Abdominal girth as an index of muscle tension during abdominal hollowing: selecting the optimal training intensity for the transversus abdominis muscle

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Key words

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ABSTRACT

The abdominal hollowing technique is used for training the transversus abdominis (TrA). However, the optimal intensity of hollowing is still unclear. The objective of the present study is to verify the validity of estimating the tension of the TrA by measuring the girth of the abdomen with a tape and to determine the optimum intensity of hollowing to effectively train the TrA. Sixteen healthy males performed hollowing with an intensity of 0%, 25%, 50%, 75%, and 100%, estimated from the girth of the abdomen. The shear elastic modulus was measured for the rectus abdominis (RA), external oblique (EO), internal oblique (IO), and TrA at all intensities via ultrasonic shear wave elastography. The shear elastic modulus was considered as the index of the tension of the abdominal muscles at each intensity, and the ratio of the TrA to RA, EO, and IO respectively was calculated as the index of TrA selectivity. As the intensity of hollowing increased, the girth of abdomen decreased and tension of all the four muscles increased. The ratio of TrA to the RA, EO, and IO did not exhibit a significant variation among hollowing

intensities of 25% to 100%. It is rational to estimate the tension of the TrA by measuring the girth of the abdomen. Moreover, considering both TrA contraction intensity and selectivity, abdominal hollowing performed at maximum intensity was effective for the maximum contraction training of the TrA.

1. INTRODUCTION

Transversus abdominis (TrA) contributes especially to the spinal stability (Hodges et al., 1996; Richardson and Jull, 1995). Contraction of the TrA and diaphragm increases the intra-abdominal pressure (Daggfeldt and Thorstensson, n.d.) and intervertebral stiffness (W Hodges et al., 2005), thereby playing a role in the control of the intervertebral motion. Therefore, in order to verify the spinal stability and the effect of the spinal stabilizing exercise, it is necessary to evaluate the muscle activity of the TrA.

To quantify the activity of the TrA, fine-wire (Hodges et al., 1996; Tsao and Hodges, 2008, 2007) and surface (Barnett and Gilleard, 2005; Chanthapetch et al., 2009; Mew, 2009; Teyhen et al., 2009, 2008) electromyography (EMG) and B-mode ultrasound (Hides et al., 2006; Hodges et al., 2003; Ota et al., 2012) have been used to provide this information. However, there are several limitations of these techniques that require consideration. Fine-wire EMG is an invasive method, and therefore, is not suitable for clinical applications. Surface EMG cannot evaluate the individual activity of the TrA by crosstalk. The muscle thickness that is measured by B-mode ultrasound does not show a linear relationship with the muscle activities of the TrA (Hodges et al., 2003). Therefore, these techniques are not suitable to be used for measurement of muscle activities of the TrA.

Ultrasonic shear wave elastography (hereafter referred as SWE) is a recently developed ultrasonic diagnostic technique that can measure the elasticity of a specific part of a muscle noninvasively in real time (Crow et al., 2011; Okubo and Tatsumura, 2010). Previous studies have reported that the shear elastic modulus measured by SWE is linearly related to muscle tension (Lacourpaille et al., 2012; Okubo and Tatsumura, 2010). Therefore, elastography presents a unique method of assessing spinal stability exercises (MacDonald et al., 2016).

The abdominal hollowing technique (hereafter referred as hollowing) is commonly used in clinical practices to preferentially target the TrA in patients with low back pain (Urquhart et al., 2005). The feedforward activity of the TrA occurs independently of other abdominal muscles during the functional tasks (Hodges and Richardson, 1999). An increase in the tension of the TrA is transferred to the linked thoracolumbar fasciae and contributes to the stabilization of the trunk. To stabilize the trunk in the feedforward control of the posture, not only should the TrA be selective, its tension should also increase. Therefore, we defined a training performed under a high tension and TrA selectivity as the optimum training.

To apply hollowing for training the TrA in clinical conditions, it is necessary to contract the TrA strongly and selectively. To the best our knowledge, however, no previous studies have quantified the optimum intensity of hollowing. Tsao and colleagues recommended performing hollowing with an intensity of 5% maximum voluntary contraction (MVC) while presenting a visual EMG feedback of the abdominal muscle via fine-wire EMG (Tsao and Hodges, 2007). However, their study did not examine other intensites, moreover feedback using fine-wire electromyography is invasive and difficult to apply in clinical situations.

