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RESEARCH

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The investigation of ultrasound to assess lateral abdominal wall activation with different types of core exercises

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Abstract

Background Core training is the foundation of physical exercise. The activation of the lateral abdominal wall (LAW) muscles in the core muscles, particularly the transversus abdominal (TrA) muscles, has a stabilizing effect on the chest and abdomen. Therefore, we need to focus on the training effect of the TrA. There are many ways to measure the LAW. Ultrasound can assess the effect of training in real time and intuitively. Therefore, we intend to evaluate the activation of the LAW in different types of core training using ultrasound, to determine the best movements that can activate the TrA and train the core muscles.

Methods 22 healthy subjects (male 10, female 12, age 22.82 ± 0.98, BMI 20.78 ± 2.27) were included. The subjects were given the following instructions to perform breathing exercises at different positions: calm breathing and deep breathing at 0° hip flexion and 0° knee flexion; calm breathing, deep breathing, abdominal crunches and ball crunches at 45° hip flexion and 90° knee flexion; and calm breathing, deep breathing, abdominal crunches and ball crunches at 90° hip flexion and 90° knee flexion. The muscle thicknesses of the bilateral transversus abdominis (TrA), internal oblique (IO), external oblique (EO), and LAW muscles were measured using ultrasonography at the end of expiration during the above movements.

Results (1) The action with the greatest contraction ratio of the TrA was deep exhalation, which was significantly greater than crunch and ball crunch; (2) During deep exhalation, the TrA had the greatest contraction ratio, significantly greater than the IO and EO. (3) The TrA was thinnest during deep exhalation at 90°, followed by 45° and 0°.

Conclusion In healthy young people, deep expiration with 90° hip flexion and 90° knee flexion was the optimal action for activating the LAW, especially the TrA.

Keywords Ultrasonography, Abdominal muscle, Central core, Respiratory

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Introduction

Core muscle training is an important part of physical exercise

The core muscle group usually refers to the muscles that maintain body stability, including the lateral abdominal wall (LAW), diaphragm, lumbar multifidus and pelvic floor muscles [1]. The LAW is formed by the transversus abdominis (TrA), internal oblique (IO) and external oblique approaches. The core muscle group is closely related to respiration, in which the lateral abdominal wall muscles are the main auxiliary expiratory muscles, and the diaphragm is the main inspiratory muscle. The lateral abdominal wall muscle and the diaphragm play an antagonistic synergistic role. The contraction of the lateral abdominal wall muscle helps to pull down the thorax, compress the abdominal contents, strengthen the abdominal pressure, push the diaphragm into the thorax, increase the intrathoracic pressure, and thus increase the expiratory flow [2]. Strengthening LAW training can increase intra-abdominal pressure and the range of diaphragm movement, to improve spinal and pelvic stability, trunk stability and motor control [3, 4]. Therefore, core muscle training is an important part of sports training. By controlling the position and movement of the trunk above the pelvis, the generated force and movement are transmitted to the distal end of the limbs, and the ability of the limbs to control movement is improved [5]. It is of great value in maintaining movement stability and improving sports performance. Core training can also provide symptomatic relief in patients with lower back pain; it has been shown that core training can significantly reduce pain, improve balance, and improve lumbar multifidus muscle thickness compared to strength training [6]. In adolescent scoliosis patients, core training can improve spinal deformity, relieve pain, and improve quality of life [7]. In stroke patients with hemiplegia, core training can improve balance and gait stability [8].

The lateral abdominal wall muscles, especially the transversus abdominis, are the most important muscles for core training

The TrA is one of the most important muscles in the LAW. Firstly, the TrA is the first LAW to be activated. In different core trainings, the activation sequence of core muscle groups varies, in which the lateral abdominal wall muscle, especially the TrA, is the most preferentially activated [9, 10]. Secondly, the structure of TrA provides a strong stabilizing effect on the abdominal wall. As the deepest part of the core muscle group, the transversus abdominis muscles connect to the thoracolumbar fascia, forming a ring in the abdomen. The contraction of the TrA muscles will increase the abdominal pressure and tension of the thoracolumbar fascia, thus creating a stable binding effect on the abdomen [11–13]. Therefore, TrA training is an important part of core exercise.

Current methods of exercising the TrA include supine deep abdominal breathing, supine crunches, single-leg extension, plank support, and other exercises. It is thus important to consider which exercise can activate the TrA to a greater extent while reducing energy expenditure. Actions can be designed from the following two aspects:

Different forms of exercise

Calm abdominal breathing is mainly completed by the rebound of the diaphragm and thorax, and does not require the participation of abdominal muscles, while deep abdominal exhalation is mainly completed by the abdominal muscles. Therefore, deep abdominal breathing can directly strengthen abdominal muscle contraction and is an ideal exercise for core muscles [9, 12, 14, 15]. Abdominal curls enhance the stability of the core muscles by modifying the instability of the spine [16, 17], but it is not clear which movement can better activate the LAW, especially the TrA. Adductor ball squeezes can activate hip adductors. The pelvic floor muscles connected to the hip adductors are part of the core muscles, which can theoretically stabilize the pelvis and improve core stability [18–20]. It has also been shown that during deep breathing while carrying out adductor ball squeezes, the muscle thickness of the LAW is greater than that during simple deep breathing [21]. However, there is no comparison between the activation of the LAW during adductor ball crunches and simple crunches.

Therefore, this study analyzed deep breathing, abdominal crunches and ball crunches to verify whether changing the stability of the spine and pelvis can help increase the activation effect of the TrA during abdominal breathing.

Different hip flexion angles

The initial states of the LAW under different hip flexion angles are inconsistent, and it is still unclear which angle can better activate the LAW and maintain the stability of the core muscles. In clinical practice, hip flexion and knee flexion at 0° and hip flexion at 45° and knee flexion at 90° are commonly used training postures. However, according to the theory of trunk asymmetry, hip flexion and knee flexion at 90° are more conducive to trunk symmetry, restoring the diaphragm's zone of apposition [22], thereby stimulating the potential of the respiratory muscles and exercising the core muscles [23]. Therefore, it is necessary to study the best training angle.

Measurement of LAW and the assessment value of ultrasound

Currently, many methods, such as visual observation, manual palpation, electromyography, and pulmonary function testing, ultrasonography are used to evaluate the activation of LAW. Visual observation and manual palpation are greatly affected by the observer's experience, and the movement data of the LAW cannot be directly obtained, which is prone to errors. Needle electromyography is an invasive procedure and is poorly tolerated by test subjects. Surface electromyography also has limitations in the measurement of LAW. Since the layers of the LAW have a large overlap in anatomical structure, surface electromyography easily interferes with each other when evaluating the activities of each layer of muscles. Moreover, the abdomen is close to the heart and is easily affected by electrocardiograph interference [24, 25]. The pulmonary function test mainly reflects the respiratory function index by measuring vital capacity and maximum expiratory volume but cannot directly obtain data on expiratory muscle movement [26]. Therefore, it is important to find an accurate, non-invasive and direct way to evaluate LAW movement. As a non-invasive method, ultrasound technology has unique advantages in the evaluation and training of core muscle strength training [27]. , as it can monitor muscle activity in real time and is easily operable.

