the level of the iliac crest.

in fascicle orientation, particularly for the TrA and OI muscles, suggest functional diversity, an assertion recent electromyographic (EMG) investigations support.[20,53,76,101,110,112-114] Appreciation of these regional differences assists researchers and clinicians in understanding the influence of these deep muscles on the fascial system and how these differences may pertain to control of the lumbar spine and pelvis. Due to the unique function of the TrA muscle during lumbopelvic loadings,[51,53] the apparent prevalence of changes in control of this muscle in people with lumbopelvic pain,[27,52] and the evidence that changes in this muscle can be identified with RUSI,[27,39] the regional anatomy of this muscle is presented in greater detail.

Anatomically, regional morphological differences in the TrA muscle are readily apparent. The upper horizontally oriented fascicles are thought to assist control of the rib cage via their origins on the lower 6 costal cartilages.[19,110,112] The middle fascicles, which have a slight inferiormedial orientation, attach extensively to the aponeurosis of the TLF,[5,110] while the lower, more medially oriented fascicles arise from the iliac crest and inguinal ligament.[110,112] These morphological differences have implications for the potential contribution of the TrA muscle to lumbopelvic control. Specifically, bilateral activation of the TrA muscle can contribute via tensioning fascial structures of the lumbar region, including the TLF,[5] via modulation of intra-abdominal pressure (IAP)[45-47] and compression of the sacroiliac joint[92] and the inferior rib cage.

The middle fibers of the TrA muscle are the only muscle fibers that consistently attach to the TLF.[104] It is through this union that bilateral activation of the TrA muscle transmits tension to the lumbar spine.[104] Barker et al[5] simulated TLF tension in fresh human cadaveric spines at an amplitude equivalent to a moderate activation of the TrA muscle and detected an increase in spinal stiffness for both flexion and extension. In an in vivo porcine study, data suggest that transection of the middle layer of the TLF compromises the effect of a bilateral TrA activation on stiffness of the lumbar spine during caudal displacement.[45] Consequently, the musculofascial unit formed by the TrA muscle, the TLF, and the anterior fascial extensions has been described as a deep muscle "corset."[39]

Intervertebral control of the lumbar spine can also be augmented by increased IAP. Increased IAP in in vivo human and porcine studies leads to reduced intervertebral motion,[45] increased spinal stiffness,[47] and a mild extension moment.[46] Due to the fixation of the attachments of the upper and lower regions of the TrA muscle to the rib cage and pelvis, respectively, and the almost circumferential fiber orientation of the middle region of the TrA muscle, it is the middle region that has the greatest potential to modulate IAP.[110] EMG studies help to confirm that muscle activation of the middle region of the TrA muscle is more closely associated with IAP than other abdominal muscles,[15] and fibers in this region of the muscle have the lowest threshold for activation during respiration.[110] However, activation of the lower and upper fibers of the TrA muscle can also contribute to IAP modulation and is necessary if IAP is to increase.

Though the primary function of the lower fibers of the TrA muscle is likely to provide support of the abdominal viscera in upright postures, the muscle fibers in this region have the capacity to compress the sacroiliac joints, thus contribute to stability of these joints via the force closure mechanism described by Snijders et al.[98] A recent in vivo study has confirmed that voluntarily drawing in the abdominal wall (without activation of the more superficial abdominal muscles) increased the stiffness across the sacroiliac joints in healthy individuals.[92]

Along with the TrA muscle, the OI muscle has the potential to contribute to an increase in IAP,[15] compression of the sacroiliac joint (lower fibers),[92] and in some cases, tension of the TLF.[4] In addition, the OE muscle has the potential to increase IAP.[15] These muscles provide an important contribution to lumbopelvic control during everyday function.[69-71] However, the contribution of these muscles to lumbopelvic control must be balanced with their contribution to torque generation.[42]

Relative Muscle Thickness When relative thickness of the abdominal muscles is considered, the RA muscle (described below) is the thickest and the TrA muscle is the thinnest.[85] In subjects without a history of lumbopelvic pain, the RA, OI, OE, and TrA muscles represent 35.0%, 28.4%, 22.8%, and 13.8% of the cumulative abdominal muscle thickness (±2.4% to ±4.8%), respectively.[85] This pattern is independent of gender, side of measurement (left versus right), or the site of measurement in the middle abdominal region. Thus, this measure has potential utility as a simple screening tool to assess muscle changes such as those that occur with atrophy or pathology.[85] Although Rankin et al[85] were the first to report relative thickness values, retrospective analysis of mean values reported by earlier researchers[24,77] provide consistent data.

Homogeneity of Muscle Thickness The thickness of the abdominal muscles is not distributed evenly throughout the abdominal wall. Thus, thickness measurements are dependent on imaging site. Specifically, the upper portions of the lateral abdominal wall muscles are generally thicker.[85,110] The TrA and the OI muscles are homogenous in thickness throughout their middle and lower regions,[110] while the OE muscle (and very occasionally the TrA muscle) may be absent below the iliac crest.[110] Occasionally, a separate fascial layer within the middle and lower regions of the OI muscle has been reported.[110] This separate layer is sometimes visible on USI as an additional thin white fascial line within the boundaries of the muscle.

Due to the superior clarity of the muscle boundaries, the ease of identification of the individual muscles, and the clarity of changes in muscle thickness during activation, the middle region of the abdominal wall is most commonly selected

for USI of the lateral abdominal muscles. Although the middle region of the lateral abdominal wall is the most common site for USI, the lower region is the primary site selected for palpation of a contraction of the TrA muscle,[89] due to the absence or only thin layer of the OE muscle present at this level.[110] The potentially diverse functional roles of the middle and lower portions of the muscle and the impact that such differences may have on evaluation and biofeedback training require further investigation.

Symmetry of Muscle Thickness Symmetry can help guide the clinical evaluation of atrophy (or hypertrophy) or potential pathologic changes. In subjects without lumbopelvic dysfunction, side-to-side differences in thickness of the lateral abdominal wall muscles (ie, within subject) have been found to vary between 12.5% to 24%.[85] Although individual absolute difference values were not presented, the differences between the group means were small, ranging from 0.01 to 0.06 cm, 0.01 to 0.04 cm, and 0.01 to 0.02 cm, for the TrA, OI, and OE muscles, respectively.[85] Symmetry was near perfect for all muscles when relative thickness of these muscles, based on a total composite thickness value, was assessed (all muscles exhibited less than 1.5% differences between sides).[85] No differences in the side-to-side resting or contracted thickness of the TrA muscle have been demonstrated based on hand dominance in those without lumbopelvic dysfunction.[99] There is potential for asymmetry in individuals who perform repetitive asymmetric forces (occupational/recreational factors) or have an underlying anatomical predisposition (eg, scoliosis, pelvic obliquity, leg length discrepancies).[39] However, in a small sample of elite cricketers, no side-to-side differences in the TrA muscle were noted despite large differences in thickness of the OI muscle (Gray et al, unpublished data). In a retrospective study of individuals with unilateral lower limb amputations (n = 70), no side-to-side differences were noted in the TrA muscle thickness at rest, but the OI and OE muscles were larger on the ipsilateral side of the amputated limb.[30]

Effect of Gender on Muscle Thickness Based on absolute thickness values, males have significantly thicker lateral abdominal muscles than females.[10,85,99] This gender difference remains, with the exception of the TrA muscle, when normalized for body mass.[85] Springer et al[99] found that in healthy, asymptomatic women the TrA muscle represents a greater proportion of the total lateral abdominal muscle thickness, both at rest and during activation, than in men. In proportion to all 4 abdominal muscles, however, the relative thickness of the OI muscle has been found to be thicker in males without a history of lumbopelvic pain.[85] Gender differences in muscle thickness may have clinical implications. For instance, this may be associated with differences in response to training. Consistent with this proposal, Hansen et al[35] reported a gender bias to success rates for different trunk-strengthening programs. However, numerous other gender differences could equally account for the differences reported in the treatment response and there have been no studies that have investigated whether the success rates of neuromuscular retraining programs are influenced by gender.

