[RESEARCH REPORT]

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Changes in Deep Abdominal Muscle Thickness During Common Trunk-Strengthening Exercises Using Ultrasound Imaging

Decreased lumbar stability, muscular strength, and altered motor control are thought to be possible causes of low back pain (LBP), which is one of the most common reasons people seek medical care in the United States.[28] Trunk stabilization and trunk-strengthening programs that target the deep abdominal muscles are designed to improve motor control and strength of the trunk region, contributing to a decrease in LBP.[1,15,26,27,33] Although a variety of these programs exist (eg, lumbar stabilization training, Pilates, yoga, motor control training), they generally attempt to target the muscles that corset the lumbar spine to improve local muscular and functional control of the lumbopelvic region.[1] Regardless of the philosophy underlying the different exercise programs, 2 of the key components for success are selection of exercises that best target the appropriate muscles and facilitate proper performance of the exercise. Exercises that target the deep abdominal muscles with minimal external loading on the spine have been shown to be effective in increasing lumbar stability, thus treating and preventing the recurrence of LBP.[2,17,27,33,36]

In addition to traditional strength (eg, isometric, isoki-

• **STUDY DESIGN:** Cross-sectional study design.

• **OBJECTIVES:** To characterize changes in muscle thickness in the transversus abdominis (TrA) and internal oblique (IO) muscles during common trunk-strengthening exercises, and to determine whether these changes differ based on age.

• **BACKGROUND:** Although trunk-strengthening exercises have been found to be useful in treating those with low back pain (LBP), our understanding of the relative responses of the TrA and IO muscles during different exercises is limited.

• **METHODS AND MEASURES:** Six commonly prescribed trunk-strengthening exercises were performed by 120 subjects (40 subjects per age group: 18-30, 31-40, and 41-50 years). Ultrasound imaging was used to measure the thickness of the TrA and IO during the resting and contracted state of each exercise. The average thickness of the muscles while in the contracted position was divided by the thickness values in the resting position for each exercise, based on 2 performances of each exercise. Two 3-by-6 repeated-measures analyses of variance were used to determine significant changes in muscle thickness of the TrA and IO, based on age group and exercise performed.

• **RESULTS:** For both muscles, the trunk exercise-by-age interaction effect (TrA, P = .358; IO, P = .217) and the main effect for age (TrA, P = .615; IO, P = .219) were not significant. A significant main effect for trunk exercise for both muscles ($P<.001$) was found. The horizontal side-support (mean ± SD contracted-rest thickness ratio: TrA, 1.95 ± 0.69; IO, 1.88 ± 0.52) and the abdominal crunch (mean ± SD contracted-rest thickness ratio: TrA, 1.74±0.48; IO, 1.63 ± 0.41) exercises resulted in the greatest change in muscle thickness for both muscles. The abdominal drawing-in maneuver (mean ± SD contracted-rest thickness ratio: TrA, 1.73 ± 0.36; IO, 1.14 ± 0.33) and quadruped opposite upper and lower extremity lift (mean ± SD contracted-rest thickness ratio: TrA, 1.59 ± 0.49; IO, 1.25 ± 0.36) exercises resulted in changes in TrA muscle thickness with minimal changes in IO muscle thickness.

• **CONCLUSION:** Changes in TrA and IO muscle thickness differed across 6 commonly prescribed trunk-strengthening exercises among healthy subjects without LBP. These differences did not vary by age. This information may be useful for informing exercise prescription.

• **LEVEL OF EVIDENCE:** Therapy, level 5.
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• **KEY WORDS:** *internal oblique, low back pain, lumbar stabilization, sonography, therapeutic exercise, transversus abdominis*

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netic, torque generation) and endurance measures, performance of the abdominal muscles has also been measured using several techniques. However, measurement techniques that quantify the deep abdominal musculature have historically been limited to either surface or fine-wire electromyography (EMG). The benefit of EMG analysis is that it allows assessment of the timing and amplitude of the muscular activity. Although surface EMG measurements have been useful in analysis of superficial muscle activation of the abdominals during trunk activities,[11-14] they are unable to differentiate between the deep abdominal muscles (transversus abdominis [TrA] and internal oblique [IO]).[20] On the other hand, fine-wire EMG has been used to differentiate muscle activation of the TrA and IO during active movement of the extremities with static trunk postures.[14] However, the invasive nature of the fine-wire EMG procedure, the location of the TrA relative to the abdominal cavity, and its inability to investigate a larger portion of the muscle[6,12-14] limit its functionality for research involving large sample sizes, its ability to assess muscle activation during active trunk movement, or its routine clinical use. Thus, due to technical limitations, studies that can differentiate the behavior of the TrA and IO musculature during exercises requiring both trunk and limb movement have been limited.