Some researchers measured muscle activity through ultrasound and electromyography and demonstrated that changes in muscle thickness on ultrasound images are consistent with the degree of muscle recruitment on electromyography [28]. Previous studies using ultrasound to observe the thickness and echo intensity of the LAW in different postures have shown that ultrasound measurements of the LAW have high reliability [27]. Researchers using real-time ultrasound feedback to train core muscle groups have achieved better results than traditional treatment methods, verifying the value of ultrasound in LAW training [29]. The above literature confirms that ultrasound has unique advantages in evaluating movement, but no study has used ultrasound to evaluate the effects of different core training methods on lateral abdominal wall muscle activation. Therefore, in this study, different types of core strength training movements were designed, and ultrasound was used to measure the subjects' contraction effects in real time to verify the degree of activation of the LAW among different types of core strength training movements to determine the optimal treatment for activating the TrA and increasing core muscle stability.

The preliminary hypothesis of this experiment is that deep breathing is an effective posture for training the LAW, and that crunch and ball crunch have effects on the LAW, but which way is the best remains to be verified; movement at different angles has different activation effects, and the specific angle needs to be determined.

Method

Subjects

Twenty-two healthy subjects were enrolled and their International Physical Activity Scale (IPAQ) was classified as moderate intensity [30].

We used the Pass software to calculate the sample size. An a priori power analysis indicated that a sample size of 15 was needed (a moderate effect size (ES) of 0.3, an α-error of 0.025, and a power of 0.95) [9].

Inclusion criteria

(1) 18–24 years old [31];
(2) No acute or chronic medical history that may affect the research process or results (such as acute upper respiratory tract infection, chronic obstructive pulmonary disease, chronic cardiac insufficiency, cerebrovascular disease, etc.);
(3) No spinal-related pain or related neurological symptom pain within half a year;
(4) No history of surgery related to the chest, abdomen, pelvis or spine;
(5) No long-term hospitalization, inactivity or injury within 2 years;
(6) No use of drugs that affect nerve or muscle motor functions within 1 year;
(7) Voluntarily join this experiment and sign the informed consent form.

Exclusion criteria

(1) Nervous, muscular, skeletal, cardiopulmonary and other diseases;
(2) Abnormal body anatomy;
(3) Professional sports trainers.

The experimental protocol was approved (approval code: 2022-YJS-ks-15) by The Second Affiliated Hospital, Guangzhou Medical University Ethics Committee in accordance with the Declaration of Helsinki.

The general information of the subjects is shown in Table 1.

Test actions

In order to test the effect of lumbar and pelvic stability on expiratory muscles, we selected deep abdominal exhalation, deep exhalation abdominal crunches, and abdominal crunches with a ball. To test the effect of trunk symmetry on expiratory muscles, we selected hip flexion 0, 45, and 90 degrees. The above action elements

Table 1 Descriptive characteristics of the participants. Mean values ± (standard deviation)

	Number of Subjects	Age	Height(cm)	Weight(kg)	Body Mass Index(kg/m^2)
Male	10	23.00 ± 1.15	171.70 ± 3.97	66.95 ± 5.41	22.72 ± 1.83
Female	12	22.67 ± 0.78	159.67 ± 5.55*	49.00 ± 5.10*	19.16 ± 0.88*
Total	22	22.82 ± 0.98	164.14 ± 7.78	57.16 ± 10.48	20.78 ± 2.27

*. Significant differences compared to males

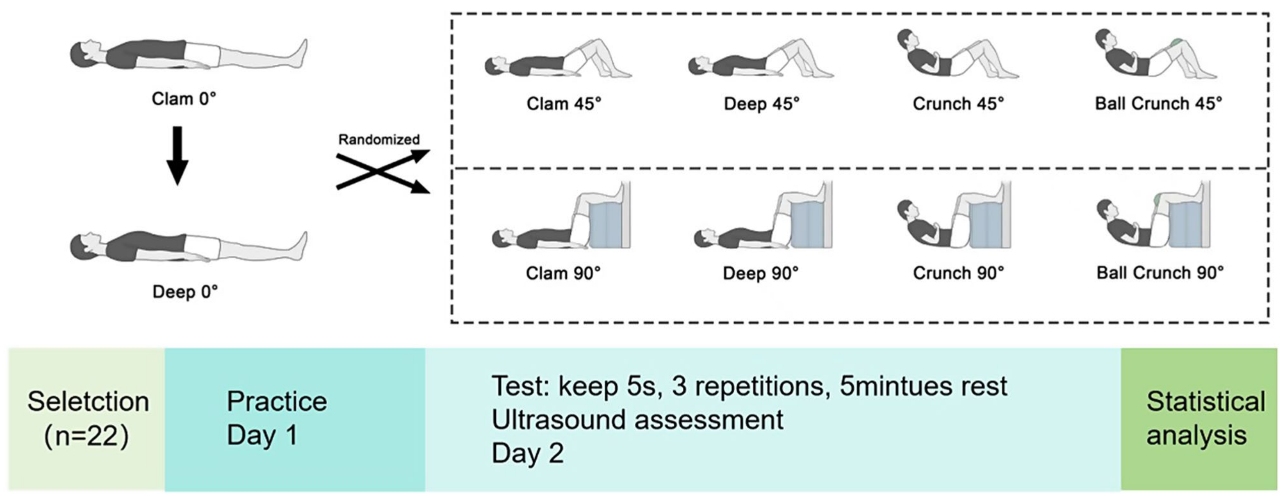

Fig. 1 Test processes and actions

are combined, and the specific action specifications are as follows.

All subjects performed prescribed actions according to verbal instructions: Calm (quiet abdominal exhalation), Deep (deep abdominal exhalation), Standard movement (Pull the navel inwards and backwards towards the spine on a deep exhalation and hold for 5 s), Crunch (Deep exhalation crunch. Standard movement: Tighten the abdomen, curl the abdomen and raise the shoulders until the shoulder blades are lifted off the bed and hold for 5 s). Ball Crunch (Deep exhalation ball crunch. Standard movement: Place a yoga ball at shoulder width between your knees and hold it between your knees throughout the exercise. Squeeze the abdomen, roll up the belly and raise the shoulders until the shoulder blades are lifted off the bed and hold for 5 s). 0° means 0° hip flexion and 0° knee flexion; 45 means 45° hip flexion and 90° knee flexion; 90 means 90° hip flexion and 90° knee flexion (Fig. 1).

The subjects were required to be familiar with the essentials of the actions and practice them at least 6–8 times first. After mastering the above actions, the subjects were required to take sufficient rest and complete the actions in sequence under the guidance of oral instructions using ultrasound the next day. At the beginning of the test, calm 0° and deep 0° were measured; then 45° or 90° movements were randomly tested, including calm, deep, crunch, and ball crunch, and the four movements were performed in order. During the test, the subjects held each action for 5 s, rested for 5 min [32], and then proceeded to the next set of action training. Each set of data was collected three times (Fig. 1).

We used the Visual Analogue Scale (VAS) to assess fatigue, ranging from no fatigue to severe fatigue, with a score of 0–10. Before each test, subjects were asked about their level of fatigue to ensure that the score was 0, indicating no fatigue. Fatigued subjects were asked to rest before performing the next set of exercises.

Ultrasound assessment

Apparatus

Ultrasound images of LAW were obtained using a portable brightness mode (B-mode) ultrasound imaging device (FUJFILM SonoSite, SE Bothell, WA, USA) and a multi-frequency linear-array probe (HFL38x/13−6 MHz, SE Bothell, WA, USA). FUJFILM SonoSite software was used to produce and digitally store images of each area in real time.

Testers

The ultrasound measurements were performed by a trained physician with experience in musculoskeletal ultrasound diagnosis. The physician applied the probe lightly to the skin to avoid compression of the tissue. During the movement, the handheld probe was slightly adjusted to follow the subject's body movement to ensure that the test image was in the same position.

Probe position
The ultrasound probe was located at the intersection of the midaxillary line and the umbilical level. The probe direction was adjusted slightly while observing the TrA, IO, and EO (Fig. 2).

