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Effects of trunk lean and foot lift exercises in sitting position on abdominal muscle activity and the contribution rate of transversus abdominis

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Declarations

Funding: Not applicable.

Conflicts of interest: Not applicable.

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Consent: Informed consent was obtained from all individual participants involved in the study.

Data and/or Code availability: All data generated or analysed during this study are included in this published article.

Authors' contribution statements: YM, HT, SN, and NI conceived and designed the research. YM, TK, and YY conducted the experiments. YM, HT, and NI analyzed the data. YM, HT, SN, and NI wrote the manuscript. All the authors have read and approved the manuscript.

Abstract

Purpose: Abdominal hollowing exercise has been recommended to improve trunk stability. Trunk lean and foot lift exercises while sitting may easily promote abdominal muscle activity even in people who cannot perform abdominal hollowing consciously. The purpose of the present study was to examine the changes in abdominal muscle activity and contribution rate of the transversus abdominis muscle (TrA) when leaning the trunk and lifting the foot during sitting.

Methods: The muscle stiffnesses (indicators of muscle activity) of the right rectus abdominis, external oblique, internal oblique, and TrA of 14 healthy men were measured during abdominal hollowing and the following nine sitting tasks: reference posture, 15° and maximal posterior trunk lean, 20° and maximal ipsilateral and contralateral trunk lean, and ipsilateral and contralateral foot lift. The TrA contribution rate was calculated by dividing the TrA stiffness by the sum of the abdominal muscles' stiffnesses.

Results: The TrA stiffness was significantly higher in abdominal hollowing than in reference posture, posterior and ipsilateral trunk lean, and ipsilateral foot lift, but not higher than in contralateral trunk lean and contralateral foot lift. There was no significant difference in the TrA contribution rates between abdominal hollowing and ipsilateral or contralateral foot lift.

Conclusion: The contralateral trunk lean or contralateral foot lift could enhance TrA activity for people who cannot perform abdominal hollowing consciously. The contralateral foot lift could particularly be beneficial to obtain selective activity of TrA.

Keywords

abdominal hollowing, muscle stiffness, transversus abdominis, internal oblique, external oblique, rectus abdominis

Abbreviations

TrA	Transversus abdominis muscle
ANOVA	Analysis of variance
SWE	Shear wave elastography

Introduction

The transversus abdominis muscle (TrA) plays an important role in trunk stabilization while moving the extremities (Hodges and Richardson 1996, 1998; Hodges et al. 1997; Okubo et al. 2013). Since the TrA acts to tighten the abdomen even when the activities of the other abdominal muscles remain unchanged, greater TrA activity may allow for a more effective increase in intra-abdominal pressure, which increases the stiffness of the lumbar spine (Hodges et al. 2005). Therefore, improving TrA contribution rate, which is the percentage of TrA activity in all the abdominal muscle activities, is required to increase spinal stiffness and reduce spinal loading (Aspden 1988).

Abdominal hollowing exercise, which retracts the abdomen consciously, has been commonly used to train the TrA (Beith et al. 2001; Koh et al. 2014). Isolated TrA activation using very low-intensity abdominal hollowing may be effective to promote muscle recruitment such as improving the delay in neuromuscular activity of TrA (Tsao and Hodges 2007). On the other hand, a previous study found that as the intensity of abdominal hollowing increased, the TrA activity increased significantly and the ratio of the TrA to the internal oblique, external oblique, and rectus abdominis did not change (Shimizu et al. 2019). That is, abdominal hollowing at a higher intensity may more effectively improve the function of the TrA that stabilizes the trunk.

Greater decrease in the abdominal cavity during abdominal hollowing reflects stronger contraction of the TrA (Richardson et al. 2004). Hides et al. (2008) reported that there was no significant difference in the TrA thickness and abdominal cavity at rest between those with and without low back pain, and the abdominal cavity during abdominal hollowing was significantly larger in those with low back pain than those without. Therefore, patients with low back pain may have difficulty exerting voluntary TrA contraction even in the absence of atrophy. Hence, training methods targeting involuntary activation of TrA are important for patients with low back pain.

The prone bridge exercise activates abdominal muscles involuntarily by resisting the gravity from the posture change (Okubo et al. 2010; Shiju Majeed et al. 2019). However, methods promoting abdominal muscle activity through dynamic posture changes, such as prone bridge, have high physical loads and are not necessarily safe for patients with low back pain (Ekstrom et al. 2008; Bhadauria and Gurudut 2017). Though some studies have reported the relation between abdominal muscle activity and sagittal spinal alignment in sitting (O’Sullivan et al. 2002; Astfalck et al. 2010; Claus et al. 2018), these studies did not focus on exercises. However, considering these studies, the TrA activity may be involuntarily increased by leaning the trunk or lifting the foot during sitting, even in patients with low back pain and elderly people with difficulty in changing posture dynamically with high intensity. Foot lift exercises are not changed trunk posture, but may increase abdominal muscle activity to increase lumbar and pelvic stiffness, in order to stabilize the pelvis and to exert hip flexion torque effectively. Revealing how the abdominal muscles activate when leaning the trunk and lifting the foot during sitting may provide knowledge for rehabilitation to stabilize trunks in patients with low back pain and elderly people.