Ultrasound imaging (USI) has recently been used to assess muscular geometry and as an indirect measure of muscle activation via changes in muscle thickness and other characteristics of muscle function (eg, muscle corseting function of the lateral abdominal muscles, as measured by slide of the anterior abdominal fascia).[19,30,31,38] Measures obtained from USI have been associated with measurements obtained from more traditional measurement techniques (eg, magnetic resonance imaging [MRI], manual muscle testing, and EMG) during supine, standing, and walking postures.[5-7,10,16] Assessment of changes in muscle geometry with USI has also been found to minimize measurement error associated with more traditional techniques (ie, surface EMG) through the elimination of cross-talk from surrounding musculature.[29] The reliability of both motion-mode[3,18] and brightness-mode[37,40] USI to assess the lateral abdominal muscles has been found to be good to excellent. Measuring thickness of the lateral abdominal muscles with USI has been validated against reference criterion measures such as MRI.[9] Although there is debate regarding whether the relationship between changes in muscle thickness of the lateral abdominal muscles relative to EMG is linear[25] or curvilinear,[11] there is agreement among researchers that during isometric contractions an increase in muscle activation (up to approximately 20% of maximum voluntary contraction) is associated with an increase in muscle thickness. However, generalizability of these studies is difficult secondary to their small sample size (n<10) and the use of only isometric contractions while the trunk is held in a relatively neutral posture.

Limitations in measurement techniques,[6,12-14] specifically their inabilities to differentiate between TrA and IO muscular behavior, have restricted researchers from directly comparing the relative contributions of these muscles during trunk-strengthening exercises. Recent evidence suggests that USI can differentiate the behavior of these deep abdominal muscles through a quantification of a change in muscle thickness.[25] Therefore, the purpose of this study was to characterize changes in muscle thickness of the TrA and IO muscles during 6 commonly performed trunk-strengthening exercises using USI in healthy subjects without LBP and to determine whether differences varied based on age.

METHODS

Subjects

A convenience sample of 120 healthy adults aged 18 to 50 years, stratified by age group (18-30, 31-40, and 41-50 years), without a current complaint of LBP was recruited to participate in this study. A sample of approximately 40 subjects per age group was necessary to ensure at least 80% power to detect a moderate effect size of 0.25 between age groups. Subjects were all Department of Defense health care beneficiaries, including active-duty military, family members, and retirees. Potential subjects were excluded if they had a current complaint of LBP, presence of chronic systemic or connective tissue disease, history of surgery to the lumbar spine, or known pregnancy. Additionally, subjects were excluded if they were unable to assume the positions necessary to perform the exercises in a pain-free range of motion. Height and body mass were collected on all subjects to calculate body mass index (BMI). All subjects provided written informed consent and signed Health Insurance Portability and Accountability Act privacy forms approved by the Brooke Army and Wilford Hall Medical Centers' Institutional Review Board prior to participation.

Exercise Selection

We analyzed 6 commonly prescribed trunk-strengthening exercises (**APPENDIX**), based on current evidence from the biomechanical and EMG literature demonstrating that these exercises increased activation of key abdominal and lower back muscles, primarily the TrA, erector spinae, lumbar multifidus, oblique abdominals, and quadratus lumborum.[2,8,22,23,40] The abdominal drawing-in maneuver was performed in conjunction with each of the exercises because of its ability to facilitate coactivation of the TrA and multifidus muscles when stabilizing the trunk and its clinical use as a foundational basis for lumbar stabilization exercises. Recently, Teyhen et al[40] found the abdominal drawing-in maneuver to preferentially activate the TrA with minimal changes in the IO. Three of the other exercises tested are promoted by the US Army Physical Fitness School's "4-for-the-Core" exercise program to improve trunk stability among soldiers.[35] These exercises include the supine lower extremity extender, quadruped opposite upper and lower extremity lift, and left and right horizontal side-support. In this study we only analyzed the right-sided horizontal side-support. The horizontal side-support has also been found to activate the IO, external oblique, and quadratus lumborum muscles with low lumbar loading.[22,23] The abdominal crunch was included based on prior research by Axler and McGill,[2] who found that the abdominal crunch has the highest muscular challenge with the least amount of spinal compression among 12 different exercises tested. Finally, the abdominal sit-back was tested based on the suggestion by Greenman[8] that this exercise can activate the deep abdominal muscles while also maintaining a neutral spine.

Exercise Procedures

Subjects were provided a standardized overview of the exercises, information on abdominal musculature, and a review of the testing procedures prior to participation. Specific exercise instructions were read to the subject prior to each exercise (**APPENDIX**). Subjects were shown pictures of the required starting and exercise positions, and subsequently allowed a maximum of 5 practice repetitions, with verbal cues as needed from the examiner, to perform the exercise to standard. These practice trials were included to measure changes in muscle thickness under "ideal" performance of these exercises. If a subject was unable to perform the exercise to standard after 5 practice repetitions, USI of the subject performing that exercise was not collected, and the subject proceeded to the next exercise. After the subject performed the exercise to standard, he or she repeated each exercise twice, to measure the muscle thickness of the deep abdominal muscles. Subjects performed each exercise for a maximum of a 10-second count. A 30-second rest was provided between repetitions of the same exercise, and a 1-minute rest was provided between each of the different exercises. Exercise order was counterbalanced throughout the study to minimize the potential for an order effect.