Measurement position
The anterior edge of the TrA on the left side of the image was displayed, the image was frozen, and the intersection point 2 cm to the right of the connection between the transversus abdominis muscle and the thoracolumbar fascia was taken as the measurement site (Fig. 3a).

The thicknesses of the transversus abdominis, internal oblique, and external oblique muscles were measured. The muscle thickness was the vertical distance between the upper and lower fascia (excluding the fascia layer) (Fig. 3b).

The muscle thicknesses were measured using the software provided with the ultrasound machine.

The formula for calculating the contraction thickness ratio was as follows: thickness at contraction/thickness at rest *100%.

Statistical methods
Statistical analysis was carried out using the SPSS version 25 software program (SPSS Inc., Chicago, IL, USA). Pearson correlation coefficients were obtained to assess the reliability of the ultrasound measurements of abdominal muscle thickness and the relationships of the dependent variables with BMI, sex and muscle condition. The ranges of 0.2< |ICC| < 0.4, 0.4< |ICC| < 0.6, and 0.6< |ICC| < 1 were defined as weak, moderate, and strong correlations, respectively [33]. Statistical comparisons for each muscle thickness and contraction ratio among the sexes were performed using an independent-samples T test. Statistical comparisons for each muscle thickness and contraction ratio among the conditions were performed using a paired-samples T test. The results are reported as the means ± standard errors. Significance was determined at values of $p \leq 0.05$.

Results
The reliability of ultrasound measurement of LAW thickness in this experiment is shown in (Table 2). The effects of BMI and gender on LAW thickness are shown in (Tables 3 and 4), and the effects on LAW contraction ratio are shown in (Table 5). The effects of different movements (deep breathe, crunch and ball crunch) on TrA contraction ratio are shown in (Tables 6 and 7; Fig. 4). The contraction ratio of the TrA during deep expiration at different angles is shown in (Table 8; Fig. 5). The changes in TrA and LAW thickness at different hip flexion angles are shown in (Tables 9 and 10; Fig. 6).

Fig. 2 The position of the ultrasound probe. EQ: external oblique abdominal muscle, IQ: internal oblique abdominal muscle, TRA: transversus abdominal muscle

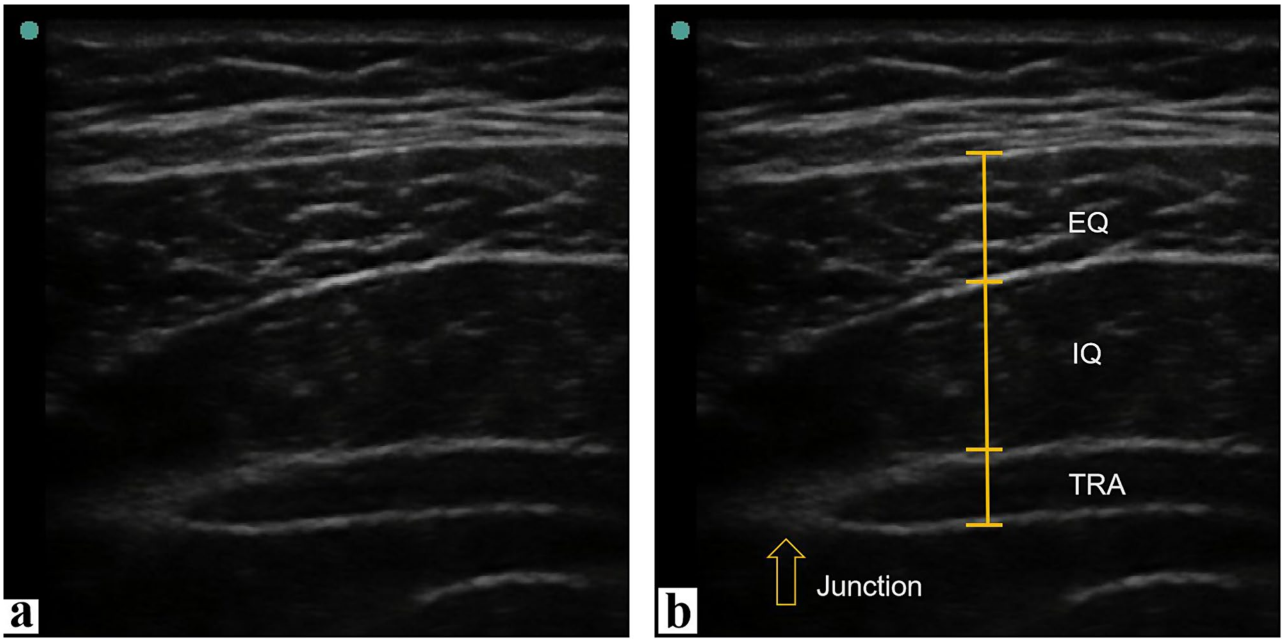

Fig. 3 Ultrasound image of the lateral abdominal wall

Table 2 The reliability of measuring the LAW thickness

	Left		Right	
	ICC	SEM	ICC	SEM
Calm 0°	0.94	0.00	0.99	0.00
Calm 45°	0.99	0.00	0.99	0.00
Calm 90°	0.99	0.00	0.99	0.00
Deep 0°	0.99	0.00	0.98	0.00
Deep 45°	0.99	0.00	0.99	0.00
Deep 90°	0.91	0.11	0.98	0.00
Crunch 45°	0.99	0.00	0.94	0.00
Ball crunch 45°	0.94	0.00	0.90	0.13
Crunch 90°	0.99	0.00	0.98	0.00
Ball crunch 90°	0.94	0.01	0.97	0.00

ICC: Intraclass correlation coefficient

SEM: Standard error of measurement

Table 3 Correlation between BMI and LAW thickness at the end of calm expiration

	Left		Right	
	ICC	SEM	ICC	SEM
Calm 0°	0.84	0.00	0.88	0.00
Calm 45°	0.70	0.00	0.88	0.00
Calm 90°	0.55	0.01	0.89	0.00

Musculoskeletal ultrasound had extremely strong reliability in measuring LAW thickness. (Table 2)

The total thickness of the bilateral abdominal wall muscles at the end of calm expiration was positively correlated with BMI. (Table 3)

The total thickness of the LAW in men was significantly greater than that in women. (Table 4) With respect to exercise, there was no correlation between BMI or sex and the contraction ratio of the LAW. (Table 5) There were no significant differences in the contraction ratio of ipsilateral abdominal wall between genders. (Table 5)

There were significant differences in the contraction ratio of the transversus abdominis muscle among different actions

The contraction ratio of the transversus abdominis muscle at the end of deep expiration was significantly greater than during crunches and ball crunches. However, there was no significant difference in contraction ratio of the transversus abdominis muscle between crunches and ball crunches, (Table 6, Fig. 4ab) and there were no significant differences in the contraction ratio of the LAW muscle among different actions (Table 7, Fig. 4cd).