Effect of Body Mass Index (BMI) on Muscle Thickness BMI is a potential predictor of muscle size. Rankin et al[85] and Springer et al[99] found positive correlations between BMI and abdominal muscle thickness. However, correlation coefficients (r = 0.36-0.57) reported by Rankin et al[85] are lower than those reported by Springer et al[99] (r = 0.66-0.80). The differences in muscle thickness of the TrA muscle associated with gender and BMI agree with data for other muscles.[56,64,107] Therefore, it may be important for future researchers to account for these relationships. For instance, gender and BMI may need to be considered as covariates. The relationship between muscle thickness and typical gender-specific patterns of fat distribution may be an important factor and has not been investigated to date. From a clinical standpoint, relative thickness values may be more meaningful than absolute values.

Effect of Age on Muscle Thickness Rankin et al[85] found a significant negative correlation between age and muscle thickness (r = −0.27 to −0.41) in the analysis of 123 subjects without a history of lumbopelvic pain, between 20 and 72 years of age. However, these correlation coefficients are considered too low to be considered clinically significant.[62] A study of 120 healthy subjects performing 6 different trunk exercises (Teyhen et al, unpublished data) found no age-related differences in the change in thickness of the TrA and OI muscles measured with USI.

Anterior Abdominal Wall

The anterior abdominal wall is comprised of the RA muscle and the anterior abdominal fascia. The anterior abdominal wall is divided into left and right by the linea alba (an intermixing of the OE, OI, and TrA aponeuroses). The RA muscle (**FIGURE 4**) is a large muscle with the primary function of approximating the rib cage with the pelvis by producing a flexion moment in the sagittal plane.[19] Measurement of the RA muscle with USI is unique amongst the abdominal muscles, as it is the only abdominal muscle for which cross-sectional area (CSA) may be measured.[85] The RA muscle has the greatest thickness of all the abdominal muscles, and men have a larger CSA than females in both absolute size and when normalized for body mass.[85] There is a significant positive correlation between BMI and the CSA of the RA muscle, but the correlation coefficient is low

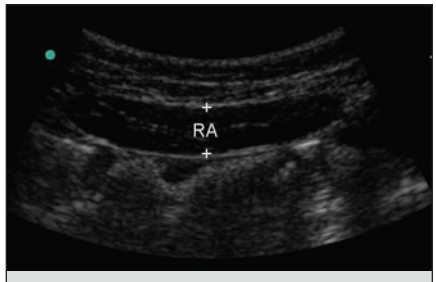

FIGURE 4. Ultrasound image of the rectus abdominis (RA) muscle (cross section). Thickness measurement is marked in alignment with the center of the image.

($r<0.54$).[85] Symmetry of the RA muscle (10%-12% difference side-to-side) is better than for any of the individual lateral abdominal muscles (12.5%-24% difference side-to-side), but is not better than the combined (total) lateral wall thickness (<10%).[85] Reid and Costigan[87] reported no significant differences in the CSA of the RA muscle associated with age.

The abdominal fascia lateral to the RA muscle is a complex arrangement of aponeurotic connections of the individual lateral abdominal wall muscles and the RA sheath.[78,93,121] The fibers of each lateral wall muscle cross midline and attach to the fibers from the contralateral lateral abdominal wall muscle to form the linea alba. The linea alba helps transmit loads between the sides of the abdominal wall. During activation of the TrA, the muscle belly shortens, thickens, and transmits its tension around the RA muscle and across midline.

Tissue Composition

Researchers have found that aging, chronic musculoskeletal dysfunctions, and/or denervation are associated with a decrease in water content and an increase in fatty fibrous content within muscles.[2,11,12,109] Although magnetic resonance imaging (MRI) is considered the gold standard for detecting these changes, researchers have suggested that USI may also provide some insight, as these tissue changes result in a degeneration of a muscle's architectural features and an increase in their echogenicity.[55,100] In a prospective study, Strobel et al[100] developed a qualitative evaluation tool (**TABLE 1**) to evaluate the accuracy of USI in depicting fatty atrophy of the supraspinatus and infraspinatus muscles, using MRI as the reference criterion. They concluded that USI is moderately accurate for the detection of significant levels of fatty atrophy in these muscles. Although research is needed to determine if a similar scale would be appropriate for the abdominal wall muscles, **FIGURE 5** helps to demonstrate the possibility of using USI for this function.

TABLE 1 Qualitative Evaluation Tool to Assess Tissue Composition Developed for the Assessment of Rotator Cuff Muscles[100]

Score*	Visibility of Muscle Contours, Pennation Angle, and Central Tendon	Echogenicity Compared to a Reference Muscle)
0	Clearly visible muscle contours	Isoechoic or hypoechoic
1	Partially visible structures	Slightly more echoic
2	Structures no longer visible	Markedly more echoic

**A score of at least 2 on 1 of these scales is required to state that the muscle has fatty infiltrate or atrophy.*

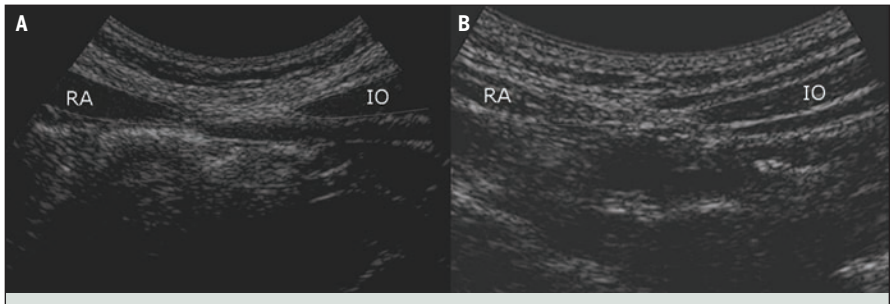

FIGURE 5. Ultrasound imaging of the lateral abdominal wall demonstrating changes in tissue composition. (A) Resting image of the right lateral abdominal wall at the point where the lateral aspect of the rectus abdominis (RA) muscle intersects with the obliquus internus abdominis (OI) muscle. Note the ease of delineating the muscle boundaries and their similarity and echogenicity. (B) A comparable image demonstrating a degeneration of the boundaries and an increase in echogenicity of the RA muscle.