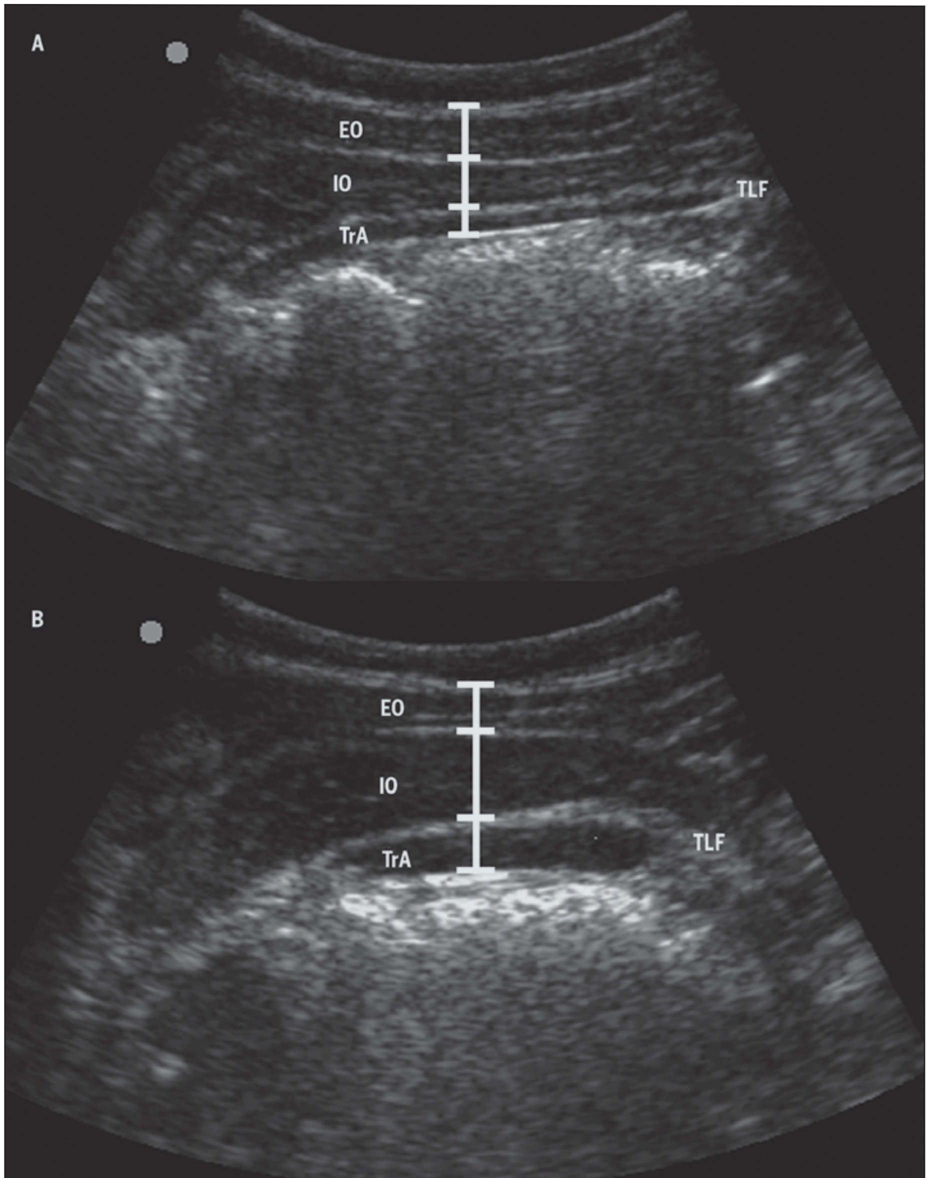

FIGURE 1. Ultrasound image of the lateral abdominal muscles at rest (A) and during the abdominal crunch (B). Note the increase in muscle thickness of both the transversus abdominis (TrA) and internal oblique (IO) muscles. The external oblique (EO) muscle and the transition from the TrA to the thoracolumbar fascia (TLF) are also visible in these images. Changes in EO muscle thickness have not been associated with changes in muscle activation. Therefore, changes in muscle thickness of the EO were not assessed.