We focused on the girth of the abdomen as a method to conveniently evaluate the intensity of hollowing in clinical conditions. The girth of the abdomen can be easily measured using a tape measure. If the optimal intensity of hollowing could be determined by this method, then it will provide useful information for training the TrA.

Therefore, the objectives of this study were (1) to verify the validity of estimating the tension of the TrA by measuring the girth of the abdomen and (2) to determine the optimum intensity of hollowing for training the TrA.

The hypothesis for objective (1) was as follows: because the function of the TrA is to hollow the abdomen when the thorax and pelvis are fixed, it was assumed that the tension of the TrA increased gradually with a decrease in the girth of the abdomen. For objective (2), considering the report that during upper limb movement, only the reaction time of the TrA was reduced when performing hollowing training at a low intensity (Tsao and Hodges, 2007), we hypothesized that the TrA was selectively activated by low-intensity exercises.

2. METHODS

2.1 Subjects

Sixteen healthy males who did not meet the following exclusion criteria volunteered to participate in this study [age: mean 25.7 (SD 3.9) y, height: mean 172.6 (SD 5.6) cm, weight: mean 67.8(SD 8.0) kg, body mass index: mean 22.7(SD 2.1)]. The participants were excluded if they had low back pain at the time of evaluation; history of orthopedic, neurological, respiratory, or circulatory disorders; previous spinal surgery; or history of low back pain lasting three months or more. All the participants provided written informed consent, and the protocol was approved by the Ethics Committee of the Kyoto University Graduate School and Faculty of Medicine (R0546).

The sample size required for the two-way repeated-measurements analysis of variance

(ANOVA) (effect size = 0.25, α error = 0.05, power = 0.8) was calculated using G*power 3.1 software (Heinrich Heine University, Dusseldorf, Germany). The results showed that 10 participants were required; therefore, 16 participants were recruited accounting for potential withdrawal.

2.2 Procedures

All the procedures were performed by the same two physical therapists: one measured the girth of the abdomen using a tape measure, whereas the other measured the shear elastic modulus to ensure reproducibility. Each participant laid in a supine position with hips flexed until the knees exhibited a 90°-flexion and the feet were flat on the bed (crook lying position). With the guidance of the same examiner, the participants practiced the hollowing movements to not move the pelvis and thorax. The participants were then instructed to stop breathing after resting exhalation at the crook lying position and hollow the abdomen maximally. Concurrently, the examiner measured the girth of the abdomen that was used as the index of hollowing at maximum intensity (100% hollowing). The girth of the abdomen was measured 1 cm below the navel. The difference between the girth of the abdomen at 100% hollowing and rest (0% hollowing) was divided by four, and the resulting value was subtracted from the girth of the abdomen at rest. It was then regulated with respect to the hollowing intensity of 25%, 50%, and 75%.

The shear elastic modulus of the abdominal muscles was measured under five conditions of hollowing: 0%, 25%, 50%, 75%, and 100% hollowing intensity. The order of intensity and muscle was randomized for each participant.

The shear elastic modulus of the RA, EO, IO, and TrA was measured via SWE (Aixplorer; Supersonic Imagine, Axi-en-Provence, France) with an ultrasound transducer (SL-10-2 linear ultrasound transducer). The measurement sites were as follows: the RA was assessed 4 cm lateral to the navel, EO was assessed 2.5 cm anterior to the axillary line at the height of the navel, and IO and TrA were examined 2 cm medial to the anterior superior iliac spine. The region of interest (hereafter referred as RoI) was determined to be near the center of the muscle belly in the ultrasound image. A 3-mm-diameter circle was drawn around the center of the RoI (Figures 1,2). The mean shear wave propagation speed (m/s) within the circle was automatically calculated. The shear wave propagation speed (V) was converted to the shear elastic modulus (G) using the following equation:

$$G = \rho V^2$$

where ρ is the muscle mass density, which was presumed to be 1000 kg/m^3 (Gennisson et al., 2005; Nakamura et al., 2014; Nordez et al., 2008). The shear elastic modulus was measured thrice at each condition, and the mean value was used for the analysis. Previous studies indicated the correlation between the calculated shear elastic modulus and the muscle tension (Ateş et al., 2015; Killian Bouillard et al., 2011).