The purpose of this study was to verify the effect of trunk lean and foot lift exercises during sitting on abdominal muscle activity and TrA contribution rate. The hypothesis was that the activity of all abdominal muscles will be highest in the posterior trunk lean because the spine is more unstable in flexion and extension than in lateral flexion (Yamamoto et al. 1989). It was also hypothesized that TrA contribution rate would be highest in the contralateral trunk lean where rectus abdominis activity may be more decreased among the abdominal muscles, according to previous studies (Masani et al. 2009; Eriksson Crommert et al. 2017).

Methods

Participants

A total of 14 healthy men (age, 24.6 ± 2.9 years; height, 172.5 ± 6.1 cm; mass, 66.9 ± 9.0 kg) volunteered for this study. The exclusion criteria were a history of low back pain lasting more than three months(Chou et al. 2007), operation and neurological or orthopedic diseases in the trunk or lower limbs. A power analysis with an α error = 0.05, power = 0.80, and effect size *f* = 0.25 (medium) was performed by the G*Power 3.1 analysis software (Heinrich Hein University, Duesseldorf, Germany) for one-way repeated measures analysis of variance (ANOVA). This produced a minimum total sample size of 12. This study was approved by the ethics committee of Kyoto University Graduate School and the Faculty of Medicine (R0546-2) and was conducted in compliance with the Declaration of Helsinki. All participants were provided written informed consent after being briefed with the objectives and the risks involved in the experiment.

Experimental protocol

To minimize the differences in muscle activity due to different spinal alignments in each participant's natural sitting position, a reference posture was defined (Fig 1. a). This is the upright sitting posture, whereby the axis from ear lobe to the floor lies between the anterior and posterior superior iliac spine on the sagittal plane. Further visual verification was done by two of our physiotherapists to ensure no remarkable spinal curvature (e.g. thoracic or lumbar hyperflexion). Participants randomly performed tasks maintaining the following postures (Fig 1. b-f): leaning the trunk posterior to 15° and maximum from reference posture (posterior trunk lean), leaning the trunk at 20° and maximum to ipsilateral and contralateral from reference posture (ipsilateral and contralateral trunk lean), and lifting the ipsilateral and contralateral foot about 1 cm from the floor (ipsilateral and contralateral foot lift). Participants received feedback from a mirror placed 1.5-m in front of them, and were instructed to perform tasks without trunk flexion/extension, lateral flexion, or rotation. The measurements were conducted while one examiner confirmed there was no obvious deviation of posture during the tasks. Then the participants performed abdominal hollowing with maximal effort in supine position without moving the trunk and pelvis (Fig 1. g). Lumbar lordosis during abdominal hollowing was confirmed by participants using the Stabilizer Pressure Biofeedback unit (PBU, Chattanooga Group, Australia) placed under the lumbar spine, with a constant pressure of 40 mmHg. This was done to standardize pelvic inclination among participants during the maneuver. They were instructed to perform abdominal hollowing while trying to maintain the pressure at 40 mmHg.

Shear wave elastography

In each task, muscle stiffnesses of the right TrA, internal oblique, external oblique, and rectus abdominis were measured three times. The measurement sites were determined based on previous studies (Shimizu et al. 2019): TrA and internal oblique muscles, 2-cm medial the anterior superior iliac spine; external oblique, 2.5-cm medial from the point on the axillary line at navel height; and rectus abdominis, 4-cm lateral the navel (Fig 2). Muscle stiffness was calculated using the following formula by shear wave elastography (SWE) mode (musculoskeletal preset) of the Aixplorer ultrasound scanner (v6.4; Supersonic Imagine, Aix-en-Provence, France):

$$\mu \ (\text{kPa}) = \rho V s^2,$$

where ρ = muscle tissue density (1,000 kg/m^3), and Vs = propagation velocity of the shear wave generated by the ultrasonic transducer. An ultrasonic probe (SL15-4 transducer) was in parallel to the fiber orientation of the target muscle. Muscle stiffness was calculated in a 3-mm diameter Q-box at the center of the region of interest placed at the center of each muscle (Fig 2). Reports state that muscle stiffness increases with muscle activity (Bouillard et al. 2011), and there is high reliability of abdominal muscle stiffness measured using SWE (MacDonald et al. 2016; Shimizu et al. 2019). Muscle stiffness was calculated as an average of three measurements for each muscle. After calculating intra-rater reliability ($ICC_{1,3}$) of these three measurements per task, the reliability of each muscle stiffness was "almost perfect": TrA, 0.93–1.00; internal oblique, 0.98–1.00; external oblique, 0.98–0.99; and rectus abdominis, 0.93–1.00. The TrA contribution rate was calculated by dividing TrA stiffness by the sum of the stiffnesses of all four abdominal muscles.