Ultrasound Imaging

Ultrasound measurements were obtained using a portable ultrasound unit (Sonosite 180 Plus; Sonosite Inc, Bothell, WA) with a 60-mm and a 2- to 5-MHz curvilinear array. The ultrasound unit was attached to a 15-in (38.1-cm) liquid crystal display to improve the researcher's visualization of the musculature. The technique used to obtain the images of the lateral abdominal muscles and the measurement techniques have been previously described.[37,39-41] The center of the transducer was placed in a transverse plane just superior to the iliac crest, in line with the mid-axillary line. To standardize the location of the transducer, the hyperechoic interface between the TrA and the thoracolumbar fascia was positioned in the right side of the ultrasound image (**FIGURE 1**). The angle of the transducer was then adjusted to optimize

TABLE 1 Descriptive Statistics*

	Age Group 1 (18-30 y)	Age Group 2 (31-40 y)	Age Group 3 (41-50 y)	Males (n = 69)	Females (n = 51)
Height (cm)	172.5 ± 9.1	172.2 ± 8.4	172.0 ± 9.6	177.0 ± 7.1	165.9 ± 7.1†
Body mass (kg)	73.5 ± 13.4	74.1 ± 12.7	73.5 ± 13.9	82.4 ± 10.5	64.4 ± 8.8†
Body mass index (kg/m²)	24.6 ± 3.4	24.9 ± 3.5	26.4 ± 4.2	26.6 ± 3.6	23.6 ± 3.2†
Male, female	26, 14	21, 19	22, 18	NA	NA
TrA thickness (mm)§	0.47 ± 0.16	0.48 ± 0.11	0.47 ± 0.11	0.50 ± 0.11	0.43 ± 0.10‡
TrA/total (%)‖	20.8 ± 3.8	21.2 ± 4.4	21.5 ± 5.5	19.7 ± 3.9	23.2 ± 4.8‡
IO thickness (mm)§	0.94 ± 0.24	0.94 ± 0.27	0.93 ± 0.30	1.09 ± 0.23	0.73 ± 0.16‡
IO/total (%)‖	41.1 ± 5.0	40.3 ± 6.0	40.7 ± 6.5	42.2 ± 6.2	38.6 ± 6.2‡

Abbreviations: IO, internal oblique muscle; TrA, transversus abdominis muscle.
* *Values are mean ± SD.*
† *P≤.001 (males compared to females).*
‡ *P≤.002 (males compared to females).*
§ *All measurements of muscle thickness were obtained at rest with the subject in supine with knees bent at 90°.*
‖ *Thickness of the TrA as a percentage of the total thickness of the lateral abdominal wall.*

visualization of the image.

Measurement of muscle thickness was obtained from the subject's right side both at starting position (rest) and again in the exercise (contracted) position of each exercise. Each exercise was performed and measured twice. TrA and IO muscle thickness was measured as the distance between the superficial and deep hyperechoic fasciae. To help control for the influence of respiration on the muscle thickness of the lateral abdominal muscles[4] and for consistency across participants, images were collected immediately at the end of exhalation, as determined by visual inspection of the abdomen. Additionally, a transparent vertical line placed in the middle of the display was used to assist with standardized placement of the measurement line in relation to the muscle fascia.

To minimize bias, the researchers collected data in teams of 2. One member of the team was designated as the examiner. The examiner positioned the transducer for optimal visualization of the musculature and performed all on-screen measurements. The other team member was designated as the observer and recorder ("recorder"). The recorder's role was to verify proper exercise performance and to annotate muscle thickness values. Both the examiner and the recorder had to agree on the specific placement of the on-screen calipers prior to recording each measurement. Initially, both team members were blinded to the actual measurement values by placing a visual barrier over the thickness values on the monitor. Once there was agreement on the on-screen caliper locations, the visual barrier was removed and the recorder annotated the muscle thickness values. The examiner remained blinded to all measurement values throughout data collection. All measurements were obtained within the same session to minimize the influence of confounding variables on the measurements of muscle thickness.

Reliability

A pilot study consisting of 10 subjects was used to establish interrater reliability for the measurement technique. Each pair of raters obtained 2 measurements during a single testing session. The intraclass correlation coefficient ($ICC_{2,2}$) for interrater reliability was greater than or equal to 0.95 for the TrA and IO muscle thickness measures. Response stability was calculated using standard error of measurement (SEM). The SEM was 0.09 mm for TrA and 0.29 mm for IO muscle thickness. These values are consistent with previous reports using the same measurement technique.[37,40]

Data Analysis

Descriptive statistics for height, body mass, and BMI were used to depict the 3 age groups. Descriptive statistics were also used to assess resting muscle thickness of the TrA and IO musculature in the supine posture. The relative thickness of each muscle was expressed as a percentage of total lateral abdominal muscle thickness (TrA, IO, and external oblique). These demographic and resting thickness values were also calculated based on sex. One-way ANOVAs and *t* tests were used to assess differences in these values based on age group and sex.

The change in muscle thickness of the deep abdominal muscles (TrA and IO) was determined by dividing the average thickness measurement during the contracted state of each exercise by the average thickness measurement of each muscle in the resting state based on the performance of 2 repetitions of each exercise. For example, a thickness ratio of 2.0 indicates the muscle doubled in thickness from its starting position (TrA contracted/TrA rest). Muscle thickness in the exercise position was divided by resting thickness to investigate the relative change in muscle thickness during each exercise and to help control for differences in muscle thickness based on body mass and sex. Two 3-by-6 repeated-measures

ANOVAs were calculated to examine the effects of the independent variables (exercise and age group) on the dependent variables (TrA and IO thickness ratios). Post hoc analyses were completed with a Sidak correction, with statistical significance set at $P<.05$. All statistical analyses were conducted using SPSS Version 11.5 (SPSS Inc, Chicago, IL).