Table 4 The thickness of the LAW in different genders at the end of calm expiration (mm)

	Left				Right			
	Male	Female	*P*	Cohen'd	Male	Female	*P*	Cohen'd
Calm 0°	31.71 ± 5.22	21.89 ± 2.85	**<0.01**	-2.40	31.31 ± 4.70	19.39 ± 2.00	**<0.01**	-3.42
Calm 45°	34.06 ± 6.78	22.85 ± 2.72	**<0.01**	-2.25	36.84 ± 7.38	23.90 ± 3.29	**<0.01**	-2.35
Calm 90°	33.26 ± 11.12	22.12 ± 3.73	**0.04**	-1.40	34.85 ± 4.44	22.53 ± 3.02	**<0.01**	-3.31

P/ Cohen'd. Significant differences compared to males

Table 5 The contraction ratio of the LAW in different genders at the end of expiration during different actions (%)

	Left				Right			
	Male	Female	*P*	Cohen'd	Male	Female	*P*	Cohen'd
Deep 45°	115.55 ± 9.20	123.42 ± 21.16	0.46	0.47	122.30 ± 14.50	120.30 ± 15.86	0.83	-0.13
Crunch 45°	119.16 ± 12.23	121.53 ± 19.16	0.82	0.14	125.84 ± 9.90	109.81 ± 27.89	0.26	-0.74
Ball crunch 45°	120.47 ± 5.81	127.21 ± 17.92	0.44	0.48	127.52 ± 11.23	111.65 ± 19.71	0.15	-0.96
Deep 90°	119.72 ± 19.87	112.95 ± 5.89	0.44	-0.49	117.78 ± 20.86	119.35 ± 14.79	0.89	0.09
Crunch 90°	119.69 ± 27.09	113.12 ± 18.44	0.64	-0.29	126.08 ± 15.03	120.54 ± 29.08	0.71	-0.23
Ball crunch 90°	124.16 ± 21.62	114.78 ± 15.59	0.42	-0.51	132.99 ± 24.26	130.28 ± 31.53	0.88	-0.10

P /Cohen'd. compared with iplateral crunch

Table 6 The contraction ratio of the TrA at the end of expiration during different actions (%)

	Left					Right				
	X ± SD	P1	Cohen'd 1	P2	Cohen'd 2	X ± SD	P1	Cohen'd 1	P2	Cohen'd 2
Deep 45°	155.86 ± 43.26	**<0.001**	0.93	**0.01**	0.66	162.24 ± 44.10	**<0.001**	1.08	**0.01**	0.62
Crunch 45°	110.83 ± 17.36	-	-	0.37	-0.20	127.01 ± 28.48	-	-	0.06	-0.39
Ball crunch 45°	119.39 ± 41.09	0.37	-0.20	-	-	140.80 ± 38.26	0.06	-0.39	-	-
Deep 90°	146.43 ± 57.30	**0.04**	0.46	**<0.001**	0.72	156.67 ± 53.11	**0.02**	0.56	**0.01**	0.64
Crunch 90°	117.05 ± 22.10	-	-	0.89	0.03	126.27 ± 32.99	-	-	0.58	0.12
Ball crunch 90°	116.19 ± 24.28	0.89	0.03	-	-	124.34 ± 32.50	0.58	0.12	-	-

P1/Cohen'd 1. compared with iplateral crunch

P2/Cohen'd 2. compared with iplateral ball crunch

Table 7 The contraction ratio of the LAW at the end of expiration during different actions (%)

	Left					Right				
	Mean ± SD	P1	Cohen'd 1	P2	Cohen'd 2	Mean ± SD	P1	Cohen'd 1	P2	Cohen'd 2
Deep 45°	119.84 ± 16.56	0.81	-0.08	0.19	-0.42	121.21 ± 14.52	0.50	-0.21	0.57	0.18
Crunch 45°	124.15 ± 13.66	-	-	0.27	-0.35	118.86 ± 17.70	-	-	0.68	0.13
Ball crunch 45°	116.03 ± 13.70	0.27	-0.35	-	-	118.64 ± 16.85	0.68	0.13	-	-
Deep 90°	120.45 ± 15.65	0.99	0.00	0.41	-0.26	117.09 ± 22.32	0.57	0.18	0.09	-0.56
Crunch 90°	116.11 ± 21.80	-	-	0.44	-0.24	123.06 ± 22.84	-	-	0.13	-0.51
Ball crunch 90°	119.05 ± 18.24	0.44	-0.24	-	-	131.51 ± 27.10	0.13	-0.51	-	-

P1/Cohen'd 1. compared with iplateral crunch

P2/Cohen'd 2. compared with iplateral ball crunch

When exhaling deeply at different angles, the contraction ratios of the TrA, IO, and EO differed. TrA contracted the most, followed by IO and EO. (Table 8; Fig. 5)

The thicknesses of the TrA and LAW decreased from 0° to 45° to 90° during deep expiration. (Table 9; Fig. 6)

The bilateral TrA at deep 0° was significantly thicker than deep 45° and 90°, while thicknesses between deep 45° and 90° were not significant. (Table 9; Fig. 6a) Bilateral LAW at deep 90° was significantly thinner than at deep 0°, while thicknesses between deep 0° and 45°, deep 45° and 90° were not significant. (Table 10; Fig. 6b)

Discussion

The core muscles refer to the muscle group that surrounds the torso and protects the stability of the spine. They play roles in maintaining balance, transmitting force, and regulating breathing, serving as a crucial link between the upper and lower limbs. As an essential part of maintaining body stability, core muscle training is the foundation of all physical activities. In therapeutic exercise, core training can not only treat diseases directly related to core muscles, such as low back pain and scoliosis, but also contribute to treating functional disorders. These exercises can enhance stability and physical endurance in patients with walking impairment from hemiplegia after stroke [8], and improve respiratory function in patients with severe pneumonia [34].

Core muscle group training can be evaluated using ultrasound. As a popular method of measuring muscle movement, musculoskeletal ultrasound can be used to monitor muscle activity noninvasively and in real time [27]. Different muscles are measured differently. In this study, the thicknesses of the TrA, IO and EO were measured at the intersection of the midaxillary line and the umbilical level by performing different exercises in different postures of hip and knee flexion. The obtained thickness data had high reliability. This experiment verified the feasibility of using ultrasound to measure the thickness of the lateral abdominal wall muscles during calm