At each intensity condition, the ratio of the TrA to each of the other abdominal muscles was considered as its selectivity index.

2.3 Statistical Analysis

Statistical analysis was performed using SPSS (version18.0; SPSS Japan Inc., Tokyo, Japan). The two-way repeated-measurements ANOVA was conducted with measurements by varying two factors, namely, the abdominal muscle (four muscles) and intensity of hollowing (five levels) to determine the shear elastic modulus of each abdominal muscle at each intensity of hollowing. The difference in the ratio of the TrA to the RA, EO, and IO as a function of the intensity of hollowing was examined using one-way ANOVA. When significant effects were found from the analysis, a post-hoc test (Bonferroni) was performed. The significance was set to $p < 0.05$.

Intra-class correlation (1,1) ($ICC_{1,1}$) was used to confirm the reliability of the shear elastic modulus measurements. $ICC_{1,1}$ was calculated using the shear elastic modulus obtained through three measurements at each muscle and intensity of hollowing. The reliability of the shear elastic modulus of the four abdominal muscles at the different intensities of hollowing is presented in Table 1. According to the table, $ICC_{1,1}$ is almost perfect (range: 0.866–0.998).

3. RESULTS

The girth of the abdomen at each intensity is presented in Table 2. The variation of the girth of the abdomen in that on going from 100% hollowing to rest (0% hollowing) was mean 18 mm (SD 7 mm).

The shear elastic modulus of the four abdominal muscles at each intensity is shown in Figure 3. It gradually increases with the increase in the intensity of hollowing. The two-way ANOVA exhibited that the intensity of hollowing ($p < 0.01$) and muscle ($p < 0.01$) had a significant effect and interaction ($p < 0.01$). The post-hoc test for each muscle revealed that the shear elastic modulus of the IO and TrA at 100% and 75% hollowing intensity was significantly higher than that at a low intensity (0% and 25%). In contrast, the shear elastic modulus of the RA and EO was high only at 100% hollowing. Moreover, none of the muscles showed a significant difference in the shear elastic modulus from 0% to 50% hollowing.

The ratio of the TrA to the three different abdominal muscles at each intensity is presented in Table 3, and it does not exhibit a significant difference among the four hollowing intensities (25%, 50%, 75%, and 100%).

4. DISCUSSIONS

We hypothesized that the tension of the abdominal muscles would increase with a decrease in the girth of the abdomen. The two-way ANOVA showed that the intensity of hollowing of the four abdominal muscles had a significant main effect. Therefore, our results are consistent with the hypothesis that the tension of the TrA increases gradually as the girth of the abdomen decreases. Anatomically, the adherent parts of the four abdominal muscles are the sternum, ribs, linea alba, thoracolumbar fascia, and illum (Askar, 1977). Hence, when the abdominal muscles contract while the thorax and pelvis are fixed, they would in turn contract the abdominal wall, producing a hollow in the abdominal cavity. Consequently, by hollowing the abdomen, all the four abdominal muscles may be activated. Our results revealed that the girth of the abdomen and tension of not only the TrA but also of the RA, EO, and IO exhibited a linear relationship. Therefore, we believe that it was rational to estimate the tension of the TrA by measuring the girth of the abdomen. Furthermore, the result of the post-hoc analysis of the four abdominal muscles demonstrated that the shear elastic modulus at a high intensity of hollowing (75% and 100% hollowing) was significantly higher than at a low intensity of hollowing (0% to 50% hollowing). Therefore, it was inferred that all the four abdominal muscles exerted a high tension when trying to hollow the abdomen at a high intensity. However, there was no significant difference in the muscle tension of any of the muscles between 0% and 50% hollowing. This result suggests that low-intensity hollowing (0% to 50%) is not sufficient to increase the tension of the abdominal muscles.