QUANTITATIVE EVALUATION

This section highlights specific considerations regarding patient positioning, transducer selection, imaging technique, and measurement options for imaging the lateral and anterior abdominal muscles. The reader is referred to Whittaker et al[120] for additional details on the imaging procedure.

Imaging Procedure for the Lateral Abdominal Muscles

Positioning (**TABLE 2**) Although the lateral abdominal muscles are typically imaged with the subject relaxed in supine with the hips and knees flexed (hook-lying posture; **FIGURE 6**),[36,39,72,85,99,106] one of the advantages of USI is its versatility in assessing these muscles in many postures and during functional tasks (quadruped,[18] sitting,[1,21] sitting on physioball,[1] reclined in a chair,[48] standing,[9,10] or walking[9,10]). As an adjunct to ensure maintenance of a consistent pelvic position, a pressure biofeedback unit (Chattanooga Group, Hixson, TN) or a blood pressure cuff can also be used to monitor and provide feedback regarding changes in the position of the spine in some postures.[89]

FIGURE 6. A picture demonstrating patient positioning for rehabilitative ultrasound imaging of the abdominal wall. As depicted, the examiner should be on the right side of a patient when lying supine.

Transducer Selection Ultrasound transducers ranging from 5 to 10 MHz have been used to assess the lateral abdominal muscles (**TABLE 2**). Although a range of transducer frequencies permits adequate visualization of the lateral abdominal muscles, a higher frequency curvilinear

TABLE 2 Reported Imaging Procedures

Researchers	Patient Position	Transducer	Transducer Location
Rankin et al[85]	Supine with 2 pillows under knees	5 MHz linear	Immediately below the rib cage in direct vertical alignment with the ASIS. Measurements obtained at the thickest part of each muscle, usually at the center point of the image
Rankin et al[85]	Supine with 2 pillows under knees	5 MHz linear	Halfway between the ASIS and the ribcage along the mid-axillary line. Measurements obtained at the thickest part of each muscle, usually at the center point of the image
Teyhen et al[106]	Supine hook lying with arms at side and head in midline	5 MHz curvilinear (handheld)	Just superior to the iliac crest along the mid-axillary line. Standardized position of the TLF on the right side of the image. Measurements were obtained in the middle of the captured image
Springer et al[99]	Supine hook lying with arms at side and head in midline	5 MHz curvilinear (handheld)	Just superior to the iliac crest along the mid-axillary line. Standardized position of the TLF on the right side of the image. Measurements were obtained in the middle of the generated image
Ainscough-Potts et al[1]	1. Supine with arms across chest 2. Sitting in a chair without arm rests and arms across chest 3. Sitting on a physioball with feet flat on the floor and arms across chest 4. Sitting on a physioball while lifting 1 limb and arms across chest	7.5 MHz linear (handheld)	Halfway between the ASIS and the lower rib along the anterior axillary line. No mention of where along the length of the muscle the measurement was taken
Ferreira et al[27]	Supine hook lying with arms across chest and lower extremities supported	5 MHz curvilinear, secured in place with a dense foam cube	Half way between the iliac crest and the inferior angle of the rib cage. The medial edge of the transducer was placed approximately 10 cm from the subject's midline and then adjusted to ensure the medial edge of the TrA muscle was approximately 2 cm from the medial edge of the ultrasound image while the subject was relaxed. Muscle thickness was measured at 3 locations along the image: in the middle of the image and 1 cm to each side of midline. The average of these 3 measurements was used to represent muscle thickness
Hodges et al[48]	Reclining chair with hip flexed 30°	5 MHz linear array	Midpoint between iliac crest and inferior border of the rib cage, medial edge of the transducer 10 cm from midline. Measurement location was not specified
Henry et al[36]	Supine hook lying	7.5 MHz linear array (handheld)	Midpoint between iliac crest and inferior border of the rib cage, 10 cm lateral to midline. Qualitative analysis was performed; no measurements were reported
McMeeken et al[72]	Supine with 20° knee flexion based on 2 pillows beneath the knees	7.5 MHz linear array and 5 MHz curvilinear array	25 mm anteromedial to the midpoint between the ribs and the ilium. Measurement location not specified
Bunce et al[9,10]	Supine, standing, walking	6-10 MHz linear, secured in place with a high-density foam belt	Between the 12th rib and the iliac crest over the anterolateral abdominal wall vertical from the ASIS. Measurements obtained during m-mode USI
Hides et al[39]	Supine with hips and knees resting on a foam wedge	7.5 MHz linear array (handheld)	Inferior and lateral to the umbilicus as per Ferreira et al.[27] Measurements were obtained approximately at the middle of the image
Critchley[17]	Quadruped	7.5 MHz linear (handheld)	2.5 cm anterior to the midpoint between ribs and iliac crest. Measurements obtained in midline of the image
DeTroyer et al[21]	Sitting (comfortable in a high-backed arm chair)	5 MHz linear	Right anterior axillary line, midway between the costal margin and the iliac crest. Measurement location was not specified

Abbreviations: ASIS, anterior superior iliac spine; m-mode, motion mode; TLF, thoracolumbar fascia; TrA, transversus abdominis; USI, ultrasound imaging.

transducer, with its diverging field of view, is ideal, as it allows for greater visualization of the muscle throughout its length. In fact, a curvilinear transducer with a large footprint (≥60 mm) may allow for visualization of the entire length of the TrA muscle on some individuals (**FIGURE 1B**). However, if the goal is to assess a specific region or movement of a region, such as the lateral slide of the anterior aspect of the TrA muscle during an abdominal drawing-in maneuver (ADIM) or functional activity, a higher frequency linear transducer may allow for greater accuracy.

Transducer Location Based on the large area of the lateral abdominal muscles, a number of different imaging locations have been proposed (**TABLE 2**) and agreement on a standardized image location is pending. In general, researchers have focused on the middle abdominal region between the border of the 11th costal cartilage and the iliac crest (either along the mid axillary or anterior axillary line). Rankin et al[85] compared 2 of the more commonly used locations and found regional variation in the measurement.

Regardless of the imaging location, the ultrasound transducer is oriented transversely (**TABLE 2**, **FIGURE 1**). The orientation marker on the side of the transducer typically is directed towards the patient's right. Therefore the right side of the anatomy will be visualized on the left side of the screen (the image is interpreted as if looking through the body from the feet). However, variations based on the functional task being analyzed are acceptable. For example, if the image is to be used for biofeedback purposes, an alternative is to always have the transducer mark towards the patient's midline (the posterior aspect of the lateral abdominal muscles would be visualized on the right side of the image). This eliminates the need for the patient to understand that the anterior and posterior borders are reversed when imaged on the opposite side.