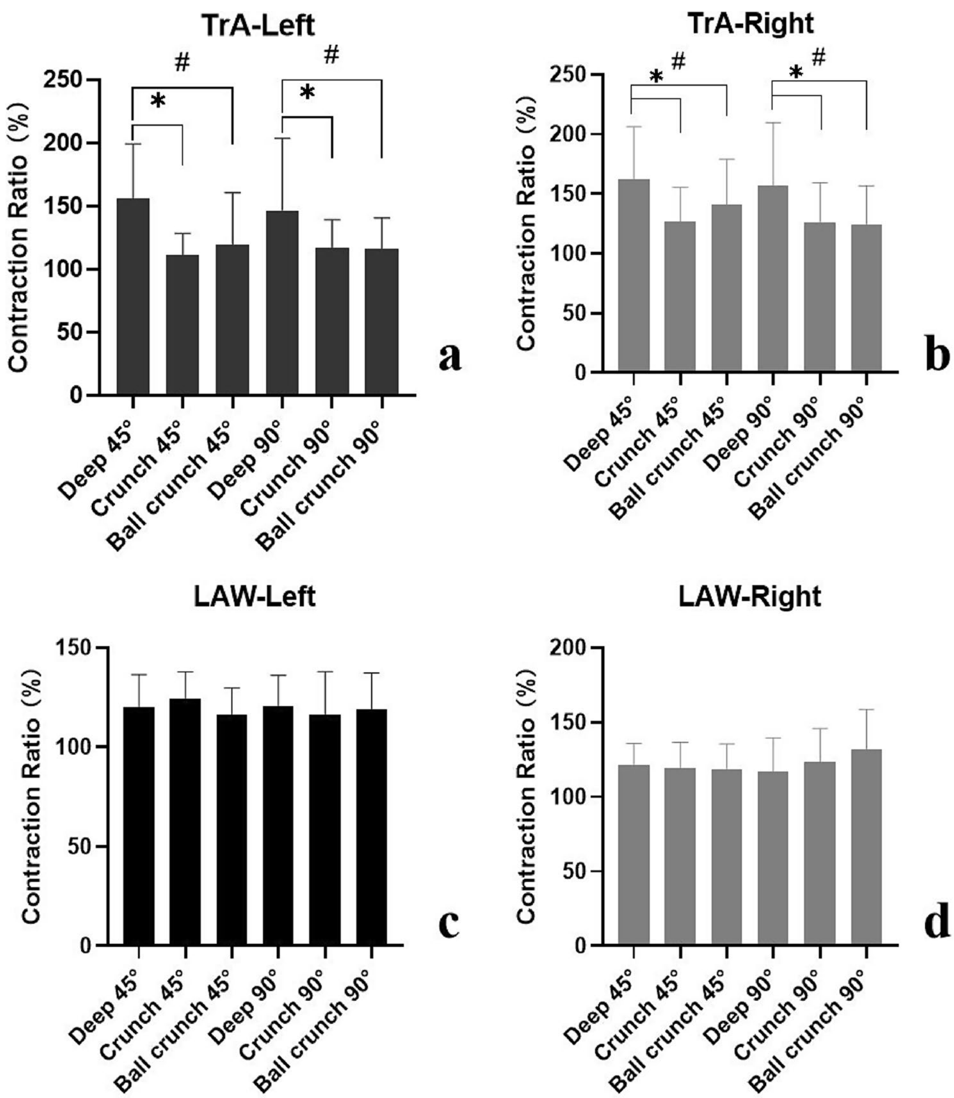

Fig. 4 The contraction ratio of the TrA and the LAW at the end of expiration during different actions (%) * $P \leq 0.05$ compared with ipsilateral crunch. # $P \leq 0.05$ compared with ipsilateral ball crunch

breathing, deep breathing, abdominal crunches, and ball crunches in different postures.

To avoid the interference of sports foundation on this study, all subjects included in this experiment were healthy young people. Their basic physical activity level assessed by the International Physical Activity Scale (IPAQ) were moderate intensity. Subjects were trained prior to testing and were ensured to have adequate rest, to minimize errors and ensure accuracy of the test. While BMI and sex were shown to affect muscle thickness during calm breathing, they had no effect on contraction ratio, which reflects that contraction ability was not affected by these two factors.

However, potential asymmetry of the LAW as the main expiratory muscle is a problem that deserves attention [35]. An example of respiratory muscle asymmetry can be appreciated in the diaphragm, where the right hemidiaphragm lies higher than the left due to the underlying abdominal viscera, and its contraction during inspiration is also asymmetrical. The bilateral abdominal wall muscles of healthy people have been shown to be symmetrical in the supine position and during bridge exercises [32]. However, as the hip flexion angle increases and the lumbar curvature becomes straight, the abdominal muscles relax and reduce pressure on the abdominal organs, which could accentuate any underlying muscle asymmetry. It is worth exploring whether relaxation affects the contraction ability and symmetry of the LAW. We found that the total contraction ratio of the bilateral abdominal wall muscles was symmetrical in healthy people during calm exhalation at 0°, 45° and 90° of hip flexion. The contraction ratio of the bilateral abdominal wall muscles remained symmetrical during deep expiration, crunch and ball crunch. This suggests that in healthy

Table 8 Contraction ratio of TrA, IO, and EO at the end of expiration during deep expiration at different angles (%)

		Deep 0°					**Deep 45°**					**Deep 90°**				
		X ± SD	P1	Cohen'd 1	P2	Cohen'd 2	X ± SD	P1	Cohen'd 1	P2	Cohen'd 2	X ± SD	P1	Cohen'd 1	P2	Cohen'd 2
Left	TrA	156.46 ± 42.91	**<0.001**	3.22	**<0.001**	1.39	126.28 ± 33.63	**0.03**	0.50	**<0.001**	1.20	146.43 ± 57.30	0.12	0.35	**<0.001**	0.99
	IO	108.91 ± 23.11	-	-	0.23	0.26	155.86 ± 43.26	-	-	**<0.001**	0.77	124.51 ± 27.78	-	-	**0.01**	0.64
	EO	99.50 ± 16.48	0.23	0.26	-	-	103.07 ± 16.62[a]	**<0.001**	0.77	-	-	99.90 ± 16.54[a]	**0.01**	0.64	-	-
Right	TrA	164.54 ± 42.15	0.55	-0.13	0.01	1.74	148.00 ± 44.43	0.14	0.33	**<0.001**	1.17	156.67 ± 53.11	0.31	0.22	**<0.001**	0.99
	IO	173.94 ± 51.31	-	-	**<0.001**	1.49	162.24 ± 44.10	-	-	**<0.001**	0.95	144.13 ± 48.35	-	-	**<0.001**	1.01
	EO	96.84 ± 12.18[a]	**<0.001**	1.49	-	-	97.61 ± 17.56[a]	**<0.001**	0.95	-	-	95.81 ± 14.89[a]	**<0.001**	1.01	-	-

P1 / Cohen'd 1. Compared with the ipsilateral IO

P2 / Cohen'd 2. Compared with the ipsilateral EO

subjects performing active trunk exercises, both sides of the abdominal core muscles could recruit muscle fibers in a timely and effective manner to maintain tension, with relatively balanced recruitment. This experiment compared the recruitment of the three muscles (i.e. the contraction ratio), and revealed that the contraction ratio of the TrA was significantly greater than that of the IO and EO. This reflected the dominant role of the TrA in core stabilization in maintaining posture, but since no temporal factors were recorded, its characteristics for intended postural adjustment could not be explained [36]. In the treatment of diseases involving truncal asymmetry, such as poststroke hemiplegia [8, 37], scoliosis [7, 38], and non-specific low back pain [6, 39], it is particularly important to maintain symmetrical activation of the bilateral trunk muscles. The movements involved in this study were all symmetrical movements, and it has been proven that both LAWs could be symmetrically activated. This study provides a reference scheme for symmetrical therapeutic exercise.

The exercises in this research are all common methods for exercising the core muscles. Deep abdominal breathing mainly increases intra-abdominal pressure through contraction of the LAW, to maintain stability of the core muscles. Abdominal curls involve stabilizing the spine through contraction of the LAW, to exercise the core muscles [40, 41]. Ball crunches can involve contraction of the hip adductors, which can maintain stability of the pelvis, and theoretically further strengthen the stability of the core muscle group [18, 21]. S9tudies have shown that a combination of deep exhalation and core stability training can more effectively activate the LAW [42].

This study revealed that among the three types of exercise, the contraction ratio of the TrA was greatest during deep breathing. Compared with those during calm expiration, the contractions of abdominal curls and ball crunches were also significantly greater, but both were weaker than those during deep expiration. This confirmed that the main function of the lateral abdominal wall muscle was to facilitate exhalation and to maintain trunk stability, rather than to dominate trunk movement [16]. Few previous studies have directly measured the role of the TrA in core training. The TrA is an important expiratory muscle, and deep exhalation is an action that directly activates the TrA. [14,15,16,17] This study further confirmed the important role of deep exhalation in activating the TrA. Deep breathing under steady conditions is the best way to exercise one's abdominal core muscles, as it provides the most contraction while requiring less effort than crunches and ball crunches. Therefore, we recommend using deep breathing exercises for TrA training.