Spinal and pelvic alignment

Another examiner who did not operate the ultrasonic equipment carefully checked visually to ensure no obvious trunk motion during the task. To verify the degree of spinal flexion and extension, sagittal spinal alignment was measured twice using the Spinal Mouse (Index Ltd., Tokyo, Japan) before every measurement for muscle stiffness. The intra-rater reliabilities ($ICC_{1,1}$) were then calculated. In 12 participants, excluding 2 with data loss, $ICC_{1,1}$ of spinal alignment data (i.e., the sum of segmental angles from Th1/2 to L5/S) (Tateuchi et al. 2018) ranged from

0.73 to 0.88. The average angles of thoracic kyphosis and lumbar lordosis were calculated from these data. The average angle of pelvic posterior inclination at the height of the second sacrum measured three times using an inclinometer (Wixey, USA) was calculated, and intra-rater reliability ($ICC_{1,1}$) ranged from 0.89 to 0.98. The average angle of the maximum spine inclination to posterior and right/left measured three times using a goniometer was calculated.

Statistical analysis

Statistical analysis was performed using SPSS version 22.0 (SPSS Japan Inc., Tokyo, Japan). The one-way repeated-measures ANOVA analysis was used to compare the paired datasets between tasks and to investigate whether specific abdominal muscle stiffness or TrA contribution rates would differ depending on the task. When a significant difference was observed, multiple comparisons corrected by the Holm method were performed as a post-hoc test. Dunnet's test was performed to compare the thoracic kyphosis, lumbar lordosis, and pelvic inclination angles between reference posture and other sitting tasks. Additionally, in order to examine the variation among participants, the Pearson correlation analysis was conducted to determine the relationship between TrA contribution rates in each task and the stiffness of the internal oblique, external oblique, and rectus abdominis in the reference posture. A P value <0.05 was considered statistically significant.

Results

The muscle stiffness for each muscle in the various tasks is shown in Table 1. All muscle stiffnesses showed significant main effects of tasks in one-way repeated measures ANOVA. TrA stiffness was significantly higher in abdominal hollowing than in all other tasks, except for contralateral trunk lean (at 20° and maximum) and foot lift. TrA stiffness in the maximum contralateral trunk lean was significantly higher than that in the reference posture, posterior trunk lean (at 15° and maximum), and ipsilateral foot lift. The stiffness of the internal oblique was significantly higher in abdominal hollowing than in all other tasks, except for contralateral trunk lean (at 20° and maximum), and was significantly higher in the maximum contralateral trunk lean than in reference posture, posterior trunk lean (at 15° and maximum), ipsilateral trunk lean (at 20° and maximum), and ipsilateral foot lift. The stiffness of the external oblique was significantly higher in the posterior trunk (at 15° and maximum) and contralateral trunk leans (at 20° and maximum) than in all other tasks, but there were no significant differences among the four tasks of the posterior trunk (at 15° and maximum) and contralateral trunk leans (at 20° and maximum). The stiffness of rectus abdominis was significantly higher in the posterior trunk lean at maximum than in all other tasks.

The TrA contribution rates in the various tasks is shown in Table 1. There was a significant main effect of task in one-way repeated measures ANOVA. The TrA contribution rate in abdominal hollowing was significantly higher than that in the posterior trunk lean (at 15° and maximum), ipsilateral trunk lean at maximum, and contralateral trunk lean (at 20° and maximum). There was no significant difference in TrA contribution rate between abdominal hollowing and reference posture, ipsilateral trunk lean at 20°, and ipsilateral and contralateral foot lift.

The results of thoracic kyphosis angle, lumbar lordosis angle, pelvic inclination angle, and maximum spinal inclination angle are shown in Table 2. The thoracic kyphosis and lumbar lordosis angles were not significantly different between reference posture and other sitting tasks. The pelvic posterior inclination angle was significantly higher in the posterior trunk lean than in reference posture.

The additional Pearson correlation analysis showed that the TrA contribution rate in those with high external oblique stiffness in the reference posture tended to be low in the ipsilateral foot lift (r = -0.742, p = 0.002) and high during maximum abdominal hollowing (r = 0.519, p = 0.057).

Discussion

The present study was the first, to our knowledge, to investigate noninvasively the effects of trunk lean and foot lift exercises during sitting on abdominal muscle activity. High TrA activity was exerted in the contralateral trunk lean and contralateral foot lift during sitting, and the TrA contribution rate in the contralateral foot lift was a similar level to that in maximum abdominal hollowing. These exercises can be performed in elderly people and patients with low back pain, who have difficulty with consciously contracting abdominal muscles such as abdominal hollowing. Our results have elucidated the specific exercises which maximize the activation of TrA and improve TrA contribution rate. Therefore, these may be useful in the consideration of targeted TrA exercises to stabilize the trunk of elderly people and patients with low back pain.