RESULTS

A convenience sample of 120 healthy adults aged 18 to 50 years (mean ± SD, 34.5 ± 8.4 years) without a current complaint of LBP participated in this study. Subjects were categorized in 3 age groups (18-30, 31-40, and 41-50 years), with 40 subjects per group. Demographic information is shown in **TABLE 1**. Male participants had greater BMI values than females ($P<.001$) and had greater resting muscle thickness of both the TrA and IO musculature ($P<.002$). It was not possible to obtain a quality image for 1 subject during the abdominal sit-back exercise within the 5 exercise trials, thus the data from this subject were not included in the analysis.

TrA Thickness Ratio Analysis

The 3-by-6 repeated-measures ANOVA revealed no interaction effect between age group and exercise (F = 1.106, P = .358), nor was a main effect present for age group (F = 0.489, P = .615). However, there was a significant main effect for exercise (F = 30.784, $P<.001$). Post hoc analysis (**TABLE 2, FIGURE 2**) revealed that the horizontal side-support resulted in significantly greater change in muscle thickness of the TrA, as determined by the TrA thickness ratio (mean ± SD contracted-rest thickness ratio, 1.95 ± 0.69) compared to all other exercises. The abdominal sit-back and supine lower extremity extender exercises resulted in the least amount of changes in muscle thickness of the TrA (mean ± SD contracted-rest thickness ratios, 1.37 ± 0.42 and 1.28 ± 0.47, respectively) compared to all other exercises.

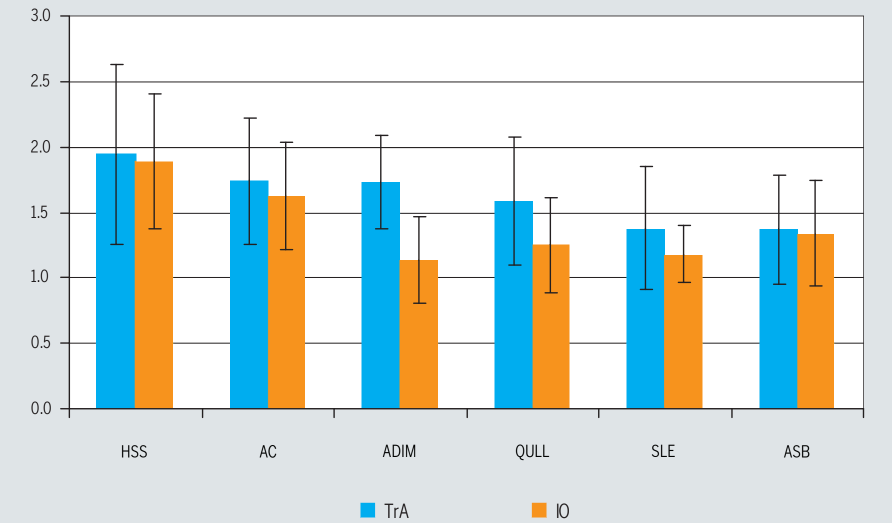

FIGURE 2. Thickness ratio (contracted/rest ratio) measurements (mean ± SD) of transversus abdominis (TrA) and internal oblique (IO) muscles for each of the 6 exercises. A value of 1.0 represents no change in muscle thickness from the starting position. Abbreviations: AC, abdominal crunch; ADIM, abdominal drawing-in maneuver; ASB, abdominal sit back; HSS, horizontal side-support; SLE, supine lower extremity extender; QULL, quadruped opposite upper and lower extremity lift.

TABLE 2 Transversus Abdominis Thickness Ratio for Each Exercise With Differences in Thickness Ratios Between Exercises*

	HSS (1.95 ± 0.69)	AC (1.74 ± 0.48)	ADIM (1.73 ± 0.36)	QULL (1.59 ± 0.49)	ASB (1.37 ± 0.42)	SLE (1.28 ± 0.47)
HSS (1.95 ± 0.69)		0.21†	0.22†	0.36‡	0.58‡	0.67‡
AC (1.74 ± 0.48)			0.01	0.15	0.37‡	0.46‡
ADIM (1.73 ± 0.36)				0.14	0.36‡	0.45‡
QULL (1.59 ± 0.49)					0.22‡	0.31‡
ASB (1.37 ± 0.42)						0.09
SLE (1.28 ± 0.47)						

Abbreviations: AC, abdominal crunch; ADIM, abdominal drawing-in maneuver; ASB, abdominal sit back; HSS, horizontal side-support; SLE, supine lower extremity extender; QULL, quadruped opposite upper and lower extremity lift.
** Thickness ratio (expressed as mean ± SD) is the average thickness exercise position/average thickness starting position.*
† Significant difference in thickness ratio between exercises (P<.05).
‡ Significant difference in thickness ratio between exercises (P≤.001).