The contraction ratio of muscle mainly reflects the recruitment ability of muscle fibers, that is, the

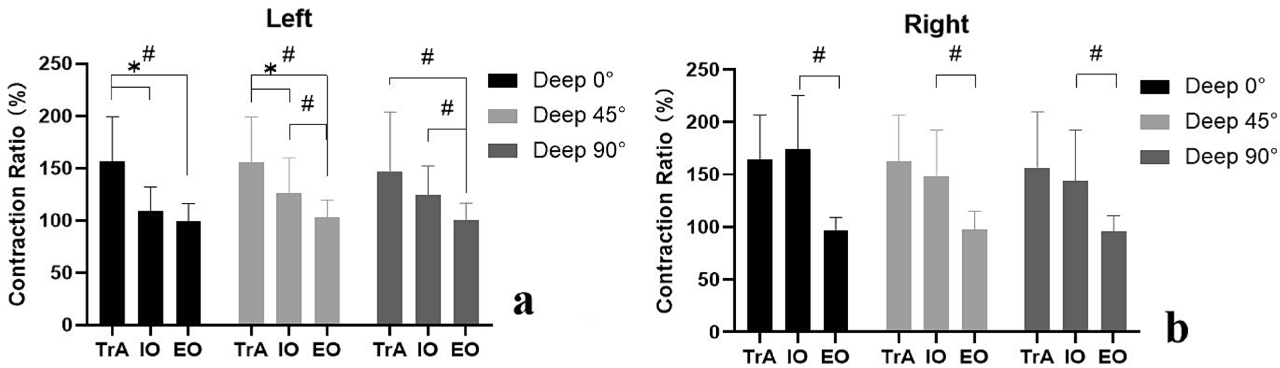

Fig. 5 Contraction ratio of TrA, IO, and EO at the end of expiration during deep expiration at different angles (%) * $P \leq 0.05$ compared with ipsilateral IO. # $P \leq 0.05$ compared with ipsilateral EO

Table 9 The thickness of the TrA during deep expiration at different angles (mm)

	Left					Right				
	X ± SD	P1	Cohen'd 1	P2	Cohen'd 2	X ± SD	P1	Cohen'd 1	P2	Cohen'd 2
Deep 0°	6.25 ± 1.45	**<0.001**	1.18	**<0.001**	1.70	7.11 ± 1.78	**<0.001**	0.96	**<0.001**	0.91
Deep 45°	4.63 ± 1.84[a]	-	-	0.12	0.35	5.07 ± 1.90[a]	-	-	0.64	-0.10
Deep 90°	4.27 ± 1.37[a]	0.12	0.35	-	-	5.21 ± 2.21[a]	0.64	-0.10	-	-

P1 / Cohen'd 1. Compared with the ipsilateral Deep 45°

P2 / Cohen'd 2. Compared with the ipsilateral Deep 90°

Table 10 The thickness of the LAW during deep expiration at different angles (mm)

	Left					Right				
	X ± SD	P1	Cohen'd 1	P2	Cohen'd 2	X ± SD	P1	Cohen'd 1	P2	Cohen'd 2
Deep 0°	29.44 ± 6.76	0.40	0.18	**<0.001**	0.69	31.57 ± 8.21	0.18	0.30	**0.01**	0.60
Deep 45°	28.91 ± 8.46	-	-	0.12	0.35	30.04 ± 11.24	-	-	0.59	0.12
Deep 90°	27.12 ± 8.21[a]	0.12	0.35	-	-	29.61 ± 9.84[a]	0.59	0.12	-	-

P1 / Cohen'd 1. Compared with the ipsilateral Deep 45°

P2 / Cohen'd 2. Compared with the ipsilateral Deep 90°

contraction ability of muscle. Although muscle thickness is often thought to directly reflect the number of muscle fibers, it can also be used to evaluate muscle fatigue [43]. Studies using combined ultrasound imaging and surface electromyography, measuring changes in muscle thickness during contraction, have found that muscle thickness increases when the muscle is fatigued. Under calm breathing at different hip flexion angles, the initial thickness of the TrA was the same. During deep breathing, the thickness of the TrA decreased at 0°, 45° and 90°, indicating that the TrA was most relaxed at 90°. This shows that an increase in hip flexion angle causes a reduction in lumbar flexion and a relaxation of the LAW, especially the TrA. However, there was no significant difference in the contraction ratio of the lower transversus abdominis muscle at different angles, which indicates that relaxation of the transversus abdominis muscle had no effect on its contractility. Therefore, it is suggested that the best training posture for transversus abdominis muscle exercise is at 90° hip flexion and 90° knee flexion. This would relax the muscles to avoid fatigue, while maintaining their contractility.

Previous studies have observed the characteristics of different core exercises on the LAW, with different training methods. While the exercises in this article were common clinical training methods, there is no research on the effects of these methods on LAW activation. Our research has used ultrasound to monitor the LAW in real time during exercise. Ultrasound is non-invasive, real-time, and intuitive, making it more accurate than other methods, such as traditional electromyography and respiratory function tests.

We hypothesized that deep exhalation can activate the LAW and that both crunch and ball crunch can activate the lateral abdominal wall. The results showed that deep breathing is the best action to activate the LAW, especially the TrA. Deep breathing with 90° hip and knee flexion is the most effective for activating the transversus abdominis, as it relaxes the muscle while maintaining contractile force. This exercise can be used in rehabilitation and physical therapy, to improve stability and muscle recovery. The movement is also easy to perform, making it suitable for patients with physical weakness or limb

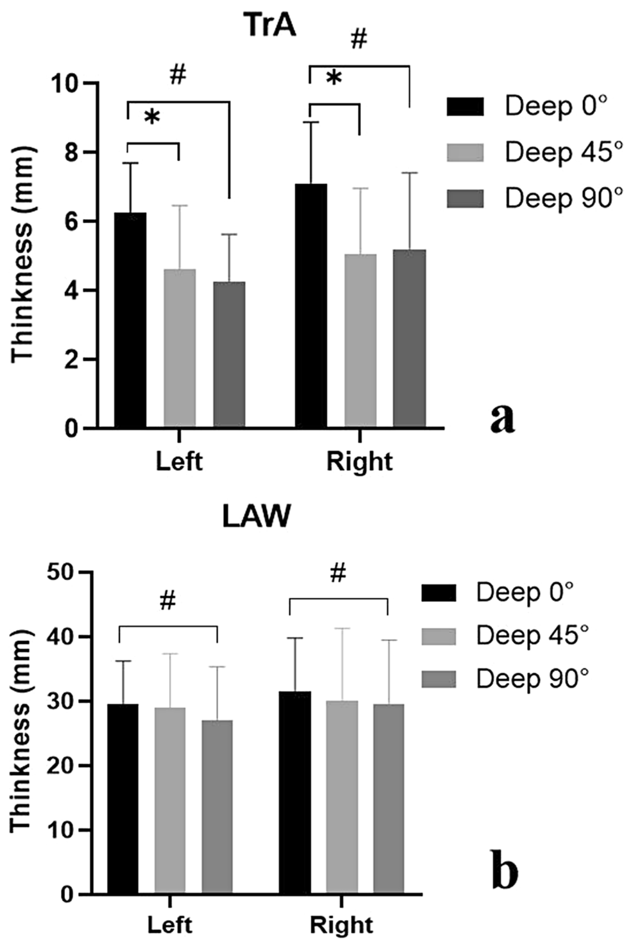

Fig. 6 The thickness of the transversus abdominis and LAW during deep expiration at different angles (mm). * $P \le 0.05$ compared with ipsilateral Deep 45° # $P \le 0.05$ compared with ipsilateral Deep 90°

dysfunction, or those who otherwise face difficulty in performing core exercises.