Although the TrA activity was highest in abdominal hollowing, TrA activity in the contralateral trunk lean during sitting showed no significant difference to that in abdominal hollowing and tended to be higher than that in reference posture, posterior trunk lean, and ipsilateral foot lift. These results differed from our hypothesis that higher TrA activity will be exerted in the posterior trunk lean because the spine is more unstable in flexion and extension than in lateral flexion (Yamamoto et al. 1989). The TrA may have an important role holding the trunk and maintaining the posture predictively while other muscles contract (Hodges and Richardson 1997; Allison et al. 2008). On the other hand, previous study showed using wire electromyography that the activity of the TrA and internal oblique increased when pulled to contralateral sides, while the activity of the external oblique and rectus abdominis increased when pulled posteriorly (Eriksson Crommert et al. 2017). This study supports our results. Therefore, the present study indicates that all abdominal muscles, even the TrA working to stabilize the trunk, may be specifically activated in postures with external moments in the opposite direction to their anatomical orientations. Moreover, the neutral zone, which is the range of inter-vertebral motion whereby spinal stiffness (i.e. the force required to make a constant displacement between the vertebrae) is the lowest (Panjabi 1992), has been reported to increase with ligament damage and disc degeneration (Panjabi et al. 1989; Hasegawa et al. 2008). Busscher et al. (2009) indicated that the lumbar vertebrae had less spinal stiffness in lateral bending in a wider range of motion than the lower thoracic vertebrae and might have less resistance of passive tissue such as ligaments. Therefore, TrA activity is more likely to increase in lateral trunk lean than posterior trunk lean due to its anatomical function. The present study supports the role of TrA in increasing spinal stiffness. However, because this study did not verify the load on the spine during the task, further studies should determine whether direction-specific activity of the TrA reflects direction-specific properties of the spine.

The TrA contribution rate was significantly higher in the foot lift than in the posterior or the contralateral trunk lean, which differed from our hypothesis. This may be because the stiffness of the lumbar spine and pelvis increased with TrA activity (Tesh et al. 1987), making it easier to exert muscle strength of the hip flexors during foot lift. The reason why the activity of the rectus abdominis and oblique abdominal muscles, which are the global muscles (Bergmark 1989), did not increase much may be because the trunk load from gravity was lower in foot lift than in contralateral trunk lean. Therefore, the increase in TrA contribution rate in foot lift may be attributed to these circumstances. On the other hand, the low TrA contribution rate during contralateral trunk lean may be due to the requirement to stabilize not only the lumbopelvic region but also the entire spinal alignment against gravity, rendering isolated TrA activity insufficient. In other words, the rectus abdominis, external oblique and internal oblique muscles may have been activated to stabilize the thorax.

TrA acts to tighten the abdomen. It is, however, a thin muscle, therefore is independently not adequate to contribute to spinal stiffness. It is hence suggestive that TrA plays a supportive role in helping the activities of other abdominal muscles. Therefore, high TrA contribution rate (i.e. higher TrA activity when those of other abdominal muscles remain unchanged) may be important in allowing for more effective increase of intra-abdominal pressure, which leads to the increase of spinal stiffness (Hodges et al. 2005; Hides et al. 2006). However, a recent Cochrane review about nonspecific low back pain reported that there were no differences in the effect on improving disability due to low back pain between the specific training for TrA and multifidus muscles and general trunk exercises such as stretching and resistance training (Saragiotto et al. 2016). This is believed to be due to diversity of potential causes of nonspecific back pain (Kiesel et al. 2007). Thus, specific training of the TrA may not necessarily be important for all low back pain patients. In the present study, the variation in the degrees of abdominal muscle stiffness among participants may have affected our results. The additional Pearson correlation analysis have verified the relationship between the TrA contribution rates in each task and the stiffness of the internal oblique, external oblique and rectus abdominis muscles in the reference posture. The results showed that TrA contribution rate in those with high stiffness of external obliques in the reference posture tended to be low during ipsilateral foot lifting (r = -0.742) and high during maximum abdominal hollowing (r = 0.519). This suggest that the particular exercises required to improve TrA contribution rate may differ according to the properties of abdominal muscles during the sitting position. Further study should better understand which subgroups of patients with low back pain require exercise with a high TrA contribution rate (Hill et al. 2008; Macedo et al. 2014).

