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Original Paper

Relationship between Lumbar Proprioception, Thickness of Trunk Muscles, and Control of Trunk Movement during the Active Hip Abduction Test

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Abstract

The active hip abduction (AHAbd) test was developed to predict the risk of developing low back pain (LBP) while standing. Individuals who develop LBP often demonstrate decreased control of trunk movement during AHAbd, but the factors causing it have not been established. To address this knowledge gap, we aimed to identify the factors involved in pelvic wobble in the transverse plane using the AHAbd test. We included 20 asymptomatic individuals and administered the AHAbd test to measure pelvic wobble, range-of-motion of passive hip abduction, position sense of the lumbar joint, and thickness and strength of the trunk muscles. We used Pearson's product-moment correlation coefficient to assess the relationship between the pelvic wobble, range of motion of passive hip abduction, lumbar proprioception, thickness of the lateral abdominal muscle and lumbar multifidus, and strength of the trunk muscle. Pelvic wobble in the transverse plane was positively correlated with absolute errors during the lumbar repositioning sense test and was negatively correlated with the thickness of the transversus abdominis. This result suggests the possibility that improving these factors can reduce the pelvic wobble and increase the control of trunk movement.

1. Introduction

Low back pain (LBP) is a major source of health-related problems and disability. Episodes of LBP are experienced by 65-85% of people during their lifetime[1,2]. The total cost of low back pain in the United States is 238 billion dollars per year, with 2/3 of this amount accounted for by indirect costs such as absenteeism and productivity loss, and the remaining 1/3 due to direct medical expenses[3]. Jobs requiring long periods of standing have been shown to be associated with LBP. It has been reported that 40% of people with healthy backs developed LBP during two hours of standing[4].

In the assessment of people with low back pain, the ability to control trunk movement, which is the

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ability to maintain a neutral zone of the trunk and pelvis during limb movements, is assessed[5,6]. One of these tests is the active hip abduction (AHAbd) test, which was reported to be able to predict the risk of developing low back pain while standing[7]. The AHAbd test assesses the ability to maintain trunk and pelvis alignment during active abduction of the hip while lying on the side with both lower limbs extended. In patients who developed LBP while standing, it has been shown that there is decreased trunk movement control during the AHAbd test, manifesting as either a pelvic wobble in the transverse plane and/or an increase in asymmetric lumbopelvic movement compared to patients without LBP[7,8]. However, little is known about the factors involved in trunk transverse wobble during the AHAbd test.

Poor lumbar proprioception has been reported to impair the maintenance of a neutral spine[9]. People with LBP display atrophy of the lumbar multifidus and transversus abdominis muscles[10-13] and an altered muscle activation pattern in these muscles[14-17]. It has been reported that trunk muscles contribute to the stability of the spine[18-21], and weakness of the trunk muscles has been reported to decrease the balance capabilities in people with LBP[22]. However, little is known about the relationship between pelvic wobble in the transverse plane during the AHAbd test and lumbar proprioception, thickness of the trunk muscle, and trunk muscle strength. Therefore, it is not clear what kind of exercise therapy may be used to prevent LBP in people with a positive AHAbd test. The purpose of this study was to determine the correlation between pelvic wobble in the transverse plane during the AHAbd test and lumbar proprioception, thickness of trunk muscle, and trunk muscle strength, and to identify the factors involved in pelvic wobble in the transverse plane during the AHAbd test.

2. Methods

2.1 Participants

Twenty healthy male subjects were recruited from university student volunteers. Volunteers were excluded if they had a history of low back pain in the past year, previous spine surgery, history of neurological or metabolic disorders, and history of fracture or ligament injury in the lower limbs. The passive hip abduction angle in adult males has been reported to range from 33 to 47° (mean ± 2 standard deviation - 40 ± 7°)[23]. Therefore, participants with a passive hip abduction angle of less than 30° were excluded such that it would not affect the results of the AHAbd test. The participants were aged 20.7 ± 0.6 years, had a height of 170.2 ± 5.6 cm, and a body weight of 61.4 ± 6.4 kg. The protocol was approved by the Ethics Committee of the Kawasaki University of Medical Welfare (#18-081). All the subjects signed written informed consent before the data collection.