Previously, no studies have examined the abdominal muscle tension at various hollowing intensities. However, Rostami and colleagues had reported that an off-road cyclist with low back pain had an atrophy of the TrA (Rostami et al., 2015). In clinical settings, to contract the TrA in cases of an atrophied TrA, it is necessary to activate the TrA at a high intensity. In these cases, instructing the subject to perform hollowing exercise so as to reduce the girth of abdomen to the maximum which corresponds to maximum muscle activity of the TrA using a tape measure as a feedback may be an optimal exercise for the TrA. It has been impossible to define the degree of contraction of the TrA non-invasively and individually. This study demonstrated that by measuring the girth of the abdomen using a tape measure, the degree of contraction of the TrA could be conveniently estimated.

The ratio of the TrA to the RA, EO, and IO, as an indicator of the TrA selectivity exhibited no significant difference as the intensity of hollowing increased from 25% to 100%. Therefore, our hypothesis that hollowing at low intensities had the highest selectivity for the TrA was contradicted. According to a study by Urquhart and colleagues that examined abdominal muscles activities as participants performed hollowing with ‘ mild effort ’, using fine-wire EMG, the ratio of the TrA activity to the RA, EO, and IO was 1.00, 4.00, and 0.67, respectively (Urquhart et al., 2005). On the other hand, in this study, the ratio of the TrA tension to the RA, EO and IO, varied from 1.61 to 2.23, 1.69 to 3.26, and 0.93 to 1.11, respectively. Therefore, comparing with the previous study, the TrA selectivity is not compromised by performing hollowing at maximum intensity.

The muscle tension of the TrA increased with the increase in the intensity of the hollowing exercise (Fig. 3), whereas the ratio of the TrA to the RA, EO, and IO exhibited no significant difference at the four intensities of hollowing (Table 3). Therefore, hollowing at maximum intensity is recommended in clinical practices to train the TrA in cases that have spinal instability owing to the atrophy of the TrA. In addition, the selectivity of the TrA was similar at the different hollowing intensities. Consequently, abdominal hollowing performed at maximum intensity was effective in realizing the maximal training effect on the TrA, without impairing its selectivity.

We would like to point out several limitations of this study. First, in this study, the shear elastic modulus of the TrA was measured 2 cm medial to the anterior superior iliac spine; therefore, we examined only the lower fiber of the TrA. Previous studies that estimated the activities of the TrA via changes in the muscle thickness or fine-wire EMG of, measured the middle fiber of the TrA (the lower end of the rib and middle point of the iliac crest) (Hides et al., 2006; Hodges et al., 2003, 1996; Ota et al., 2012; Tsao and Hodges, 2007; Urquhart et al., 2005). Therefore, it may not be appropriate to directly compare our work with the results of such studies. In addition, a previous study that evaluated the muscle activity of the upper, middle, and lower fibers of the TrA during hollowing via needle EMG, showed that the muscle activity varied with the site of the TrA. Therefore, the results of this study cannot be applied to the entire TrA.

Second, the degrees of the pelvic tilt were not examined herein. It has already been reported that the muscular activity of the RA (Urquhart et al., 2005) and EO (Vezina and Hubley-kozey, 2000) increases with the posterior tilt of the pelvis. It is possible that differences in the pelvic tilts of the subjects existed that may have affected the results of this study. Therefore, further research is required to determine the effect of the pelvic tilt on the shear elastic modulus of the abdominal muscles.

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Conflict of interest statement

The authors in this study have no conflicts of interest to declare.

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Table1 Reliability of the shear elastic modulus measurements

ICC(1,1)	0% (rest)	25%	50%	75%	100%
RA	0.866	0.934	0.952	0.938	0.956
EO	0.987	0.959	0.941	0.987	0.976
IO	0.955	0.994	0.933	0.991	0.946

TrA	0.967	0.998	0.956	0.982	0.965

ICC(1,1): intra-class correlation coefficient (1,1),

RA: rectus abdominis, EO: external oblique, IO: internal oblique, TrA: transversus abdominis

Table 2 The girth of the abdomen at each intensity

mm	0% (rest)	25%	50%	75%	100%
Mean(SD)	792.8 (7.04)	788.3 (7.32)	783.8 (7.36)	779.3 (7.05)	774.8 (7.07)

Table3 Transversus abdominis ratio

Mean(SD)	25%	50%	75%	100%
TrA/RA	1.61 (1.88)	1.62 (1.04)	1.87 (1.55)	2.23 (1.90)
TrA/EO	1.69 (1.64)	2.06 (1.84)	3.09 (3.14)	3.26 (2.31)
TrA/IO	1.04 (0.40)	0.96 (0.17)	1.11 (0.55)	0.93 (0.19)

The shear elastic modulus ratio of the TrA to the RA, EO, and IO

Comparison of the TrA ratios to the RA, EO, and IO in the post-hoc tests at different intensities of hollowing showed that there were no significant differences.