In this study, characteristics of abdominal muscles were investigated using SWE. Since measurement values of muscle stiffness in this study were similar to those in a previous SWE study (Shimizu et al. 2019), verification of abdominal muscle activities using abdominal muscles' stiffnesses is considered appropriate. Neuromuscular activity measured by a surface or wire electromyography and muscle thickness by an ultrasonic device have been commonly used to verify abdominal muscle activity. However, abdominal muscle thickness changes during contraction may not necessarily be proportional to increases in abdominal muscle activities (Hodges et al. 2003; Whittaker et al. 2013). In addition, surface electromyography cannot measure the TrA, a deep muscle, and wire electromyography is invasive. The SWE in the present study can measure a deep muscle noninvasively and may be useful for verifying abdominal muscle (especially TrA) activity.

This study had some limitations. First, spinal lateral flexion and rotation could not be evaluated objectively. Since spinal motion greatly influences abdominal muscle activity because of abdominal muscle anatomy, the experiment paid attention to spinal motion. To avoid fatigue due to an increase in the number of tasks measured, only spinal mobilities in flexion and extension were measured by the Spinal Mouse. However, there were no significant differences in thoracic kyphosis, lumbar lordosis, and pelvic inclination angles between tasks; thus, evident spinal motion probably did not occur in this study. The second limitation was that only men participated in the present study. The mobilities of and load on the sacroiliac joint are reported to be greater in women than in men (Joukar et al. 2018); therefore, since lower fibers of the TrA increase the stiffness of the sacroiliac joint, results may differ in a female study population. Third, the tasks used in present study were not exercises whereby TrA was activated in isolation. Lastly, they may not be appropriate for all patients with low back pain.

Conclusion

This study investigated noninvasively the effects of trunk lean and foot lift exercises during sitting on abdominal muscle activity. Higher TrA activity was exerted by leaning the trunk to the contralateral side and lifting the contralateral foot. Furthermore, TrA contribution rate in the contralateral foot lift was similar to that in maximum abdominal hollowing. As elderly people and patients with low back pain who have difficulty in consciously contracting abdominal muscles can easily perform trunk lean and foot lift during sitting, these results may be useful for rehabilitation to stabilize the trunks in elderly people and patients with low back pain.

Compliance with Ethical Standards

Disclosure of potential conflicts of interest

Conflict of Interest: The authors declare that they have no conflict of interest.

Research involving Human Participants and/or Animals

Ethics approval: All the procedures performed in the studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. This study was approved by the ethics committee of Kyoto University Graduate School and the Faculty of Medicine (R0546-2)

Informed consent

Informed consent was obtained from all individual participants involved in the study.

References

Allison GT, Morris SL, Lay B (2008) Feedforward Responses of Transversus Abdominis Are Directionally Specific and Act Asymmetrically: Implications for Core Stability Theories. J Orthop Sport Phys Ther 38:228–237. doi: 10.2519/jospt.2008.2703

Aspden RM (1988) A new mathematical model of the spine and its relationship to spinal loading in the workplace. 319–323.

Astfalck RG, O'Sullivan PB, Straker LM, et al (2010) Sitting postures and trunk muscle activity in adolescents with and without nonspecific chronic low back pain: an analysis based on subclassification. Spine (Phila Pa 1976) 35:1387–1395. doi: 10.1097/BRS.0b013e3181bd3ea6

Beith ID, Synnott RE, Newman SA (2001) Abdominal muscle activity during the abdominal hollowing manoeuvre in the four point kneeling and prone positions. Man Ther 6:82–87. doi: 10.1054/math.2000.0376

Bergmark A (1989) Stability of the lumbar spine: A study in mechanical engineering. Acta Orthop 60:1–54. doi: 10.3109/17453678909154177

Bhadauria EA, Gurudut P (2017) Comparative effectiveness of lumbar stabilization, dynamic strengthening, and Pilates on chronic low back pain: randomized clinical trial. J Exerc Rehabil 13:477–485. doi: 10.12965/jer.1734972.486

Bouillard K, Nordez A, Hug F (2011) Estimation of individual muscle force using elastography. PLoS One. doi: 10.1371/journal.pone.0029261

Busscher I, Van Dieën JH, Kingma I, et al (2009) Biomechanical characteristics of different regions of the human spine: An in vitro study on multilevel spinal segments. Spine (Phila Pa 1976) 34:2858–2864. doi: 10.1097/BRS.0b013e3181b4c75d

Chou R, Snow V, Casey D, et al (2007) Clinical Guidelines Diagnosis and Treatment of Low Back Pain : A Joint Clinical Practice Guideline from the American College of Physicians and the American. Ann Intern Med 147:478–491.