IO Thickness Ratio Analysis

The 3-by-6 repeated-measures ANOVA revealed no interaction effect between age group and exercise (F = 1.350, P = .217), nor was a main effect present for age group (F = 1.536, P = .219). However, there was a significant main effect for exercise (F = 86.033, $P<.001$). Post hoc analysis (**TABLE 3, FIGURE 2**) revealed that the horizontal side-support resulted in significantly greater change in muscle thickness of the IO, as determined by the IO thickness ratio (mean ± SD contracted-rest thickness ratio, 1.88 ± 0.52) compared to all other exercises. Other than the horizontal side-support, the abdominal crunch resulted in significantly greater changes in IO muscle thickness (mean ± SD contracted-rest thickness ratio, 1.63 ± 0.41) compared to the re-

TABLE 3 Internal Oblique Thickness Ratio for Each Exercise With Differences in Thickness Ratios Between Exercises*

	HSS (1.88 ± 0.52)	AC (1.63 ± 0.41)	ASB (1.34 ± 0.41)	QULL (1.25 ± 0.36)	SLE (1.18 ± 0.22)	ADIM (1.14 ± 0.33)
HSS (1.88 ± 0.52)		0.25‡	0.54‡	0.63‡	0.70‡	0.74‡
AC (1.63 ± 0.41)			0.29‡	0.38‡	0.45‡	0.49‡
ASB (1.34 ± 0.41)				0.09	0.16†	0.20‡
QULL (1.25 ± 0.36)					0.07	0.11
SLE (1.18 ± 0.22)						0.04
ADIM (1.14 ± 0.33)						

Abbreviations: AC, abdominal crunch; ADIM, abdominal drawing-in maneuver; ASB, abdominal sit-back; HSS, horizontal side-support; SLE, supine lower extremity extender; QULL, quadruped opposite upper and lower extremity lift.
* *Thickness ratio (expressed as mean ± SD) is the average thickness exercise position/average thickness starting position.*
† *Significant difference in thickness ratio between exercises (P<.05).*
‡ *Significant difference in thickness ratio between exercises (P≤.001).*

maining 4 exercises. The IO thickness ratio for the abdominal sit-back exercises (mean ± SD contracted-rest thickness ratio, 1.34 ± 0.41) was greater than the IO thickness ratios for the supine lower extremity extender and the abdominal drawing-in maneuver. The other exercises tested (quadruped opposite upper and lower extremity lift, supine lower extremity extender, and abdominal drawing-in maneuver) had a mean IO thickness ratio values smaller than 1.25.

DISCUSSION

Of the 6 exercises tested, the horizontal side-support and the abdominal crunch, when performed with the abdominal drawing-in maneuver, resulted in the greatest changes in muscular thickness of both the TrA and IO muscles regardless of age. These results are in agreement with McGill et al's[22-24] recommendation that the horizontal side-support be used as a trunk exercise based on its activation of the multiple trunk-stabilizing muscles (quadratus lumborum, IO, and EO muscles), combined with its low-lumbar loading. Although the horizontal side-support was shown to elicit the greatest change in muscle thickness of the TrA and IO, this exercise may prove difficult for patients with shoulder pathology. This exercise requires the individual to elevate his/her body using the shoulder as a weight-bearing joint.

The increase in muscular thickness of both the TrA and IO during the abdominal crunch is in agreement with Axler and McGill's[2] recommendation for using the abdominal crunch for training based on its high muscular challenge combined with its low lumbar loading. Historically, the abdominal crunch is perceived as a sagittal plane exercise focused on strengthening the rectus abdominis muscle. However, our findings are in agreement with the results of Karst and Willett,[17] who demonstrated that activation of the deep lateral abdominal muscles could be enhanced with proper instruction during the abdominal crunch, such as performing the abdominal crunch while holding the abdominal drawing-in maneuver.

The abdominal drawing-in maneuver and the quadruped opposite upper and lower extremity lift exercises generated statistically similar changes in TrA muscle thickness to those of the abdominal crunch, with minimal changes in IO muscle thickness. Additionally, the magnitude of the TrA thickness ratio for these 2 exercises was not statistically different from the magnitude of the TrA thickness ratio during the abdominal crunch exercise. Our findings are in agreement with previous researchers that have advocated the abdominal drawing-in maneuver based on its ability to preferentially activate the TrA muscle.[40] The quadruped opposite upper and lower extremity lift also demonstrated preferential changes in TrA thickness, with minimal changes in IO thickness between the starting and exercise position. It is possible that the addition of the upper and lower extremity lift from the quadruped position requires minimal additional muscle activation of the lateral abdominal muscles and, therefore, the measurements obtained are similar to those measured during the abdominal drawing-in maneuver. The ability of the abdominal drawing-in maneuver and the quadruped opposite upper and lower extremity lift exercises to generate preferential changes in TrA, with minimal changes in IO muscle thickness, provides additional evidence for their incorporation into early phases of motor control exercise programs that emphasize the function of the TrA muscle.[32,34]

Although the abdominal sit-back and the supine lower extremity extender have been previously incorporated into trunk exercise programs, these exercises elicited the least amount of change of the TrA muscle thickness and only modest changes of IO muscle thickness compared to the other exercises tested. It is unclear from this current study how the magnitude of change in muscle thickness for these exercises would influence clinical outcomes of trunk exercise programs. The minimal changes noted in muscle thickness with these 2 exercises may reflect the limitations in the use of USI to assess muscle behavior. Specifically, it is possible that the trunk posture at the starting position and changes in intra-abdominal pressure associated with these exercises could have influenced the muscle thickness values.