Limitations and future works

This study only focused on subjects with normal levels of exercise, and more research is needed on those with high or low levels of exercise. We had trained the subjects in standard movements before the experiment, and the test procedure was standardized as much as possible. During the test, we ensured that there was a rest period to avoid fatigue, so there was no variation. However, the IPAQ used in the enrolment only stratified the amount of exercise, but did not classify the type of exercise performed by the subjects. In the future, it may be considered to group subjects according to their previous basic exercise types to more accurately assess the effects of different interventions. The subjects included in this study were all healthy young people, and research subjects with asymmetrical trunk diseases will be included in the future to further verify the optimal posture for transversus abdominis muscle training. This study investigated the activation of the LAW to provide a theoretical basis for training methods for the core muscle group. However, the core muscle group also includes the diaphragm, lumbar multifidus, and pelvic floor muscles. In the future, it is necessary to expand the range of muscles observed to determine the best mode of training for the core muscle group. The musculoskeletal ultrasound measurements used in this study were all converted by muscle thickness. Although they can reflect muscle fatigue and contraction ability, they are not direct indicators. More direct parameters reflecting muscle performance could be obtained in the future, such as M-mode ultrasound and electromyography. This article found that deep 90° is the best way to activate the core muscles, but it is a cross-sectional study. In the future, we plan to include people with different health conditions in a randomized controlled trial to verify the effect of this exercise, and determine the optimal dose and duration.

Conclusion

Deep breathing with 90° hip flexion and 90° knee flexion was the best action for activating the LAW, especially the TrA, in healthy young people. Exercises based on this action can improve the training efficiency of the core muscles and enhance training effects. This exercise is also suitable for patients with core muscle weakness, as it provides the most contractility while keeping the muscle relaxed and minimizing risk of injury.

Abbreviations

LAW	Lateral Abdominal Wall
TrA	Transversus Abdominis
IO	Internal Oblique
EO	External Oblique
BMI	Body Mass Index
ICC	Intraclass correlation coefficient
SEM	Standard error of measurement

Supplementary Information

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Supplementary Material 1

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Author contributions

Concept and design: Nan Hu, Fengshan Huang and Ping Miao, date collection and analysis: Nan Hu, Fengshan Huang, Rui Yu and Zeng Yi, critical revision of the article for important intellectual content: Ping Miao and Neil Chen Yi Lun MacAlevey, and study supervision: Ping Miao.

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Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
The experiments reported in the article were undertaken in the Rehabilitation Department of The Second Affiliated Hospital, Guangzhou Medical University and the experimental protocol was approved (approval code:2022-YJS-ks-15) by The Second Affiliated Hospital, Guangzhou Medical University Ethics Committee in accordance with the Declaration of Helsinki. All participants agreed to take part in the test and have signed informed consent forms.

Consent for publication
Not Applicable.

Competing interests
The authors declare no competing interests.

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References
1. Cervera-Cano M, López-González L, Valcárcel-Linares D, Fernández-Carnero S, Achalandabaso-Ochoa A, Andrés-Sanz V, Pecos-Martín D. Core synergies measured with Ultrasound in subjects with chronic non-specific low back Pain and healthy subjects: a systematic review. Sensors. 2022;22(22):8684. https://doi.org/10.3390/s22228684.
2. Liu T, Khalaf K, Adeeb S, El-Rich M. Numerical Investigation of intra-abdominal pressure effects on spinal loads and load-sharing in Forward Flexion. Front Bioeng Biotechnol. 2019;7:428. https://doi.org/10.3389/fbioe.2019.00428.
3. Bordoni B, Marelli F, Bordoni G. A review of analgesic and emotive breathing: a multidisciplinary approach. J Multidisciplinary Healthc. 2016;9:97–102. https://doi.org/10.2147/JMDH.S101208.
4. Fan C, Fede C, Gaudreault N, Porzionato A, Macchi V, DE Caro R, Stecco C. Anatomical and functional relationships between external abdominal oblique muscle and posterior layer of thoracolumbar fascia. Clin Anat (New York N Y). 2018;31(7):1092–8. https://doi.org/10.1002/ca.23248.
5. McGill SM, Grenier S, Kavcic N, Cholewicki J. Coordination of muscle activity to assure stability of the lumbar spine. J Electromyogr Kinesiology: Official J Int Soc Electrophysiological Kinesiol. 2003;13(4):353–9. https://doi.org/10.1016/s1050-6411(03)00043-9.
6. Hlaing SS, Puntumetakul R, Khine EE, Boucaut R. Effects of core stabilization exercise and strengthening exercise on proprioception, balance, muscle thickness and pain related outcomes in patients with subacute nonspecific low back pain: a randomized controlled trial. BMC Musculoskelet Disord. 2021;22(1):998. https://doi.org/10.1186/s12891-021-04858-6.
7. Gür G, Ayhan C, Yakut Y. The effectiveness of core stabilization exercise in adolescent idiopathic scoliosis: a randomized controlled trial. Prosthet Orthot Int. 2017;41(3):303–10. https://doi.org/10.1177/0309364616664151.
8. Lee J, Jeon J, Lee D, Hong J, Yu J, Kim J. Effect of trunk stabilization exercise on abdominal muscle thickness, balance and gait abilities of patients with hemiplegic stroke: a randomized controlled trial. NeuroRehabilitation. 2020;47(4):435–42. https://doi.org/10.3233/NRE-203133.
9. Mesquita Montes A, Baptista J, Crasto C, de Melo CA, Santos R, Vilas-Boas JP. Abdominal muscle activity during breathing with and without inspiratory and expiratory loads in healthy subjects. J Electromyogr Kinesiology: Official J Int Soc Electrophysiological Kinesiol. 2016;30:143–50. https://doi.org/10.1016/j.jelekin.2016.07.002.
10. Barnett F, Gilleard W. The use of lumbar spinal stabilization techniques during the performance of abdominal strengthening exercise variations. J Sports Med Phys Fit. 2005;45(1):38–43.
11. Ishida H, Watanabe S. Changes in lateral abdominal muscles' thickness immediately after the abdominal drawing-in maneuver and maximum expiration. J Bodyw Mov Ther. 2013;17(2):254–8. https://doi.org/10.1016/j.jbmt.2012.12.002.
12. Chino K, Ohya T, Suzuki Y. Association between expiratory mouth pressure and abdominal muscle activity in healthy young males. Eur J Appl Physiol. 2024;124(7):2139–51. https://doi.org/10.1007/s00421-024-05430-5.
13. Hides J, Wilson S, Stanton W, McMahon S, Keto H, McMahon K, Bryant M, Richardson C. An MRI investigation into the function of the transversus abdominis muscle during drawing-in of the abdominal wall. Spine. 2006;31(6):E175–8. https://doi.org/10.1097/01.brs.0000202740.86338.df.
14. Kim Y, Kim J, Nam H, Kim HD, Eom MJ, Jung SH, Han N. Ultrasound maging of the trunk muscles in acute stroke patients and relations with balance scales. Annals Rehabilitation Med. 2020;44(4):273–83. https://doi.org/10.5535/arm.19125.
15. De Troyer A, Estenne M. Functional anatomy of the respiratory muscles. Clin Chest Med. 1988;9(2):175–93.
16. Kim HD, Jeon DM, Bae HW, Kim JG, Han N, Eom MJ. Changes in activation of abdominal muscles at selected angles during trunk Exercise by using Ultrasonography. Annals Rehabilitation Med. 2015;39(6):950–6. https://doi.org/10.5535/arm.2015.39.6.950.
17. Malanga GA, Aydin SM, Holder EK, Petrin Z. (2017). Functional therapeutic and core strengthening. In: Seidenberg MD, FAAFP, FACSM, RMSK P, Bowen MD, FAAPMR, CAQSM, King RMSK,CSCS,J MD, D, editors The hip and pelvis in Sports Medicine and Primary Care. Springer, Cham. https://doi.org/10.1007/978-3-319-42788-1_10.
18. Park SY, Oh S, Baek KH, Bae SS, Kwon JW. Comparison of abdominal muscle thickness between the Abdominal draw-in Maneuver and Maximum Abdominal Contraction Maneuver. Healthc (Basel Switzerland). 2022;10(2):251. https://doi.org/10.3390/healthcare10020251.
19. Eickmeyer SM. Anatomy and physiology of the pelvic floor. Phys Med Rehabil Clin North Am. 2017;28(3):455–60. https://doi.org/10.1016/j.pmr.2017.03.003.
20. Boyle KL, Olinick J, Lewis C. The value of blowing up a balloon. North Am J Sports Phys Therapy: NAJSPT. 2010;5(3):179–88.
21. Kwon JW, Park SY, Baek KH, Youk K, Oh S, Kaunas. Lithuania), 57(2), 129. https://doi.org/10.3390/medicina57020129.
22. Petroll WM, Knight H, Rochester DF. (1990). Effect of lower rib cage expansion and diaphragm shortening on the zone of apposition. Journal of applied physiology (Bethesda, Md.: 1985), 68(2), 484–488. https://doi.org/10.1152/jappl.1990.68.2.484
23. Sannasi R, Dakshinamurthy A, Dommerholt J, Desai V, Kumar A, Sugavanam T. Diaphragm and core stabilization exercises in low back pain: a narrative review. J Bodyw Mov Ther. 2023;36:221–7. https://doi.org/10.1016/j.jbmt.2023.07.008.
24. Yoon TL, Kim KS, Cynn HS. Slow expiration reduces sternocleidomastoid activity and increases transversus abdominis and internal oblique muscle activity during abdominal curl-up. J Electromyogr Kinesiology: Official J Int Soc Electrophysiological Kinesiol. 2014;24(2):228–32. https://doi.org/10.1016/j.jelekin.2013.10.003.
25. Babyar SR, Holland TJ, Rothbart D, Pell J. Electromyographic Analyses of Trunk Musculature after stroke: an integrative review. Top Stroke Rehabil. 2022;29(5):366–81. https://doi.org/10.1080/10749357.2021.1940725.
26. Lee DK, Kim SH. The effect of respiratory exercise on trunk control, pulmonary function, and trunk muscle activity in chronic stroke patients. J Phys Therapy Sci. 2018;30(5):700–3. https://doi.org/10.1589/jpts.30.700.
27. Taghipour M, Mohseni-Bandpei MA, Behtash H, Abdollahi I, Rajabzadeh F, Pourahmadi MR, Emami M. Reliability of real-time Ultrasound Imaging for the Assessment of Trunk Stabilizer Muscles: a systematic review of the literature. J Ultrasound Medicine: Official J Am Inst Ultrasound Med. 2019;38(1):15–26. https://doi.org/10.1002/jum.14661.
28. Ferreira PH, Ferreira ML, Nascimento DP, Pinto RZ, Franco MR, Hodges PW. Discriminative and reliability analyses of ultrasound measurement of abdominal muscles recruitment. Man Therap. 2011;16(5):463–9. https://doi.org/10.1016/j.math.2011.02.010.
29. Lin S, Zhu B, Zheng Y, Huang G, Zeng Q, Wang C. Effect of real-time ultrasound imaging for biofeedback on trunk muscle contraction in healthy subjects: a preliminary study. BMC Musculoskelet Disord. 2021;22(1):142. https://doi.org/10.1186/s12891-021-04006-0.
30. Craig CL, Marshall AL, Sjöström M, Bauman AE, Booth ML, Ainsworth BE, Pratt M, Ekelund U, Yngve A, Sallis JF, Oja P. International physical activity questionnaire: 12-country reliability and validity. Med Sci Sports Exerc. 2003;35(8):1381–95. https://doi.org/10.1249/01.MSS.0000078924.61453.FB.
31. GLOBAI-ISSUES. Youth [EB/OL]. (1981) [2024-08-25] https://www.un.org/en/globai-issues/youth
32. Kelli A, Kellis E, Galanis N, Dafkou K, Sahinis C, Ellinoudis A. Transversus Abdominis thickness at Rest and Exercise in individuals with Poststroke Hemiparesis. Sports (Basel Switzerland). 2020;8(6):86. https://doi.org/10.3390/sports8060086.
33. Cohen J. Statistical power analysis for the behavioral sciences. 2nd ed. Hillsdale, NJ: Lawrence Erlbaum; 1988. https://doi.org/10.4324/9780203771587. Associates.Page:83.
34. Shi ZH, Jonkman A, de Vries H, Jansen D, Ottenheijm C, Girbes A, Spoelstra-de Man A, Zhou JX, Brochard L, Heunks L. Expiratory muscle dysfunction in