2.2 Procedures

To minimize the effects of fatigue, tests were performed in the following order: measurement of muscle thickness of the lateral abdominal muscle and lumbar multifidus, passive hip abduction range of motion, pelvic wobble in the transverse plane during the AHAbd test, joint repositioning sense test in the transverse plane, and trunk muscle strength.

2.2.1 Muscle thickness of the lateral abdominal muscle and lumbar multifidus

Muscle thickness of the bilateral transverse abdominis, internal oblique, external oblique, and lumbar multifidus was measured using a B-mode ultrasound imaging system (Noblus; Hitachi Ltd., Tokyo, Japan) with a 3-7 MHz linear probe (L34; Hitachi Ltd., Tokyo, Japan). The participants assumed supine and prone positions to store images of the lateral abdominal muscle and lumbar multifidus, respectively. The transducer was positioned 2.5 cm anteromedial to the midaxillary line and at the midpoint between the iliac crest and inferior rib for the lateral abdominal muscle, and approximately 2 cm lateral to the L3/4 spinous process for the lumbar multifidus. Gel was applied between the skin and the transducer. A transverse image was taken for the lateral abdominal muscle and a longitudinal image for the lumbar multifidus. Minimum pressure was applied to the probe to achieve a clear image. Images of the lateral abdominal muscle were taken at the end of expiration. Measurements were carried out by a single researcher with extensive experience in musculoskeletal ultrasound. Muscle thickness was measured twice. The average value was normalized for weight (muscle thickness / weight). The normalized values were then averaged over the right and left side muscles and average values of both sides were used in the analysis.

2.2.2 Passive hip abduction range of motion

Passive hip abduction range of motion was measured using a goniometer (OG Giken, Okayama, Japan). The values were then averaged over the right and left side. This value was used in the analysis.

2.2.3 Active hip abduction test

To perform the AHAbd test, subjects were positioned lying on their sides with both lower limbs extended while their lumbar spine was in a neutral position. Shoulder, trunk, pelvis, and lower extremities were aligned in the frontal plane. The top arm was placed on the trunk with the hand on the chest. A target bar was placed so that hip abduction was limited to 30°. A metronome set to 60 beats / min was used as a guide for the speed of movement of the lower limbs. Subjects were asked to raise their top leg at a speed of 15 deg/s until their lower leg touched the target bar and then return it to the starting position at a speed of 15 deg/s. Subjects were instructed to keep their knee extended while maintaining the frontal plane alignment of the pelvis, trunk, and both legs during the AHAbd test (Figure 1). Acceleration of the pelvic and leg movement was recorded using two tri-axis accelerometers (MVP-RF10-AC; Microstone, Nagano Japan) which were attached to the third sacral vertebra and 5 cm proximal to the dorsal ankle joint, respectively. The acceleration data was recorded at 1000 Hz. The acceleration of the leg was recorded to determine onset and end of leg movement. Onset of the leg movement was determined visually as the first change in acceleration vertically above the baseline, and the end of the leg movement was determined visually as its return to the baseline. Pelvic wobble has been used as an indicator of trunk movement control during the AHAbd test in previous studies[7]. Therefore, the acceleration in the anterior-posterior direction of the pelvis was recorded to evaluate pelvic wobble in the transverse plane during leg movement in the AHAbd test. The difference between values of the maximum and the minimum acceleration of the pelvis in the anterior-posterior direction was calculated as an index of pelvic wobble in the transverse plane. This measurement was performed on each leg three times with a 1-min rest between repetitions. The values for pelvic wobble in the transverse plane were then averaged over the right and left side. This value was used in the analysis.