RA: rectus abdominis, EO: external oblique, IO: internal oblique, TrA: transversus abdominis

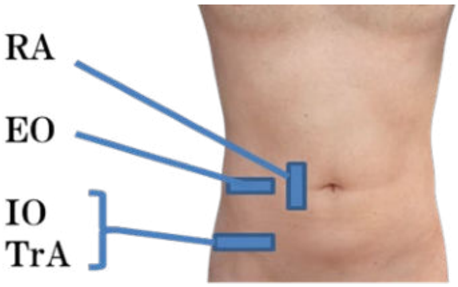


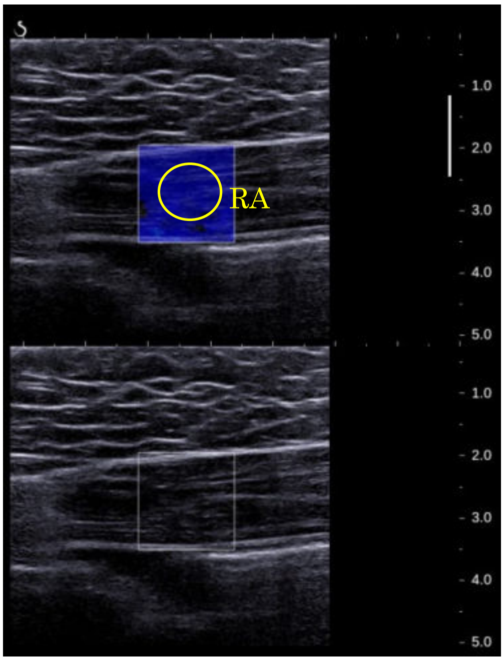
Figure1 Measurement locations

The measurement sites: RA was assessed 4 cm lateral to the navel, EO was assessed 2.5

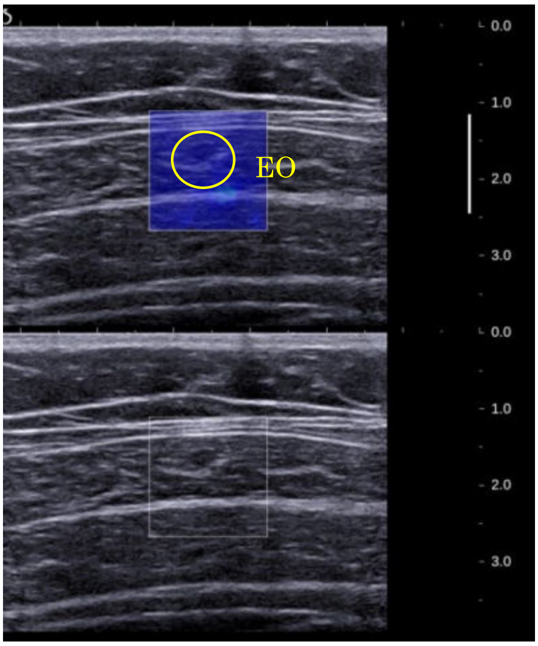
cm anterior to the axillary line at the height of the navel, and IO and TrA were assessed 2 cm medial to the anterior superior iliac spine.