critically ill patients: towards improved understanding. Intensive Care Med. 2019;45(8):1061–71. https://doi.org/10.1007/s00134-019-05664-4.
35. Liu X, Yang Y, Jia J. Respiratory muscle ultrasonography evaluation and its clinical application in stroke patients: a review. Front NeuroSci. 2023;17:1132335. https://doi.org/10.3389/fnins.2023.1132335.
36. Biały M, Adamczyk WM, Marczykowski P, Majchrzak R, Gnat R. Deformations of abdominal muscles under experimentally induced low back pain. European spine journal: official publication of the European Spine Society, the European Spinal Deformity Society, and the European section of. Cerv Spine Res Soc. 2019;28(11):2444–51. https://doi.org/10.1007/s00586-019-06016-y.
37. Monjo H, Fukumoto Y, Asai T, Ohshima K, Kubo H, Tajitsu H, Koyama S. Changes in muscle thickness and Echo Intensity in Chronic Stroke survivors: a 2-Year longitudinal study. J Clin Neurol (Seoul Korea). 2022;18(3):308–14. https://doi.org/10.3988/jcn.2022.18.3.308.
38. Alanazi MH, Parent EC, Dennett E. Effect of stabilization exercise on back pain, disability and quality of life in adults with scoliosis: a systematic review. Eur J Phys Rehabil Med. 2018;54(5):647–53. https://doi.org/10.23736/S1973-9087.17.05062-6.
39. Moissenet F, Rose-Dulcina K, Armand S, Genevay S. A systematic review of movement and muscular activity biomarkers to discriminate non-specific chronic low back pain patients from an asymptomatic population. Sci Rep. 2021;11(1):5850. https://doi.org/10.1038/s41598-021-84034-x.
40. Ha SY, Shin D. The effects of curl-up exercise in terms of posture and muscle contraction direction on muscle activity and thickness of trunk muscles. J Back Musculoskelet Rehabil. 2020;33(5):857–63. https://doi.org/10.3233/BMR-191558.
41. Crommert ME, Bjerkefors A, Tarassova O, Ekblom MM. Abdominal muscle activation during common modifications of the trunk curl-up Exercise. J Strength Conditioning Res. 2021;35(2):428–35. https://doi.org/10.1519/JSC.0000000000002439.
42. Ishida H, Watanabe S. Maximum expiration activates the abdominal muscles during side bridge exercise. J Back Musculoskelet Rehabil. 2014;27(4):481–4. https://doi.org/10.3233/BMR-140469.
43. Shi J, Zheng YP, Chen X, Huang QH. Assessment of muscle fatigue using sonomyography: muscle thickness change detected from ultrasound images. Med Eng Phys. 2007;29(4):472–9. https://doi.org/10.1016/j.medengphy.2006.07.004.

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