Thickness Measurement Measurement of thickness of the lateral abdominal muscles is dependent on the location where the measurement is obtained along the length of the muscle and the point in the respiratory cycle. Although the lateral abdominal muscles have a relatively uniform thickness in the middle and lower regions, this can vary and the location of the measurement should be noted. **TABLE 3** compares different measurement locations. Regardless of the region of the muscle being measured, the thickness values should be obtained perpendicularly between adjacent fascial borders. As activity of the abdominal muscles is modulated with respiration and the thickness of the abdominal muscles changes with activation, it is predictable that the muscles would be thicker during expiration than during inspiration.[1,21,77,101] Thus recordings should be made at a consistent point in the cycle. It has been proposed that the most consistent point to make measurements is at the end of a relaxed expiration (when the respiratory muscles can relax) and with the glottis open (to avoid bracing).[48]

TABLE 3 Comparison of Different Measurement Techniques

Location	Benefits	Drawbacks
Specified distance (eg, 2 cm) from the anterior border of the TrA muscle	Visualize the lateral slide of the anterior aspect of the muscle	Reliability of using the medial edge needs to be established
Specified distance (eg, 2 cm) from the posterior reach of the TrA muscle	The junction between the TrA and the TLF is easy to visualize with excellent reliability	Unable to consistently visualize the slide of the anterior abdominal fascia. Although a posterior slide appears to exist it has not been studied to date
Middle of the muscle belly	Middle of the muscle belly is similar regardless if the anterior or posterior reach of the TrA muscle is used to standardize the image	Error associated with examiner estimating the middle of the muscle belly. However, this error is probably minimal because the fascial lines are relatively parallel in this region
Multiple measurements of muscle thickness. Examples: 1. Measurement 1, 2, 3, and 4 cm from the anterior or posterior border of the TrA muscle 2. Measurement in the middle of the muscle belly and 1 cm to the left and right of this position	Multiple measurements across the muscle provide a broader representation of the muscle thickness values and its changes with activity	Time. Image processing techniques are being developed to help facilitate this process

Abbreviations: TLF, thoracolumbar fascia; TrA, transversus abdominis muscle.

The measure used for analysis will vary depending on the intention of the evaluation in clinical practice or research. As outlined above, absolute and relative thickness values may be appropriate for assessment of thickness of adjacent muscle layers. Assessment of asymmetry in baseline thickness values may be best represented as a percent difference between the symptomatic and nonsymptomatic side. Finally, statistical techniques or study designs that address potential confounding variables (eg, BMI, gender) as covariates are an option.

Dynamic Measurements Measures of change with activity have been investigated in a range of tasks, including volun-

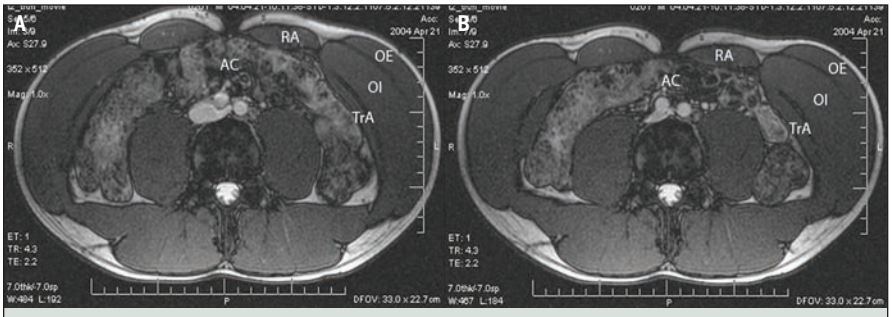

FIGURE 7. Magnetic resonance imaging of the deep musculofascial "corset" of the lumbopelvic region (cross section). Images include the transversus abdominis (TrA), obliquus internus abdominis (OI), obliquus externus abdominis (OE), and the rectus abdominis (RA) muscles. (A) The deep musculofascial "corset" at rest. (B) The deep musculofascial corset during the abdominal drawing-in maneuver, depicting a bilateral concentric activation of the TrA muscle and a decrease in cross-sectional area of the abdominal content (AC).

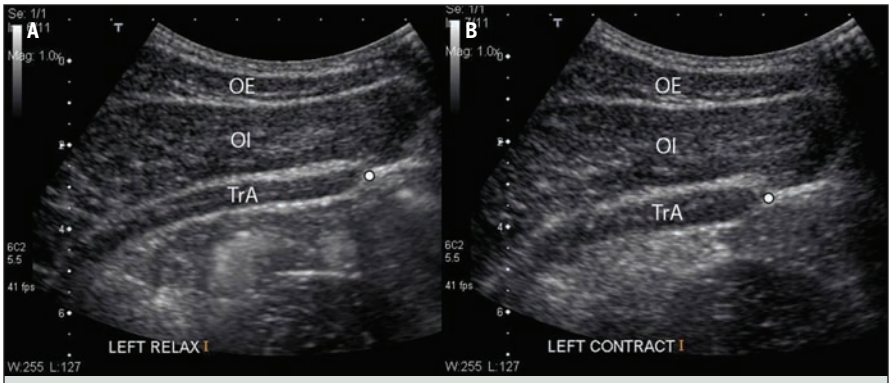

FIGURE 8. Ultrasound imaging of the lateral abdominal wall muscles during the abdominal drawing in maneuver (ADIM). Images include the transversus abdominis (TrA), obliquus internus abdominis (OI), and obliquus externus abdominis (OE) muscles. The white dot represents the anterior reach of the TrA muscle. (A) An ultrasound image of the left lateral abdominal wall at rest. (B) An ultrasound image of the left lateral abdominal wall during the ADIM. Note the ability to appreciate the shortening of the TrA muscle (eg, the lateral slide) by comparing the change in location of the anterior reach of the TrA muscle at rest and while contracted.

tary activation and automatic activation tasks, as described in the "Muscle Behavior" section of this commentary. During dynamic tasks, performance measures can be assessed by measuring a change in the thickness of a muscle[48] or a lateral displacement (slide) of the anterior medial edge of a muscle.[48,89] For the purpose of this section, we will use the ADIM as an example of how dynamic tasks can be measured using USI. This voluntary gentle inward displacement of the lower abdominal wall is a strategy that is commonly used for training, as an initial component of lumbar stabilization exercises.[89] Researchers have found that when individuals without LBP are asked to perform the ADIM by pulling their belly up (cranially) and in towards their spine, there is preferential and symmetrical activation of the bilateral TrA muscle with minimal activity of the more superficial abdominal muscles and without movement of the lumbar spine.[39,106] This can be visualized as a shortening and thickening of each side of the TrA muscle. **FIGURE 7** illustrates the relaxed (A), then contracted (B), deep musculofascial corset, using MRI; **FIGURE 8** demonstrates the ADIM using USI.

The change in muscle thickness is typically presented either as a percent change in muscle thickness or as muscle thickness during activity as a ratio to muscle thickness at rest.[60,99,106] Both are mathematically similar. It is important to consider that the change in shape of a muscle with activation is complex and not only dependent on the neural drive to the muscle. For instance, the changes in shape of a muscle appear to be dependent on whether the muscle is shortening or lengthening. During activities that cause the lateral abdominal muscles to shorten, the muscles appear to thicken, this is necessary to conserve the volume of the muscle. During activities where the lateral abdominal muscles lengthen, the muscles also appear to get thinner, despite activity level. Thus it is critical to consider the type of activity when interpreting changes visualized on USI. The potential for a muscle to change in shape is also dependent on the activity of adjacent muscles. For instance, there is potential for interaction between the thin layers of the lateral abdominal muscles. Theoretically, thickening of the OI with activation may compress and thin the adjacent muscles. The thickness of the abdominal muscles may also vary with passive change in the length of the muscles. For example, if the abdominal circumference increases, the muscles may appear to become thinner, without any change in activity.