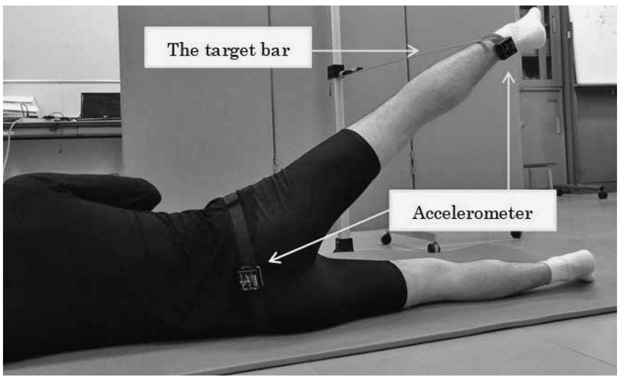

Figure 1 Active hip abduction test

Subjects were positioned in the side-lying position with both legs extended while their lumbar spine was in a neutral position. Subjects were asked to raise their leg until it touched the target bar while keeping the frontal plane alignment of the pelvis, trunk, and legs during the active hip abduction test.

2.2.4 Lumbar repositioning sense test in the transverse plane

Lumbar proprioception was assessed using a custom-built device resembling one reported by Boucher et al.[24] and Cholewicki et al.[25]. This device could produce passive motion of the lumbar spine in the transverse plane and perform a lumbar repositioning task (Figure 2). Subjects were placed in the sitting position. The participant's upper trunk was fixed to the backrest by straps and the pelvis was fixed to the seat by a strap. The seat was moved in the transverse plane at a speed of 2 deg/s by the motor. Since the upper trunk was fixed while the lower trunk moved in the transverse plane, the effect of vestibular feedback was removed. The subjects were blindfolded in order to remove visual information. The seat, and thus the participant's lower trunk, was passively rotated to a target position of 10° from the neutral sitting position (zero), and then the motor paused in this position for 3 seconds. After the participant memorized this position, the seat and the participant's lower trunk was returned to the neutral sitting position. The seat (and participant's lower trunk) was then rotated towards the target position from the neutral sitting position by the motor. Participants stopped the device by pushing a switch when they perceived being in the target position. The angle of the seat when the device was stopped was recorded. The repositioning error was calculated as absolute error with respect to target angle. This lumbar repositioning sense test in the transverse plane was performed twice in each of the right and left rotation directions. The absolute errors were then averaged over the rotation to the right and left. The average absolute error was used in the analysis.

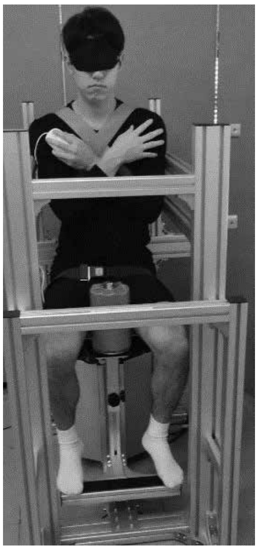

Figure 2 Lumbar repositioning sense test

Participant's upper trunk was fixed to the backrest, and pelvis was fixed to the seat. Participant's upper trunk was fixed to the backrest by straps while the seat and lower trunk were moved in the transverse plane at a speed of 2 degree/sec by motor.

2.2.5 Measurement of trunk muscle strength

Maximum voluntary isometric trunk extension and flexion muscle strength were measured using the trunk extension/flexion dynamometer (Isoforce GT-350; OG Wellness Co., Ltd., Okayama, Japan). Participants assumed an upright sitting posture. The center of the sensor pad of the trunk extension/flexion dynamometer was placed at the height of the angulus inferior scapula. The participant's thigh, pelvis, and upper trunk were fixed to the device by straps. Before testing, subjects performed some sub-maximum exertion practice. Trunk muscle strength was measured in random order and each measurement was taken twice with a 3-min rest between repetitions. The maximum value was normalized for weight (trunk muscle strength/weight). This value was used for analysis.

2.3 Statistical analysis

SPSS Statistics 22 for Windows (IBM Inc, Chicago, IL) was used for statistical analyses. The significance level chosen was $p < 0.05$. We selected the parametric statistical method because the Shapiro-Wilk test demonstrated that all variables were normally distributed. Pearson's product- moment correlation coefficient was used to assess the relationship between pelvic wobble in the transverse plane during the AHAbd test and passive hip abduction range of motion, lumbar proprioception, muscle thickness of lateral abdominal muscle and lumbar multifidus, and trunk muscle strength.