Claus AP, Hides JA, Moseley GL, Hodges PW (2018) Different ways to balance the spine in sitting: Muscle activity in specific postures differs between individuals with and without a history of back pain in sitting. Clin Biomech 52:25–32. doi: 10.1016/j.clinbiomech.2018.01.003

Ekstrom RA, Osborn RW, Hauer PL (2008) Surface Electromyographic Analysis of the Low Back Muscles During Rehabilitation Exercises. J Orthop Sport Phys Ther 38:736–745. doi: 10.2519/jospt.2008.2865

Eriksson Crommert M, Tucker K, Holford C, et al (2017) Directional preference of activation of abdominal and paraspinal muscles during position-control tasks in sitting. J Electromyogr Kinesiol 35:9–16. doi: 10.1016/j.jelekin.2017.05.002

Hasegawa K, Kitahara K, Hara T, et al (2008) Evaluation of lumbar segmental instability in degenerative diseases by using a new intraoperative measurement system. J Neurosurg Spine 8:255–262. doi: 10.3171/spi/2008/8/3/255

Hides J, Stanton W, Freke M, et al (2008) MRI study of the size, symmetry and function of the trunk muscles among elite cricketers with and without low back pain. Br J Sports Med 42:509–513. doi:

10.1136/bjsm.2007.044024

Hides J, Wilson S, Stanton W, et al (2006) An MRI investigation into the function of the transversus abdominis muscle during “drawing-in” of the abdominal wall. Spine (Phila Pa 1976) 31:175–178. doi: 10.1097/01.brs.0000202740.86338.df

Hill JC, Dunn KM, Lewis M, et al (2008) A primary care back pain screening tool: Identifying patient subgroups for initial treatment. Arthritis Care Res 59:632–641. doi: 10.1002/art.23563

Hodges PW, Eriksson AEM, Shirley D, Gandevia SC (2005) Intra-abdominal pressure increases stiffness of the lumbar spine. 38:1873–1880. doi: 10.1016/j.jbiomech.2004.08.016

Hodges PW, Gandevia SC, Richardson CA (1997) Contractions of specific abdominal muscles in postural tasks are affected by respiratory maneuvers. J Appl Physiol 83:753–760.

Hodges PW, Pengel LHM, Herbert RD, Gandevia SC (2003) Measurement of muscle contraction with ultrasound imaging. Muscle and Nerve 27:682–692. doi: 10.1002/mus.10375

Hodges PW, Richardson CA (1996) Inefficient muscular stabilization of the lumbar spine associated with low back pain. A motor control evaluation of transversus abdominis. Spine (Phila. Pa. 1976). 21:2640–50.

Hodges PW, Richardson CA (1997) Contraction of the abdominal muscles associated with movement of the lower limb. Phys Ther 77:132–142; discussion 142-144.

Hodges PW, Richardson CA (1998) Delayed postural contraction of transversus abdominis in low back pain associated with movement of the lower limb. J Spinal Disord 11:46–56. doi: 9493770

Joukar A, Shah A, Kiapour A, et al (2018) Sex Specific Sacroiliac Joint Biomechanics During Standing Upright:

A Finite Element Study. Spine (Phila Pa 1976) 43:E1053–E1060. doi: 10.1097/BRS.0000000000002623

Kiesel KB, Underwood FB, Mattacola CG, et al (2007) A Comparison of Select Trunk Muscle Thickness Change Between Subjects With Low Back Pain Classified in the Treatment-Based Classification System and Asymptomatic Controls. J Orthop Sport Phys Ther 37:596–607. doi: 10.2519/jospt.2007.2574

Koh HW, Cho SH, Kim CY (2014) Comparison of the Effects of Hollowing and Bracing Exercises on Cross-sectional Areas of Abdominal Muscles in Middle-aged Women. J Phys Ther Sci 26:295–299. doi: 10.1589/jpts.26.295

MacDonald D, Wan A, McPhee M, et al (2016) Reliability of Abdominal Muscle Stiffness Measured Using Elastography during Trunk Rehabilitation Exercises. Ultrasound Med Biol 42:1018–1025. doi: 10.1016/j.ultrasmedbio.2015.12.002

Macedo LG, Maher CG, Hancock MJ, et al (2014) Predicting Response to Motor Control Exercises and Graded Activity for Patients With Low Back Pain: Preplanned Secondary Analysis of a Randomized Controlled Trial. Phys Ther 94:1543–1554. doi: 10.2522/ptj.20140014

Masani K, Sin VW, Vette AH, et al (2009) Postural reactions of the trunk muscles to multi-directional perturbations in sitting. Clin Biomech 24:176–182. doi: 10.1016/j.clinbiomech.2008.12.001

O’Sullivan PB, Grahamslaw KM, Kendell M, et al (2002) The Effect of Different Standing and Sitting Postures on Trunk Muscle Activity in a Pain-Free Population. Spine (Phila Pa 1976) 27:1238–1244. doi: 10.1097/00007632-200206010-00019

Okubo Y, Kaneoka K, Imai A, et al (2010) Electromyographic analysis of transversus abdominis and lumbar multifidus using wire electrodes during lumbar stabilization exercises. J Orthop Sport Phys Ther 40:743–750. doi: 10.2519/jospt.2010.3192

Okubo Y, Kaneoka K, Shiina I, et al (2013) Abdominal Muscle Activity During a Standing Long Jump. J Orthop Sport Phys Ther 43:577–582. doi: 10.2519/jospt.2013.4420

Panjabi M, Abumi K, Duranceau J, Oxland T (1989) Spinal stability and intersegmental muscle forces. A biomechanical model. Spine (Phila. Pa. 1976). 14:194–200.