For these reasons, changes in thickness of the TrA muscle are most likely to accurately reflect changes in activation during activities that require a shortening contraction of the muscle with minimal activation of the adjacent muscles, such as during the ADIM. It may be difficult to interpret more functional tasks due to variation in activity of adjacent muscles and activation type. Measurement during gait[9] and tasks, such as high-level stabilization exercises, may require clarification with EMG recordings to fully understand muscle activation.

As the TrA muscle thickens and shortens, a lateral slide of the anterior aspect of the TrA muscle and its fascia can be observed on USI. This lateral displacement is readily observed for the TrA muscle during the ADIM.[39,89] The lateral slide has been associated with tensioning of the anterior fascias, resulting in increased tension of the deep muscular corset, and is considered to be an important observation with RUSI of the lateral abdominal muscles.[39,89] Slide of

the anterior aspect of the TrA muscle is measured by comparing the distance between the medial edge of the TrA muscle at rest and while contracted during the ADIM.[39] This can be undertaken using off-line analysis with image analysis software to superimpose the image at rest on the image during the ADIM. The distance between these medial points is measured as the amplitude of lateral slide of the muscle. Alternatively, the distance between the medial border of the muscle and edge of the image can be used for this measurement. This alternative requires care to maintain the orientation and location of the transducer constant relative to the body. Any change in transducer alignment would render this measure invalid. Comparative measures can also be obtained by using video capability to capture the entire activation and hence lateral slide of the TrA muscle. Measurement of lateral slide is used as an indication of tightening of the anterior fascia associated with the TrA muscle and an indirect measure assessing the shortening of the TrA muscle during activation. Evaluation techniques that assess the shortening of the TrA muscle from a posterior approach have not been reported. Studies comparing variables for different tasks are required.

Imaging Procedure for the RA Muscle

Unlike the 1-dimensional measure of the lateral abdominal muscles, the CSA, thickness, and width of the RA muscle can be calculated using USI. The patient is typically supine, with the hips and knees flexed. The transducer choices are similar to those outlined above for the lateral abdominal muscles; however, the footprint of the transducer needs to be wide enough (~11 cm) to image the entire muscle. Based on the work by Rankin et al,[85] the image can be generated with the inferior border of the transducer placed immediately above the umbilicus and moved laterally from the midline, until the muscle cross section is centered in the image. Muscle CSA can be measured by outlining the muscle border just inside the muscle fascial layer. Muscle thickness can be obtained by measurement of the greatest perpendicular thickness between the superficial to deep fascial layers. This is typically found in the middle of the muscle belly.[85] Width can be measured from the most medial to the most lateral border of the muscle. In addition, the distance between the right and left RA muscle can be measured to assess those with diastasis recti and to track changes in the distance between the recti associated with pregnancy (**FIGURE 9**).[13,119]

Reliability of Static and Dynamic Measures

Measurement of the thickness of the lateral abdominal muscles has been assessed for both intrarater and interrater reliability using both brightness mode (b-mode) and motion mode (m-mode) USI (**TABLE 4**). Despite the excellent[82] intraclass correlation coefficient (ICC) values reported to date, further investigation is required to identify if methods can be used to reduce measurement error. Springer et al[99] reported that by averaging the thickness values at rest and while performing the ADIM over 3 trials, the associated standard error of the measurement (SEM) was reduced by more than 50%. Reduction of the SEM is advantageous for longitudinal studies or for tracking changes over time, because the minimal detectable difference in measured muscle thickness change is based on the SEM value. A minimum detectable difference of at least $2 \times \text{SEM}$,[82] or more conservatively, $\text{SEM} \times 1.96 \times \sqrt{2}$,[6,23,94,117] is required to be 95% confident that a change has occurred. Using the latter formula, a reported SEM value for the TrA muscle based on a single thickness value at rest of 0.31 mm[99] would require a 41% change in muscle thickness to detect hypertrophy (based on a thickness of the TrA muscle of 2.1 mm at rest). When an average of 3 measures is used (SEM, 0.13 mm),[99] this required percentage change is reduced to 17%. Due to the variability associated with submaximal and maximal effort tasks, the assessment of muscular function should be based on an average of multiple attempts of the task.[7,57,81] Additional techniques to achieve a more representative value for muscle thickness, while possibly decreasing associated measurement error, may include measuring muscle thickness in 3 locations along the muscle belly,[27] the use of postprocessing techniques to enhance the image, or using computer algorithms to automatically measure the thickness.

Measurement techniques that use anatomical markers, such as placement of the transducer just superior to the iliac crest along the mid-axillary line, in which the anterior or posterior edge of a particular lateral abdominal muscle is placed a set distance from the image border and the middle of the muscle belly is maintained within the center of the image, have been suggested to facilitate consistent placement of the transducer

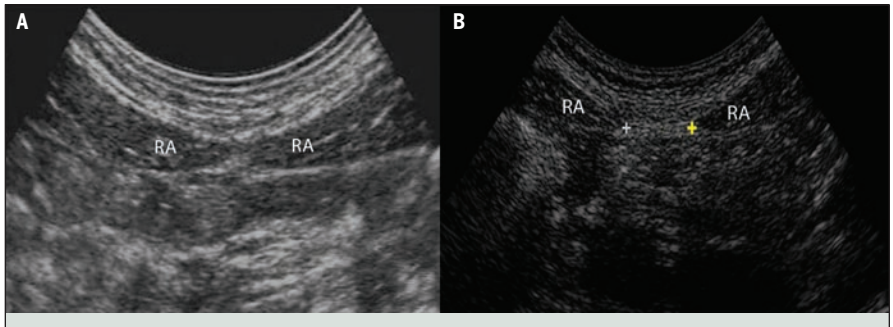

FIGURE 9. Ultrasound imaging of interrecti distance. Both the left and right rectus abdominis (RA) muscles, as well as their intervening fascia, are observable. (A) Note the RA muscles are adjacent in midline resulting in a small interrecti distance. (B) Note the increased in the interrecti distance associated with diastasis recti. The interval between the plus signs represents the interrecti distance. (From Whitakker J. *Ultrasound Imaging for Rehabilitation of the Lumbopelvic Region: A Clinical Approach.* ©2007, Elsevier. Reprinted with permission).

over time.[99,106] Although consistent transducer location may be more difficult when imaging along the anterior axillary line where the iliac crest does not provide a structural base to position the inferior border of the transducer, this location may allow for better visualization of the lateral slide of the anterior aspect of the TrA muscle.