3. Results

The average value of pelvic wobble combining left and right side measurements in the transverse plane during AHAbd was 2.4 ± 0.7 m/s^2. The average value of passive hip abduction range of motion combining left and right side measurements was 37.4 ± 4.6°. The average absolute error in the joint repositioning sense test was 1.08 ± 0.42°. The values of muscle thickness of the lateral abdominal muscle and lumbar multifidus and the value of the trunk muscle strength are listed in Table 1. The results of the correlation analysis are shown in Table 2. Pelvic wobble in the transverse plane during AHAbd was significant and positively correlated with absolute errors during the lumbar repositioning sense test ($r = 0.54$, $p < 0.05$) and was significant and negatively correlated with thickness of the transversus abdominis ($r = -0.47$, $p < 0.05$). There was no significant correlation between pelvic wobble in the transverse plane during AHAbd and passive hip abduction range of motion, trunk flexion and extension muscle strength, and thickness of internal oblique, external oblique, and multifidus.

4. Discussion

We investigated the factors involved in pelvic wobble in the transverse plane during the AHAbd test. Increased pelvic wobble was significantly associated with the increase in absolute errors during the lumbar repositioning sense test and decrease in thickness of the transversus abdominis in this study.

Poor trunk proprioception has been theorized to impair trunk movement control and decrease capacity for maintaining the lumbar neutral zone[9,26]. During sitting, larger lumbar repositioning errors were found to increase the incidence of LBP in nursing students[27]. Additionally, a more ankle-steered proprioceptive control strategy which increased reliance on ankle proprioceptive signals compared to back muscle

Table 1 Results of muscle thickness of the lateral abdominal muscle and lumbar multifidus and trunk muscle strength

Variable	Values
Muscle thickness (mm/kg)	
TrA	0.05 ± 0.01
IO	0.18 ± 0.03
EO	0.14 ± 0.02
Multifidus	0.45 ± 0.05
Muscle strength (Nm/kg)	
Trunk extension muscle strength	7.1 ± 2.7
Trunk flexion muscle strength	5.5 ± 33.7

TrA: transverse abdominis; IO: internal oblique; EO: external oblique.

Table 2 Correlation between pelvic transverse wobble during active hip abduction and other variables

Variable	r Value	P Value
Passive hip abduction range of motion (°)	-0.263	0.262
Absolute error in joint repositioning sense test (°)	0.536	0.015*
Thickness of TrA (mm/kg)	-0.473	0.035*
Thickness of IO (mm/kg)	-0.398	0.082
Thickness of EO (mm/kg)	-0.021	0.929
Thickness of multifidus (mm/kg)	-0.141	0.554
Trunk extension strength (Nm/kg)	0.204	0.387
Trunk flexion strength (Nm/kg)	0.267	0.255

*: $p < 0.05$
TrA: transverse abdominis; IO: internal oblique; EO: external oblique.

proprioceptive signals during standing has been reported to increase the incidence of LBP[28]. Claeys et al.[28] hypothesized that the mechanism of increased risk for developing LBP by a more ankle-steered proprioceptive control strategy was similar to the mechanism of increased risk for developing LBP during prolonged standing[29]. Development of LBP during prolonged standing has been hypothesized to be related to lumbar proprioception impairment[28]. Furthermore, people who had decreasing control of the trunk during the AHAbd test were found to be at increased risk of developing LBP during prolonged standing[7]. Therefore, it is plausible that decreased control of the trunk during the AHAbd test was associated with poor proprioception in this study.

Increased pelvic wobble in the transverse plane during AHAbd was significantly correlated with a decrease in thickness of the transversus abdominis. The transversus abdominis has been found to contribute to maintaining the posture of the lumbar spine, controlling the intervertebral relationships in the spinal segment by increasing intra-abdominal pressure, and increasing force closure by compressing the sacroiliac joints[30-33]. In addition, delayed trunk muscle responses have been reported to increase the risk of LBP[34]. Individuals with LBP showed delayed activity of the transversus abdominis and the transverse fibers of internal oblique during the AHAbd test[35], as well as decreased transversus abdominis thickness when compared to healthy subjects[11,12]. Morphologic changes in transversus abdominis in individuals with LBP are thought to be related to changes in muscle activation patterns[11]. Therefore, it is plausible that increased pelvic wobble in the transverse plane during AHAbd, which is a test for predicting individuals who are at risk for LBP, can be correlated with the muscle thickness of the transverse abdominis muscle.