Panjabi MM (1992) The stabilizing system of the spine. Part II. Neutral zone and instability hypothesis. J. Spinal Disord. 5:390–396; discussion 397.

Richardson CA, Hides JA, Wilson S, et al (2004) Lumbo-pelvic joint protection against antigravity forces: motor control and segmental stiffness assessed with magnetic resonance imaging. J Gravit Physiol 11:119–122.

Saragiotto BT, Maher ÃCG, Tie Ã (2016) Motor Control Exercise for Nonspecific Low Back Pain. Spine (Phila Pa 1976) 41:1284–1295. doi: 10.1002/14651858.CD012004.

Shiju Majeed A, Anish TS, Sugunan A, Arun MS (2019) The effectiveness of a simplified core stabilization program (TRICCS—Trivandrum Community-based Core Stabilisation) for community-based intervention in chronic non-specific low back pain. J Orthop Surg Res 14:86. doi: 10.1186/s13018-019-1131-z

Shimizu I, Tateuchi H, Motomura Y, et al (2019) Abdominal girth as an index of muscle tension during abdominal hollowing: Selecting the optimal training intensity for the transversus abdominis muscle. J Biomech. doi: 10.1016/j.jbiomech.2019.04.018

Tateuchi H, Akiyama H, Goto K, et al (2018) Sagittal alignment and mobility of the thoracolumbar spine are associated with radiographic progression of secondary hip osteoarthritis. Osteoarthr Cartil 26:397–404. doi: 10.1016/j.joca.2017.12.005

Tesh KM, Dunn JS, Evans JH (1987) The abdominal muscles and vertebral stability. Spine (Phila Pa 1976) 12:501–508.

Tsao H, Hodges PW (2007) Immediate changes in feedforward postural adjustments following voluntary motor training. Exp Brain Res 181:537–546. doi: 10.1007/s00221-007-0950-z

Whittaker JL, McLean L, Hodder J, et al (2013) Association Between Changes in Electromyographic Signal Amplitude and Abdominal Muscle Thickness in Individuals With and Without Lumbopelvic Pain. J Orthop Sport Phys Ther 43:466–477. doi: 10.2519/jospt.2013.4440

Yamamoto I, Panjabi MM, Crisco T, Oxland T (1989) Three-dimensional movements of the whole lumbar spine and lumbosacral joint. Spine (Phila Pa 1976) 14:1256–60. doi: 10.1097/00007632-198911000-00020

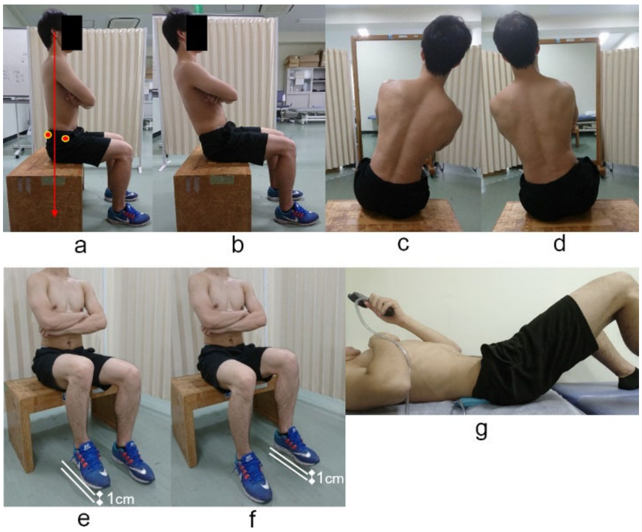

Fig. 1 Task postures. a reference posture; b posterior trunk lean; c ipsilateral trunk lean; d contralateral trunk lean; e ipsilateral foot lift; f contralateral foot lift; g abdominal hollowing with maximal effort. The reference posture was defined as a natural posture for each participant where the perpendicular line from ear hole to the floor was between the anterior and posterior superior iliac spine on the sagittal plane