Although there is a relationship between increases in muscle thickness and increases in muscle activation (as measured by EMG) during isometric contractions of less than 20% maximum voluntary contraction,[11,25] the relationship between changes in muscle thickness during isotonic contractions, such as the trunk-strengthening exercises measured in this study, remains unknown. The dynamic trunk postures, the isotonic nature of the contractions, and the influence of intra-abdominal pressure influence the interpretation of these data. Another limitation of this study is that we assessed the relative change in muscle thickness from the starting position to the exercise position for each exercise. These values do not account for any baseline activity required to hold the starting posture. So, despite our instructions for the subject to relax during the starting posture of each exercise, if the starting position required a contraction approximately equivalent to 20% maximum voluntary contraction, this might have influenced the potential for additional changes in muscle thickness during the exercise. Therefore, the modest changes in muscle thickness during the abdominal sit back and the supine lower extremity extender may reflect the limitations of this measurement technique in certain postures, instead of an indication of lower muscle activation values.

The IO muscles were approximately twice as thick as the TrA muscles at rest. This is in agreement with the pattern of relative muscle thickness of the abdominal muscles in subjects without LBP.[30] Additionally, findings that muscle thickness of the TrA and IO musculature was greater in males than females, while the TrA as a proportion of total lateral abdominal musculature was larger in females (with the reverse being true for IO musculature), are in agreement with findings from prior researchers.[37]

The difference in relative changes in thickness of the TrA and IO muscles during the horizontal side-support, abdominal crunch, abdominal drawing-in maneuver, and the quadruped opposite upper and lower extremity lift help to validate the use of USI to differentiate patterns of muscle behavior during trunk-strengthening exercises. These findings also highlight the need for further comparative studies that assess the relationship between changes in muscle thickness during trunk-strengthening exercises and muscle activation. Additionally, it is important to note that, due to limitations in using fine-wire EMG measuring techniques to assess muscle activation in this region of the body, the existing EMG validation studies have been limited to assessing only isometric contractions with the spine in a relative neutral posture using only a small sample of subjects ($n<10$).[11,25] Therefore, until these limitations can be addressed, there is a need to assess trunk muscle response patterns during trunk-strengthening exercises to inform exercise prescription decision making. Although there are known limitations[11,25] associated with using changes in muscle thickness as a proxy measure of muscle activation and we did not incorporate a treatment component in this study, these findings provide preliminary evidence to guide exercise selection for patients being prescribed trunk-strengthening exercises.

Future research should validate the USI findings of this study, while simultaneously assessing muscle activation with fine-wire EMG. Additionally, future research should investigate if these exercises elicit similar changes in muscle thickness of the deep abdominal muscles in populations with a history of LBP, a current diagnosis of mechanical LBP, or lumbar instability, and if these changes differ based on sex. Although the TrA and IO muscles showed significantly greater changes during performance of the horizontal side-support in a normal population, it is unknown what implication this will have with symptomatic patients. Exercises such as the abdominal drawing-in maneuver and the quadruped opposite upper and lower extremity lift exercise that resulted in greater preferential changes of the TrA muscle, with minimal additional changes of the IO, may be more appropriate during the acute phase of LBP.[21] Further research is necessary to test these hypotheses.

Clinically, these exercises are often thought of as either motor control and/or strengthening exercises. Further research is also necessary to identify the effects of multiple repetitions and fatigue on the ability to contract these deep abdominal muscles. Additionally, the ability of these exercises to influence motor control strategies and/or hypertrophy of the muscles remains unknown. The current study only investigated abdominal muscle contractions when specific exercises were performed properly, in a laboratory setting, and with specific instructions. Although the instructions were simple and the majority of subjects were able to perform the exercises without verbal cues, it is currently unknown whether the relative abilities of specific exercises to activate abdominal musculature will vary with multiple repetitions and the onset of fatigue.

CONCLUSIONS

We found greater changes in muscle thickness of the TrA and the IO when performing the horizontal side-support and abdominal crunch compared to other exercises investigated. The abdominal drawing-in maneuver, when performed in isolation or with the quadruped opposite upper and lower extremity lift, resulted in preferential changes in the TrA, with only minimal changes in IO thickness. Age does not appear to affect the action of the TrA or IO muscles during these trunk-strengthening exercises among those without LBP. Understanding the relative contributions of the deep abdominal muscles during trunk-strengthening exercises may assist clinicians in optimizing exercise prescription for patients with LBP. ◉

KEY POINTS

FINDINGS: Changes in TrA and IO muscle thickness differed during 6 trunk-strengthening exercises as assessed with USI. Specifically, the greatest changes in muscle thickness of both muscles were found with the horizontal side-support and the abdominal crunch. Preferential changes in muscle thickness of the TrA muscles were found during the abdominal drawing-in maneuver performed in isolation or during the quadruped opposite upper and lower extremity lift exercise. All exercises tested in this study included the subject performing the abdominal drawing-in maneuver as part of the exercise instructions.