There was no significant correlation between pelvic wobble and trunk flexion and extension muscle strength in this study. Systematic reviews found no association between trunk muscle strength and the risk of future low back pain because of inconsistent results in multiple studies[36]. In addition, trunk flexion and extension muscles do not antagonize pelvic rotation; rather, the muscles that do this are trunk rotation muscles such as the internal and external oblique muscles[37,38]. However, we did not assess the relationship between pelvic wobble and trunk rotation muscle strength. Therefore, no significant association was found between pelvic wobble and trunk muscle strength in this study.

The increased pelvic wobble was significantly associated with an increase in absolute errors during the lumbar repositioning sense test, and a decrease in thickness of the transversus abdominis. This result has relevance for the prevention and treatment of LBP. Sensory function training comprises focused attention to sensations, conscious attention to posture and movement, and repositioning training[39]. Abdominal draw-in exercise can facilitate isolated transverse abdominal contraction[40]. Therefore, sensory function training and abdominal draw-in exercise may contribute to increased trunk movement control and prevent the future development of LBP.

There are several limitations to our work. First, the sample size was small. Second, although the population in this study was similar to the population in a previous study which predicted the development of LBP in prolonged standing using the AHAbd test, it is unclear whether subjects with a large pelvic wobble in this study will develop LBP during prolonged standing. Third, we did not assess the relationship between trunk muscle activation patterns and pelvic wobble. Future studies are required to clarify specifics of lumbar proprioception, trunk rotation muscle strength, thickness of the transversus abdominis, and trunk muscle activation patterns in people who develop LBP during prolonged standing. In addition, future studies are required to determine whether improvement in these factors decreases the risk for future LBP.

In conclusion, the amount of pelvic wobble in the transverse plane during AHAbd displays positive association with absolute errors during the lumbar repositioning sense test and negative association with thickness of the transversus abdominis. This result suggests the possibility that improving these factors can reduce pelvic wobble and increase the control of trunk movement.

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References

1. Andersson GB : Epidemiological features of chronic low-back pain. *Lancet*, 354, 581-5, 1999.
2. Manchikanti L : Epidemiology of low back pain. *Pain Physician*, 3, 167-192, 2000.
3. Ma VY, Chan L and Carruthers KJ : Incidence, prevalence, costs, and impact on disability of common conditions requiring rehabilitation in the United States: Stroke, spinal cord injury, traumatic brain injury, multiple sclerosis, osteoarthritis, rheumatoid arthritis, limb loss, and back pain. *Archives of Physical Medicine and Rehabilitation*, 95, 986-995.e1, 2014.
4. Nelson-Wong E and Callaghan JP : Is muscle co-activation a predisposing factor for low back pain development during standing? A multifactorial approach for early identification of at-risk individuals. *Journal of Electromyography and Kinesiology*, 20, 256-263, 2010.
5. Liebenson C, Karpowicz AM, Brown SH, Howarth SJ and McGill SM : The active straight leg raise test and lumbar spine stability. *PM & R : The Journal of Injury, Function, and Rehabilitation*, 1, 530-535, 2009.
6. Park KN, Cynn HS, Kwon OY, Lee WH, Ha SM, Kim SJ and Weon JH : Effects of the abdominal drawing-in maneuver on muscle activity, pelvic motions, and knee flexion during active prone knee flexion in patients with lumbar extension rotation syndrome. *Archives of Physical Medicine and Rehabilitation*, 92, 1477-1483, 2011.
7. Nelson-Wong E, Flynn T and Callaghan JP : Development of active hip abduction as a screening test for identifying occupational low back pain. *The Journal of Orthopaedic and Sports Physical Therapy*, 39, 649-657, 2009.
8. Sorensen CJ, Johnson MB, Norton BJ, Callaghan JP and Van Dillen LR : Asymmetry of lumbopelvic movement patterns during active hip abduction is a risk factor for low back pain development during standing. *Human Movement Science*, 50, 38-46, 2016.
9. Tong MH, Mousavi SJ, Kiers H, Ferreira P, Refshauge K and van Dieen J : Is there a relationship between lumbar proprioception and low back pain? A systematic review with meta-analysis. *Archives of Physical Medicine and Rehabilitation*, 98, 120-136.e2, 2017.
10. Hides J, Gilmore C, Stanton W and Bohlscheid E : Multifidus size and symmetry among chronic LBP and healthy asymptomatic subjects. *Manual Therapy*, 13, 43-49, 2008.
11. Rahmani N, Mohseni-Bandpei MA, Salavati M, Vameghi R and Abdollahi I : Comparative study of abdominal muscle thickness on ultrasonography in healthy adolescents and patients with low back pain. *Journal of Ultrasound in Medicine*, 37, 905-912, 2018.