There are many potential sources of measurement error when assessing activities that involve tasks with significant increases in IAP, such as coughing, sneezing, or limb motion. Diligent attention to steadying the position, orientation, and inward pressure of the ultrasound transducer is required. Failure to do so will produce motion of the transducer with respect to the body, resulting in changes in the image based on transducer movement and not solely on changes in muscle behavior.[86] When using a technique that involves a handheld transducer, the physical therapist should attempt to control the transducer's motion and maintain consistent inward pressure of the transducer by matching the outward increase in pressure during the task. It may be beneficial for the examiner to use both hands and to steady the forearms on the patient's torso and treatment table to help stabilize the transducer. Another option may be to use a high-density foam cube.[9] Transducers secured in a foam cube may facilitate more constant pressure and ultimately more consistent measurements. However, this technique may limit accuracy for dynamic tasks, during which it may be optimal to move the transducer

TABLE 4 Reliability

Researchers	Mode	Muscles Measured	Intrarater Reliability (ICC)	Intrarater Response Stability	Interrater Reliability	Interrater Response Stability
Rankin et al[85]	B-mode	TrA, OI, OE, RA at rest	Across all muscles measured on the same day: 0.98-0.99 (95% CI: 0.91-1.0) Across all muscles measured 7 days apart: 0.96-0.99 (95% CI: 0.85-1.0)	95% limits of agreement for between-day reliability, measurements varied up to: OI, 2.2 mm; OE, 1.3 mm; TrA, 1.2 mm; RA, 0.7 mm, 0.69 cm^2	Not reported	Not reported
Teyhen et al[106]	B-mode	TrA	ICC, 0.93-0.98	SEM, 0.13-0.31 mm	Not reported	Not reported
Springer et al[99]	B-mode	TrA and total lateral abdominal muscle thickness at rest and during ADIM	Not reported	Not reported	ICC (single measure): 0.93-0.99 (95% CI: 0.86-1.0) ICC (average measure): 0.98-1.0 (0.92-1.0)	SEM (single measure): 0.32-0.80 mm SEM (average measure): 0.13-0.35 mm
Hides et al (in press)	B-mode	TrA and OI thickness at rest and during the ADIM and shortening of the TrA (slide)	Intraday ICC: for thickness, 0.62-0.82; for slide, 0.44 Interday (4-7 d): for thickness, 0.63-0.85; for slide, 0.36	SEM (Interday): IO rest, 0.37 mm; IO contract, 0.66 mm; TrA rest, 0.4 mm; TrA contract, 0.5 mm; slide, 2.86 mm		
Ainscough-Potts et al[1]	B-mode	TrA and OI during inspiration and expiration	ICC: 0.97-0.99	Not reported	Not reported	Not reported
Hides et al[39]	B-mode	Shortening of the TrA (slide)	ICC: 0.78-0.91	Not reported	Not reported	Not reported
Bunce et al[10]	M-mode	TrA	ICC: 0.88-0.94	SEM: 0.35-0.66 mm	Not reported	Not reported
Kidd et al[58]	M-mode	TrA	ICC: 0.90-0.96	SEM: 0.29 to 0.57 mm	Not reported	Not reported
McMeeken et al[72]	M-mode and b-mode	TrA	ICC: b-mode, 0.99; m-mode, 0.98; b-mode versus m-mode, 0.82	Not reported	Not reported	Not reported

Abbreviations: ADIM, abdominal drawing-in maneuver; b-mode, brightness mode; ICC, intraclass correlation coefficient; OE, obliquus externus abdominis muscle; OI, obliquus internus abdominis muscle; m-mode, motion mode; RA, rectus abdominis muscle; SEM, standard error of the measurement; TrA, transversus abdominis muscle; CI, confidence interval.

slightly to maintain the center of the muscle belly in the center of the image. The reader is referred to Whittaker et al[120] for additional details regarding measurement error associated with musculoskeletal USI.

Validity

MRI and indwelling EMG have been used to establish the validity of RUSI measurements of the morphology and activation, respectively, of the abdominal wall muscles. Validity with respect to assessing muscle composition with RUSI for the abdominal muscles will require further investigation.

Validation of USI of the Lateral Abdominal Muscles with EMG Two research groups[48,72] have compared changes in EMG and USI to assess the validity of measurement of changes in muscle thickness, with or without analysis of the lateral slide, as a measure of the amplitude of muscle activity during isometric activation. In a study involving 3 subjects, Hodges et al[48] reported a curvilinear relationship. The authors concluded that large changes in muscle thickness and lateral slide of the TrA muscle and thickness changes of the OI muscle are expected with changes in activity from a resting state. However, these changes plateaued around 20% of a maximal voluntary effort for the TrA and OI muscles. This curvilinear relationship during an isometric (fixed-end) activation is expected, as the change in muscle thickness is dependent on the shortening of the muscle fibers with activation. During an isometric activation, this can only occur as a result of tendon stretch. At low forces, tendon stiffness is low and small changes in force produce relatively large changes in tendon length and, therefore, large potential for shortening of the muscle fibers. Stiffness of the tendon increases with increasing force,[54] so changes in muscle fascicle length become progressively smaller. This would explain why the relationship between shortening of muscle fascicles and activation level appears to be curvilinear for an isometric activation. This relationship has been reported for other muscles as well.[37,65,88] During other activation types (shortening or lengthening) the relationship will be more complex. Due to this curvilinear relationship during isometric activations, changes in muscular activity from a moderate to strong level are unlikely to be determined by purely assessing changes in muscle thickness or lateral slide of the TrA muscle. In addition, changes in OE muscle thickness did not correlate with changes in EMG signal amplitude and, therefore, activation of the OE muscle can not currently be assessed with USI. In a study of 9 subjects, McMeeken et al[72] reported a linear relationship between changes in TrA muscle thickness and EMG signal amplitude during an isometric activation. However, these authors did not determine if a curvilinear relationship would have fit their data more accurately.

Future research is required to assess the relationship between EMG and changes in muscle thickness during other activation types and with consideration of changes in activity of adjacent muscles. Future studies should investigate the relationship between muscle activity and changes in muscle thickness using larger sample sizes, and include individuals with pathology. Additionally, researchers should provide further details regarding how their maximal voluntary activation was performed, to allow for comparison of values across studies.

Validation of USI of the Lateral Abdominal Muscles With MRI MRI is the accepted gold standard for evaluation of muscle morphology. Recently, MRI has been used to assess changes in the thickness of the lateral abdominal muscles during rest and with the ADIM, as well as changes in trunk CSA. These changes can help to determine the influence of the ADIM on the activation of the lateral abdominal wall muscles and its influence on the deep musculofascial system.[39,91] The technique used to evaluate the lat-

TABLE 5 Abdominal Drawing-in Maneuver (ADIM)[32,34,90,89,118]

Optimal pattern of activation	1. The TrA muscle shortens and tensions the anterior abdominal fascia and the thoracolumbar fascia 2. The TrA muscle thickens in width, indicating that it has contracted 3. The TrA muscle forms an arc laterally ("corset" action) 4. The dimensions of the OE and OI muscles remain relatively unchanged 5. The pattern is symmetrical
Features of nonoptimal global pattern of activation	1. The TrA, OI, and OE muscles all thicken and increase their width simultaneously, often rapidly 2. Despite activation of the TrA muscle, it is evident that the TrA muscle does not shorten and apply tension to the adjacent fascia 3. The TrA muscle does not wrap around the waistline; the waistline may widen rather than narrow 4. The pattern may be asymmetrical
Common substitution patterns	1. Breath holding or forced expiration 2. Bracing of the superficial abdominal muscles 3. Posterior pelvic tilt or trunk flexion during ADIM 4. Rib cage depression during ADIM 5. Increased weight bearing through the heels if performed supine 6. Fast phasic activations and not slow and controlled activations 7. Minimal or no movement of the lower abdomen