RA: rectus abdominis, EO: external oblique, IO: internal oblique,

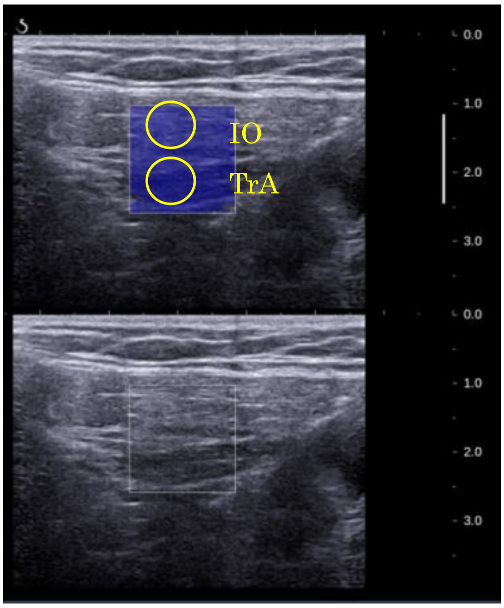
TrA: transversus abdominis



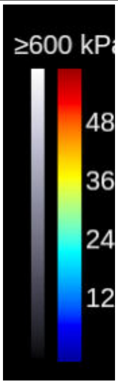
A Rectus abdominis



B External oblique



C Internal oblique and transversus abdominis



D Color scale

Figure2 Region of interest (ROI) locations

A typical example of the shear elastic modulus of the rectus abdominis (A), external oblique (B), and internal oblique, and transversus abdominis (C) captured by ultrasonic shear wave elastographic imaging. The shear elastic modulus is presented on a color-coded scale (D).

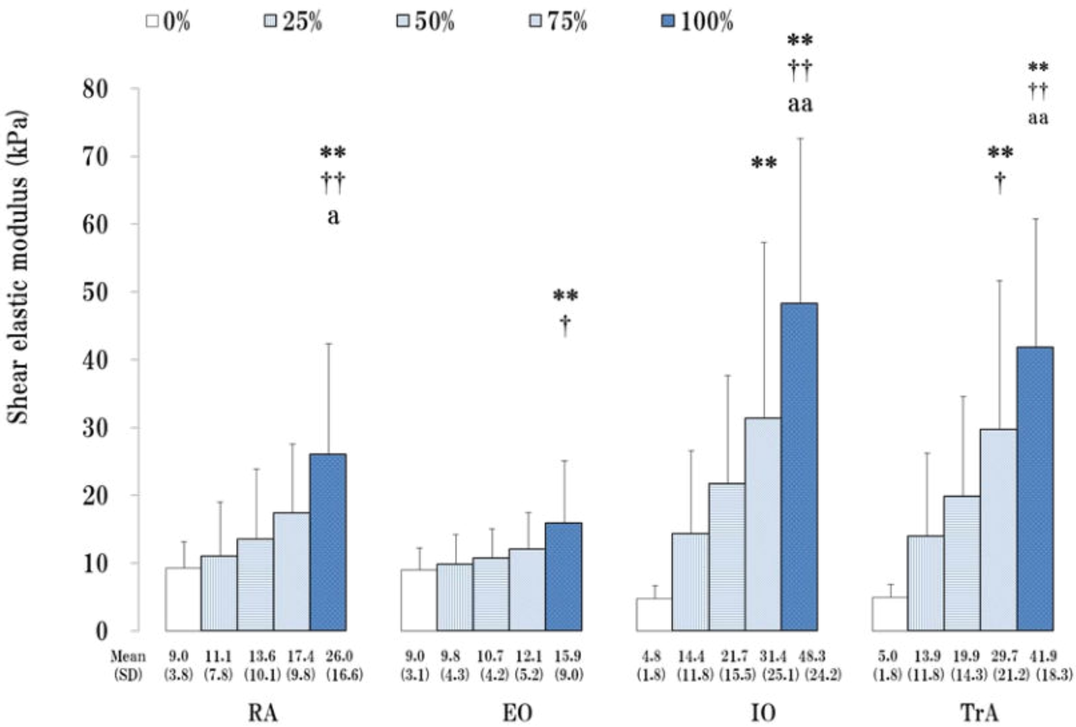


Figure3 Comparison of the shear elastic modulus (kPa) obtained in the post-hoc test at different intensities of the hollowing.

**: vs. 0%, $p < 0.01$; *: vs. 0%, $p < 0.05$; ‡: vs. 25%, $p < 0.01$; †: vs. 25%, $p < 0.05$;

aa: vs. 50%, $p < 0.01$; a: vs. 50%, $p < 0.05$

RA: rectus abdominis, EO: external oblique, IO: internal oblique, TrA: transversus abdominis.