12. Rostami M, Ansari M, Noormohammadpour P, Mansournia MA and Kordi R : Ultrasound assessment of trunk muscles and back flexibility, strength and endurance in off-road cyclists with and without low back pain. *Journal of Back and Musculoskeletal Rehabilitation*, 28, 635-644, 2015.
13. Goubert D, Oosterwijck JV, Meeus M and Danneels L : Structural changes of lumbar muscles in non-specific low back pain: A systematic review. *Pain Physician*, 19, e985-e1000, 2016.
14. Hodges PW, Moseley GL, Gabrielsson A and Gandevia SC : Experimental muscle pain changes feedforward postural responses of the trunk muscles. *Experimental Brain Research*, 151, 262-271, 2003.
15. MacDonald D, Moseley GL and Hodges PW : Why do some patients keep hurting their back? Evidence of ongoing back muscle dysfunction during remission from recurrent back pain. *Pain*, 142, 183-188, 2009.
16. Suehiro T, Ishida H, Kobara K, Osaka H and Watanabe S : Altered trunk muscle recruitment patterns during lifting in individuals in remission from recurrent low back pain. *Journal of Electromyography and Kinesiology*, 39, 128-133, 2018.
17. Silfies SP, Mehta R, Smith SS and Karduna AR : Differences in feedforward trunk muscle activity in subgroups of patients with mechanical low back pain. *Archives of Physical Medicine and Rehabilitation*, 90, 1159-1169, 2009.
18. Panjabi MM : Clinical spinal instability and low back pain. *Journal of Electromyography and Kinesiology*, 13, 371-379, 2003.
19. Panjabi MM : The stabilizing system of the spine. Part II. Neutral zone and instability hypothesis. *Journal of Spinal Disorders*, 5, 390-397, 1992.
20. Vera-Garcia FJ, Brown SH, Gray JR and McGill SM : Effects of different levels of torso coactivation on trunk muscular and kinematic responses to posteriorly applied sudden loads. *Clinical Biomechanics*, 21, 443-455, 2006.
21. Vera-Garcia FJ, Elvira JL, Brown SH and McGill SM : Effects of abdominal stabilization maneuvers on the control of spine motion and stability against sudden trunk perturbations. *Journal of Electromyography and Kinesiology*, 17, 556-567, 2007.
22. Behennah J, Conway R, Fisher J, Osborne N and Steele J : The relationship between balance performance, lumbar extension strength, trunk extension endurance, and pain in participants with chronic low back pain, and those without. *Clinical Biomechanics*, 53, 22-30, 2018.
23. Svenningsen S, Terjesen T, Auflem M and Berg V : Hip motion related to age and sex. *Acta Orthopaedica Scandinavica*, 60, 97-100, 1989.
24. Boucher JA, Roy N, Preuss R and Lariviere C : The effect of two lumbar belt designs on trunk repositioning sense in people with and without low back pain. *Annals of Physical and Rehabilitation Medicine*, 60, 306-311, 2017.
25. Cholewicki J, Shah KR and McGill KC : The effects of a 3-week use of lumbosacral orthoses on proprioception in the lumbar spine. *The Journal of Orthopaedic and Sports Physical Therapy*, 36, 225-231, 2006.
26. Willigenburg NW, Kingma I and van Dieën JH : Precision control of an upright trunk posture in low back pain patients. *Clinical Biomechanics*, 27, 866-871, 2012.
27. Mitchell T, O'Sullivan PB, Burnett A, Straker L, Smith A, Thornton J and Rudd CJ : Identification of modifiable personal factors that predict new-onset low back pain: a prospective study of female nursing students. *The Clinical Journal of Pain*, 26, 275-283, 2010.
28. Claeys K, Dankaerts W, Janssens L, Pijnenburg M, Goossens N and Brumagne S : Young individuals with a more ankle-steered proprioceptive control strategy may develop mild non-specific low back pain. *Journal of Electromyography and Kinesiology*, 25, 329-338, 2015.
29. Nelson-Wong E and Callaghan JP : Transient low back pain development during standing predicts future clinical low back pain in previously asymptomatic individuals. *Spine*, 39, e379-e383, 2014.
30. Arjmand N, Shirazi-Adl A and Parnianpour M : A finite element model study on the role of trunk muscles in generating intra-abdominal pressure. *Biomedical Engineering*, 13, 181-189, 2001.
31. Richardson CA, Snijders CJ, Hides JA, Damen L, Pas MS and Storm J : The relation between the