Abbreviations: OE, obliquus externus abdominis muscle; OI, obliquus internus abdominis muscle; TrA, transversus abdominis muscle.

eral abdominal muscles morphology with MRI is described elsewhere.[39,91] In the pilot study,[91] measures of TrA muscle function were made on 7 subjects (4 subjects with LBP and 3 asymptomatic subjects). During the ADIM in subjects without LBP, there was a symmetrical contraction of the TrA muscle associated with a decrease in the trunk CSA, forming what has been labeled a deep musculofascial corset (**FIGURE 7**). This was not observed in the small number of subjects with LBP.[91]

To validate the use of RUSI, which has a much smaller field of view than MRI (**FIGURE 8**), Hides et al[39] compared measurements obtained at rest and during the ADIM using both modalities. MRI and ultrasound measures of abdominal muscle function were performed on a convenience sample of 13 elite cricket players without a history of LBP. On the same day, subjects were assessed, first using MRI, then with RUSI using previously defined protocols.[27,39,91] Measurements conducted on the MR and US images were performed by 2 independent operators who were blinded to the other's results.

Results of the MRI data concurred with the findings of Richardson et al,[91] in which there was a significant decrease in the CSA of the trunk during the ADIM. The mean CSA of the trunk at rest was 393.90 $\pm$ 8.07 cm^2, which decreased to 362.61 $\pm$ 8.85 cm during the ADIM.[2,39] There was a corresponding significant increase in thickness of the TrA and OI muscles during the ADIM, as measured by both MRI and USI. The activation was symmetrical between sides. The relationship between the thickness measures obtained by MRI and USI had $ICC_{3,1}$ values ranging from 0.84 to 0.95.[39] Although changes in CSA can not be assessed with RUSI, the anterior slide of the anterior abdominal fascia has been proposed as a proxy measurement. The correlation between the MRI measures of changes in trunk CSA (corseting) during the ADIM and the amount of TrA fascial slide was $r = 0.78$ ($P = .008$).[91]

MUSCLE BEHAVIOR

In addition to the measurement of the morphology of the abdominal muscles, USI can be used to evaluate the behavior or function of the abdominal muscles. This is possible because elements of muscle shape (muscle length, muscle fascicle length, pennation angle, and muscle thickness) change with activation.[48,77] Clinically, this helps to provide additional information regarding the resting state of the muscles, the ability of the patient to contract the muscles during both voluntary and automatic tasks, and coordination of muscle activity during such tasks.

Resting Activity In upright postures there is ongoing activity, albeit small, of most of the abdominal muscles, while an individual is quietly standing. This is greatest for the muscles in the lower region of the abdominal wall, specifically the lower fibers of the TrA muscle, and has been associated with a hydrostatic gradient to support the abdominal contents.[113] This muscular activity at rest has also been suggested to help maintain the length of the diaphragm[98] and maintain compression on the sacroiliac joint.[21] There is also gentle respiratory modulation of the abdominal muscles, with greater activity (thickness) during expiration.[1,21,77,101] Increased baseline activity of the abdominal muscles has been associated with activities in which postural demand is increased, such as during arm movements[44] and walking.[96] Conversely, the muscle activity level appears to be reduced in supine. Therefore, it is important to consider that baseline thickness measurements in unsupported postures (ie, sitting and standing) may not represent the muscles at rest.

It is speculated that pain, reflex guarding, and the presence of trigger points or taut bands within a muscle may influence observed resting baseline muscle thickness. Although researchers have not investigated if changes in resting baseline muscle activity are detectable with USI, clinical observations have been noted.[119] For example, a muscle with an increase in relative thickness due to increased baseline activity may appear enlarged in comparison to what is typical for an individual of a comparable size, gender, and activity level, with a characteristic appearance of protruding into its fascia and adjacent muscle layers (**FIGURE 2B**). The assumption that there is increased baseline activity can be supported clinically, if the shape of the muscle changes based on positioning or following treatment (such as manual therapy[31,84]), or if the image differs from the contralateral abdominal wall. In the future, researchers should assess how these qualitative characteristics seen with a static ultrasound image correlate with clinical indicators.

Coordination of Muscle Activity Activation of the abdominal muscles is required to control movement and stability of the trunk during most functional activities. Although all of the abdominal muscles contribute to the control of stability of the spine and pelvis,[71] there is evidence that the TrA muscle is controlled independently of the other abdominal muscles in a range of tasks, such as upper extremity[51,53] and lower extremity[49] movements, and locomotion.[96] In general, the TrA muscle is activated early (in anticipation of a predictable force)[16,51] in a tonic manner and independent of the direction of the forces acting on the spine.[15,51] In contrast, the activity of the more superficial abdominal muscles is dependent on the direction of forces acting on the trunk and generally occurs phasically, as required by movement demands.[3,51] This pattern of trunk muscle activation is modified in people with low back and pelvic pain. In these individuals, activity of the more superficial muscles, such as the OE and RA, is often increased in conjunction with increased activity of the long extensor muscles. The pattern of activation in the superficial muscles is variable between individuals.[43,83] In contrast, activity of the deeper TrA muscle is often delayed,[50,52] reduced,[27] or is less tonic[95] than in healthy individuals. Delayed activation of the TrA muscle has

also been reported in people with groin pain.[14] Recent data suggest that these factors can be changed with specific motor retraining to improve the coordination of the trunk muscles[108] and possibly with other interventions.[68] USI may be able to provide insight into the control of the abdominal muscles. Although research groups are attempting to measure the relative timing of abdominal muscle activation with Doppler imaging,[116] doing so with conventional USI is difficult, as the period of delay is in the order of tens of milliseconds and therefore impossible to detect visually.

Activation During Automatic Tasks Assessment of automatic activation of the TrA muscle seeks to evaluate the strategy for activation of this muscle during movements of the trunk or limbs. These tasks require only general instruction, such as "flex or extend your lower extremities," without any instructions requesting the patient to specifically attend to activation of the abdominal muscles. Tasks such as these provide an indication of the recruitment of the TrA muscle during a semifunctional, but controlled activity. One such task involves non–weight-bearing isometric limb loading (to a force equivalent to 7.5% of body weight) into flexion and extension, with the subject supine and the lower extremities supported. The researchers found that during this task the TrA muscle was activated tonically in both directions of limb movement, whereas the more superficial muscles were activated with only 1 direction of limb motion.[27] During both of these tasks, the mean increase in TrA thickness was approximately 20% in those without LBP, while the mean increase in thickness for those with LBP was significantly smaller (approximately 4%).[27] There was no difference in the change of muscle thickness for the OI or OE muscles between groups.