IMPLICATION: Although there are limitations in the interpretation of these data, until researchers are able to assess the muscle activation of these deep trunk muscles during trunk-strengthening exercises using a more direct technique, the findings help to inform decision making in regard to exercise prescription.

CAUTION: Further research is required to assess the relationship between the changes in muscle thickness measured with USI and changes in muscle activation measured with EMG. The results of this study were assessed in subjects without a history of LBP and may not directly pertain to individuals with LBP.

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APPENDIX

Abdominal Drawing-in Maneuver

Starting position (**FIGURE A1**): The subject was supine in the standard sit-up position, knees bent at 90°, with hands folded across the chest.

Exercise instructions (**FIGURE A1**): On the command "Begin exercise," the subjects were instructed to "take a breath in and after you exhale pull your belly button in and back" towards their spine.

FIGURE A1. Start and end position for the abdominal drawing-in maneuver and the start position for the abdominal crunch.

Abdominal Crunch

Starting position (**FIGURE A1**): The subject was supine in the standard sit-up position, knees bent at 90°, and hands folded across the chest.

Exercise instructions (**FIGURE A2**): On the command "begin exercise," the subjects contracted the abdominal muscles by drawing the belly button inwards (toward the spine), then raised the head and shoulders upwards until the shoulder blades cleared the table. Subjects held this position until told to return to the starting position.

FIGURE A2. End position for the abdominal crunch

Abdominal Sit-Back

Starting position (**FIGURE A3**): The subject started in the "up" position of the standard sit-up, with the arms folded across the chest and the feet secured to the plinth.

Exercise instructions (**FIGURE A4**): On the command "Begin exercise," subjects kept their arms folded across the chest, contracted the abdominal muscles by drawing the belly button inwards (toward the spine), and slowly lowered the upper body until they lightly felt the wedge against their back.

FIGURE A3. Start position for the abdominal sit-back.

FIGURE A4. End position for the abdominal sit-back.

Quadruped Opposite Upper and Lower Extremity Lift

Starting position (**FIGURE A5**): The subject was on the hands and knees with back flat while looking forward.

Exercise instructions (**FIGURE A6**): On the command "Begin exercise," subjects contracted the abdominal muscles by drawing the belly button inwards (toward the spine), then slowly raised the left upper extremity and right lower extremity until they were horizontal with the trunk. They maintained a straight line with the trunk, upper extremity, and lower extremity, while avoiding trunk rotation and not allowing the back to sag. Subjects held this position until told to return to the starting position.

FIGURE A5. Start position for the quadruped opposite upper and lower extremity lift.

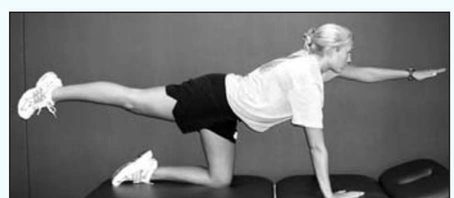

FIGURE A6. End position for the quadruped opposite upper and lower extremity lift.

Supine Lower Extremity Extender

Starting position (**FIGURE A7**): The subject was supine with the hips and knees bent at 90°, and hands folded across the chest. A sphygmomanometer cuff (not shown) preinflated to 40 mmHg was placed under the lower back to help ensure proper position throughout the exercise.

FIGURE A7. Start position for the supine lower extremity extender.

Exercise instructions (**FIGURE A8**): On the command "Begin exercise," subjects contracted the abdominal muscles by drawing the belly button inwards (toward the spine), and slowly lowered their feet until they lightly touched the table. Subjects held this position until told to return to the starting position.

FIGURE A8. End position for the supine lower extremity extender.

Additional instructions: When performing this exercise, subjects maintained a neutral spine posture, which was monitored by maintaining contact between the lower back and a sphygmomanometer cuff (not pictured) preinflated to 40 mmHg.

Horizontal Side-Support

Starting position (**FIGURE A9**): The subject was on the right side, supported by the elbow, forearm, and fist, and keeping the lower extremities straight.

FIGURE A9. Start position for the horizontal side-support.

Exercise instructions (**FIGURE A10**): On the command of "begin exercise," subjects contracted the abdominal muscles by drawing the belly button inwards (toward the spine), firmly pressed into the table with the supporting arm, then raised the trunk and pelvis upwards until they formed a straight line with the lower extremities.

FIGURE A10. End position for the horizontal side-support.

Additional instructions: Subjects did not let the trunk rotate forward or backward, nor the hips move toward the rear.