transversus abdominis muscles, sacroiliac joint mechanics, and low back pain. *Spine*, 27, 399-405, 2002.

32. Hu H, Meijer OG, Hodges PW, Bruijn SM, Strijers RL, Nanayakkara PW, van Royen BJ, Wu W, Xia C and van Dieën JH : Understanding the active straight leg raise (ASLR): An electromyographic study in healthy subjects. *Manual Therapy*, 17, 531-537, 2012.
33. Hu H, Meijer OG, Van Dieen JH, Hodges PW, Bruijn SM, Strijers RL, Nanayakkara PW, Van Royen BJ, Wu W and Xia C : Muscle activity during the active straight leg raise (ASLR), and the effects of a pelvic belt on the ASLR and on treadmill walking. *Journal of Biomechanics*, 43, 532-539, 2010.
34. Cholewicki J, Silfies SP, Shah RA, Greene HS, Reeves NP, Alvi K and Goldberg B : Delayed trunk muscle reflex responses increase the risk of low back injuries. *Spine*, 30, 2614-2620, 2005.
35. Nelson-Wong E, Poupore K, Ingvalson S, Dehmer K, Piatte A, Alexander S, Gallant P, McClenahan B and Davis AM : Neuromuscular strategies for lumbopelvic control during frontal and sagittal plane movement challenges differ between people with and without low back pain. *Journal of Electromyography and Kinesiology*, 23, 1317-1324, 2013.
36. Hamberg-van Reenen HH, Ariens GA, Blatter BM, van Mechelen W and Bongers PM : A systematic review of the relation between physical capacity and future low back and neck/shoulder pain. *Pain*, 130, 93-107, 2007.
37. Park KH, Ha SM, Kim SJ, Park KN, Kwon OY and Oh JS : Effects of the pelvic rotatory control method on abdominal muscle activity and the pelvic rotation during active straight leg raising. *Manual Therapy*, 18, 220-224, 2012.
38. Urquhart DM and Hodges PW : Differential activity of regions of transversus abdominis during trunk rotation. *European Spine Journal*, 14, 393-400, 2005.
39. Hodges PW, Cholewicki J and Van Dieën JH : *Spinal control: The rehabilitation of back pain: State of the art and science*. Elsevier Health Sciences, Edinburgh, 2013.
40. Teyhen DS, Miltenberger CE, Deiters HM, Del Toro YM, Pulliam JN, Childs JD, Boyles RE and Flynn TW : The use of ultrasound imaging of the abdominal drawing-in maneuver in subjects with low back pain. *The Journal of Orthopaedic and Sports Physical Therapy*, 35, 346-355, 2005.