In a clinical setting, automatic activation of the lateral abdominal muscles may be assessed during the performance of the active straight-leg raise (ASLR) test.[73-75] O'Sullivan et al[79] measured altered activity of the pelvic floor muscles using USI during the ASLR test in those with sacroiliac dysfunction. The ASLR test may make it possible to detect diminished or nontonic activity of the lateral abdominal muscles. Specifically, when limb motion is initiated, a bilateral activation of the TrA should be observed.[27] The absence, observable delay, or premature loss (eg, relaxation before the limb is lowered) of these architectural changes, or an excessive response followed by inability to fully relax after the task, may be considered abnormal. The first 3 scenarios listed may indicate a deficiency in either motor control or capacity of the TrA muscle and/or fascia, and the fourth a potential hyperactivity. Currently, changes in the lateral abdominal muscles during the ASLR test are under investigation.

Voluntary Preferential Activation of the TrA Muscle In addition to assessing automatic activation of these muscles, RUSI can be used to assess voluntary activation of the TrA muscle during tasks such as the ADIM (**FIGURES 7** and **8**). During the ADIM, Springer et al[99] found that the TrA muscle represented 22% of the lateral abdominal muscle thickness at rest and increased by 52% while contracted, to represent 34% of the lateral abdominal muscle thickness. Additionally, Teyhen et al[106] found that in those able to perform the ADIM, the TrA muscle doubled in thickness while the other lateral abdominal muscle thickness values remained relatively unchanged. Characteristics of those unable to perform the ADIM are a more generalized activation of the more superficial trunk muscles, as well as patterns of substitution by the more superficial muscles (**TABLE 5**). A point of clinical relevance is that the ADIM, along with lumbar multifidus isometric activation, serves as the foundational component in a comprehensive treatment approach that aims to restore coordination of the entire lumbopelvic muscular system.[89]

It is notable that experimentally induced pain has been found to decrease the ability of an individual to contract the TrA muscle during the ADIM.[59] Kiesel et al[59] induced pain by injecting a 5% hypertonic saline solution into the longissimus muscle at the level of L4. Patients had a diminished ability to perform the ADIM (approximately 20% decrement) after the injection, as measured by a decrease in the ability to thicken the muscle ($P<.01$). The researchers concluded that USI can be used to measure pain-related changes in the ability to activate the TrA muscle.

TREATMENT: ULTRASOUND BIOFEEDBACK

Motor learning of various skills can be enhanced by precise visual feedback[61,67,123] that provides the learner with knowledge of performance (KP) of the motor task.[29] RUSI of the anterior and lateral abdominal wall can be used to provide precise visual feedback of performance. RUSI has been used to enhance motor learning by providing feedback in attempts to improve voluntary activation of the multifidus[41,60] and the TrA muscles[36,106,122] in subjects with and without LBP. RUSI has also been used to provide feedback to the physical therapist about an individual patient's performance.[33] Researchers have suggested that RUSI is a beneficial tool for provision of augmented feedback that facilitates consistency of performance of the ADIM in a population with[41,122] and without LBP.[36,115] Although RUSI imaging appears to facilitate initial learning, its benefit for improvement of the retention of the performance of the ADIM performance is inconclusive for control subjects.[36,115] It also appears that RUSI may be more beneficial in some subgroups of individuals with LBP and not in others; RUSI did not enhance performance of the ADIM in a group of patients with a LBP history of less than 3 months.[106] Additional research needs to address the sensitivity of single-factor measurements of success (eg, change in muscle thickness) versus multifactorial determinations of success, such as those used by Henry et al[36] and Van et al[115] in determining improved performance across a variety of tasks.

Several clinical trials have included RUSI for feedback regarding activation of the abdominal and/or paraspinal muscles in rehabilitation of acute[40] and chronic LBP.[25] These studies indicate that rehabilitation that included RUSI for feedback of activation led to reduced recurrence of LBP in people following an initial acute episode[40] and reduced pain and disability in people with disabling chronic pain.[25,80] Furthermore, a subset analysis from the latter study showed that the increase in thickness of the TrA muscle during a lower extremity loading task was greater following the motor control intervention that included RUSI for feedback, but not after a general exercise program or spinal manipulative therapy.[26] The improvement in thickening of the TrA muscle during the lower extremity loading task was also correlated with clinical improvement.[26] Although these studies provide initial insight into the utility of RUSI for feedback, these studies have not compared motor control training with and without feedback. Thus, it is not yet clear whether providing feedback with RUSI improves outcomes. However, as indicated above, feedback may improve the initial component of training.

Although preliminary evidence supports RUSI imaging for teaching the ADIM, future studies should address the optimum number of practice trials per session as well as the optimal feedback schedule. The degree to which the provision of feedback of exercise quality improves training and the type and amount of feedback also should be explored. Additional studies are needed to examine the relationship between various quantifiable RUSI parameters and EMG recordings in different subgroups of LBP populations, so that RUSI can be further validated as a noninvasive tool for quantification of muscle function. In addition, the appropriateness of RUSI during the different stages of motor learning has yet to be evaluated.

The majority of the preliminary work on the use of RUSI as a feedback tool has been performed in individuals with LBP and pelvic pain.[22] However, there are a large number of other potential applications for this method within these same populations. In design of research protocols, attention must be paid to the effect of pretraining as well as the timing, type, and amount of feedback, as these factors affect skill acquisition.[66] In future studies, investigators must be explicit about operational definitions of improved performance, parameters used to determine improved performance, as well as the amount and type of feedback provided. Through careful, systematic manipulation of research paradigms, it will be possible to elucidate the optimal manner in which to use RUSI as a feedback tool for the benefit of patients with low back and pelvic pain.

FUTURE DIRECTIONS

Although preliminary work has established a link between assessment of impairments with RUSI and functional outcomes,[33,40] continued research is required. Researchers should determine if baseline impairments associated with the abdominal muscles using RUSI techniques help predict which types of patients may respond favorably to a specific exercise approach, which patients may be prone to longer term disability, or which patients benefit from the adjunct of RUSI as a biofeedback tool. RUSI provides a means by which physical therapists can see what they are feeling with their hands. Researchers should address the use of RUSI as a tool to assist physical therapists in clinical decision making, reliably determining impairments, improving specificity of prescribed therapeutic exercises, and establish its influence on outcomes. It is known that exercise compliance is low.[97] From a treatment perspective, the feedback afforded with RUSI may not only facilitate a patient's ability to perform an exercise properly, it also may improve compliance by allowing a patient to visualize the underlying muscular dysfunction the exercise regimen is designed to address and thus impact patient motivation and enhance compliance.

SUMMARY

The goal of this commentary has been to provide an overview of the use of RUSI for assessment and treatment of the abdominal wall muscles in those with lumbopelvic dysfunction. As knowledge continues to accumulate regarding the importance of the role of the deep abdominal muscles, physical therapists need access to tools that allow specific assessment and assist focused treatment of the underlying morphology and specific muscular behaviors. As outlined in this commentary, RUSI is an emerging tool that has a potential role in both enhancing clinical care and research for certain subclassifications of low back and pelvic pain. More research is needed to better define the role of RUSI and its limitations.

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