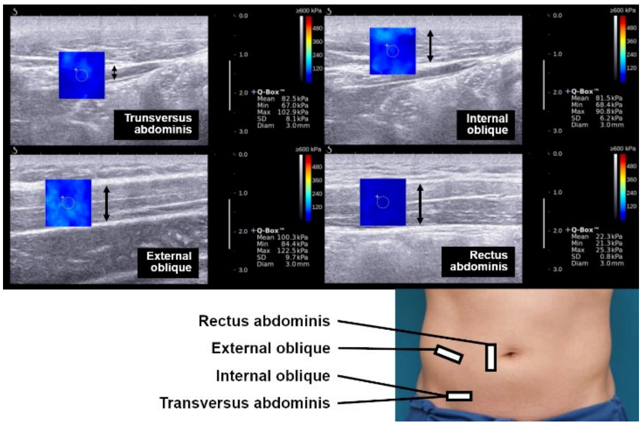

Fig. 2 Representative images and measurement sites of the stiffness of abdominal muscles

Table 1 The stiffnesses of abdominal muscles and the contribution rate of transversus abdominis during tasks

	Transversus abdominis [kPa]	Internal oblique [kPa]	External oblique [kPa]	Rectus abdominis [kPa]	Contribution rate of transversus abdominis [%]
Abdominal hollowing with maximal effort (1)	39.5 ± 18.0^{2,3,4,5,6,9}	48.2 ± 20.9^{2,3,4,5,6,9,10}	12.4 ± 9.3	18.2 ± 8.9^{2}	33.8 ± 7.5^{3,4,6,7,8}
Reference posture (2)	11.3 ± 4.7	13.8 ± 7.9	6.8 ± 4.3	7.9 ± 3.2	28.7 ± 8.4^{3,4}
Posterior trunk lean at 15° (3)	12.3 ± 10.7	11.3 ± 10.1	36.3 ± 14.1^{1,2,5,6,9,10}	36.1 ± 19.0^{2,7,9}	12.0 ± 7.7
Posterior trunk lean at max (4)	9.3 ± 4.3	10.7 ± 4.8	66.4 ± 21.1^{1,2,5,6,9,10}	70.6 ± 22.0^{1,2,3,5,6,7,8,9,10}	6.1 ± 2.8
Ipsilateral trunk lean at 20° (5)	13.3 ± 6.4	14.3 ± 6.0	8.0 ± 4.9	18.0 ± 17.7	25.9 ± 8.9^{4}
Ipsilateral trunk lean at max (6)	18.8 ± 9.4	20.5 ± 10.1^{3,4}	12.8 ± 6.9	20.1 ± 10.2^{2}	25.8 ± 7.0^{3,4}
Contralateral trunk lean at 20° (7)	19.6 ± 8.1^{2,4}	26.5 ± 10.6^{3,4,5,9}	42.1 ± 10.3^{1,2,5,6,9,10}	13.7 ± 6.2	19.5 ± 7.7^{4}
Contralateral trunk lean at max (8)	26.1 ± 11.5^{2,3,4,9}	36.1 ± 15.3^{2,3,4,5,6,9}	55.4 ± 19.0^{1,2,5,6,9,10}	27.7 ± 18.4	18.3 ± 7.0^{4}
Ipsilateral foot lift (9)	14.0 ± 4.6	15.4 ± 6.4	9.6 ± 7.0	9.2 ± 5.7	29.3 ± 7.7^{3,4,8}
Contralateral foot lift (10)	18.0 ± 7.8^{2,4}	20.7 ± 7.7^{2,4}	7.1 ± 7.1	13.6 ± 11.4	31.2 ± 8.8^{3,4,7,8}

Values are expressed as mean ± standard deviation

$^{1\text{-}10}$ $P < 0.05$ vs. the task, which is corresponded to numbers

Table 2 Spinal alignment during each task

	Thoracic kyphosis [°] (n=12)	Lumbar lordosis [°] (n=12)	Pelvic inclination [°] (n=14)	Spinal inclination [°] (n=14)
Reference posture	29.1 ± 6.0	2.8 ± 7.3	1.0 ± 9.1	
Posterior trunk lean at 15°	31.0 ± 6.1	4.0 ± 9.6	11.9 ± 8.8 *	
Posterior trunk lean at max	32.0 ± 6.4	5.8 ± 8.0	24.8 ± 11.5 *	28.7 ± 5.2
Ipsilateral trunk lean at 20°	34.0 ± 8.2	10.9 ± 10.8	-1.5 ± 9.6	
Ipsilateral trunk lean at max	29.6 ± 6.8	8.2 ± 6.4	-1.8 ± 8.9	28.5 ± 3.8
Contralateral trunk lean at 20°	31.2 ± 6.4	8.7 ± 7.6	-1.4 ± 9.5	
Contralateral trunk lean at max	31.1 ± 6.8	6.8 ± 6.9	-4.2 ± 8.7	29.4 ± 4.6
Ipsilateral foot lift	28.2 ± 5.9	7.9 ± 8.4	1.7 ± 10.1	
Contralateral foot lift	26.8 ± 6.0	7.1 ± 6.5	0.2 ± 9.9	

Values are expressed as mean ± standard deviation

The positive values in pelvic inclination represent the sacral posterior inclination angle on the sagittal plane

* $P < 0.05$ vs. reference posture