The Role of Ultrasound in Diagnosis of the Causes of Low Back Pain: a Review of the Literature

Citation

Published Version

Permanent link

Terms of Use

Share Your Story

Accessibility

The Role of Ultrasound in Diagnosis of the Causes of Low Back Pain: a Review of the Literature

Pedram Heidari [1]; Farzin Farahbakhsh [2,3]; Mohsen Rostami [2]; Pardis Noormohammadpour [2]; Ramin Kordi [2,*]

[1]Nuclear Medicine and Molecular Imaging, Massachusetts General Hospital, Harvard Medical School, Boston, United States
[2]Sports Medicine Research Center, Tehran University of Medical Sciences, Tehran, IR Iran
[3]Departement of Spine, Noorafshar Rehabilitation and Sports Medicine Hospital, Tehran, IR Iran

*Corresponding author: Ramin Kordi, Sports Medicine Research Center, Tehran University of Medical Sciences, P.O.Box: 14395-578, Tehran, IR Iran. Tel: +98-2188630227-8, E-mail: ramin_kordi@tums.ac.ir

Context: Low back pain (LBP) is among the most prevalent musculoskeletal conditions in the developed countries. It is a common problem causing disability and imposing a huge economic burden to individuals and state organizations. Imaging plays an important role in diagnosis of the etiology of LBP.

Evidence Acquisition: The electronic databases included: PubMed (1950 to present), Ovid SP Medline (1950 to present) and ISI (1982 to present) and Google Scholar. In every search engine another search was performed using various permutations of the following keywords: ultrasonography, ultrasound imaging, low back pain, back muscles, paraspinal muscles, multifidus, transverse abdominis, muscle size, spinal canal, sacroiliac joint and spondylolisthesis.

Results: Magnetic resonance imaging (MRI) is widely used in evaluation of patients with LBP; however, high costs, limited availability and contraindications for its use have restricted MRI utilization. In a quest for a less expensive and readily available tool to investigate LBP, clinicians and researchers found ultrasonography (US) as an alternative. In this review we discuss the US application in diagnosis of some common causes of non-specific chronic LBP. Discussed topics include evaluation of spinal canal diameter, paraspinal and transabdominal muscles, sacroiliac joint laxity, pregnancy related LBP, sacroiliitis, and spondylolisthesis using US in patients with LBP.

Conclusions: While the first researches on employing ultrasound in diagnosis of patients with LBP had been focused on spinal canal diameter, recent studies have been mostly performed to evaluate the role of transabdominal and paraspinal muscles on core stability and thereby LBP occurrence. On the other side, Doppler ultrasonography has recently played an important role in objective measurement of joint laxity as a common etiology for LBP. Doppler imaging also in pregnant patients with LBP has been recommended as a safe and sensitive method. As conclusion, according to recent and most prestigious studies, focusing more on transabdominal muscle thickness can be considered as future approach in investigations.

Keywords: Ultrasonic Diagnosis; Low Back Pain; Review Literature

1. Context

Low Back Pain (LBP) not only is one of the most common causes of disability (1-3) and absence from work (4, 5), but also is reported as one of the major reasons of physician visits (3, 6, 7). It occurs in various groups of population with different socioeconomic states (8-11). Nevertheless, increasing incidence of LBP has been reported in recent years (7, 11-14). Imaging plays an important role in diagnosis of causes of LBP (15, 16). Although computerized Tomography (CT) and magnetic resonance imaging (MRI) have been widely used in diagnosis of the etiology of LBP (16), high costs, complications and complexity are main problems in generalization of employing these imaging techniques for all patients (17).

Ultrasonography (US) has been reported as a safe, inexpensive and easy to use technique used in diagnosis of many diseases (18). Due to the high prevalence of LBP and also exclusive features of US, some investigators have focused on the diagnostic roles of US in patients with LBP from many years ago (19, 20). Recently, in light of achieved progression in US and also inferring some evolved US parameters for evaluation of LBP patients, researchers have discovered a number of obscure aspects of LBP (21-23). In the present paper, we are to review the diagnostic role of US in patients with LBP arising from a handful of common etiologies, which have been debated in the literature.

2. Evidence Acquisition

Literature searches were conducted in December of 2012 on all accessible library databases of published research reports available at Tehran University of Medical Sciences' library. No date limit was applied to any of the databases searched, thus each database was searched

since its inception. The electronic databases included: PubMed (1950 to present), Ovid SP Medline (1950 to present) and ISI (1982 to present) and Google Scholar. In every search engine another search was performed using various permutations of the following keywords: ultrasonography, ultrasound imaging, low back pain, back muscles, paraspinal muscles, multifidus, transverse abdominis, muscle size, spinal canal, sacroiliac joint and spondylolisthesis. Secondary searching (or PEARLing) was however undertaken, whereby the reference lists of the selected articles were reviewed for additional references not identified in the primary search. The full text of all potentially relevant articles were retrieved and screened by the authors, in order to determine the eligibility of the paper for inclusion in the review.

3. Results

3.1. Ultrasonography and Spinal Canal Diameter

Employing US in measurement of spinal canal diameter was firstly reported by Porter et al. (24) who measured the diameter of spinal canal by placing the transducer of ultrasound in an oblique midsagittal plane 1 centimeter lateral to midline (24, 26-28). Porter et al.(24) reported that spinal diameter in trefoil shaped vertebras such as L5 is less than other vertebras and the incidence of LBP due to bony stenosis or laminar hypertrophy might be more in trefoil shaped vertebrae in comparison to other vertebrae. Porter et al.(26) also found that mean spinal canal diameter in patients with LBP was 1.44 cm, compared to a diameter of 1.61 in normal subjects and this difference was found to be statistically significant. It was suggested that a diameter of < 1.4 cm increases the risk of LBP and subjects with a wider spinal canal can escape from the root entrapment on account of the greater space in their spinal canal. In the latter study, however, the patients of two groups were not well-matched demographically (e.g. age which is a determinant in the size of spinal canal was higher in LBP group). In a large scale study (27), a significant correlation was found between the incidence of neurologic claudication, disc lesion and nerve root entrapment and the spinal canal diameter of the subjects. Subsequent studies showed that the extreme of small spinal canal diameter is correlated with number of days one is absent from work; more than 32% of days lost due to the LBP were related to men whose spinal canal size was less than the 10th percentile of the measurements achieved from the subjects (29). The odds ratio of a spinal canal size in the lower 10th percentile spinal canal size and absence from work was reported to be 10.7 (30). Regarding the measurement of spinal canal diameter employing ultrasonography, reliability studies have reported the ease of learning the technique and rapid development of operator's skill in performing the procedure (25, 29, 31). It was also demonstrated that the technique has a high inter and intra observer reliability with an average error of < 0.2 mm between measurements (24, 32); this was, however, a non-uniform finding and a number of studies concluded that the technique is operator dependent (33), lacks acceptable reliability in elderly patients (34), and has a high interobserver (0.9 to 1.5 mm) and intraobserver error (0.6 mm to 0.9 mm) (35).

Transabdominal ultrasonography was also used in measurement of spinal canal size (36, 37); this technique was suggested to have an acceptable role in measurement of spinal canal size both in epidemiologic and pre-employment screening tests (36, 37). Missere et al. (36) reported a sensitivity of 84% and specificity of 60% for transabdominal ultrasound in diagnosis of LBP with a cut-off spinal diameter of 14 mm; nevertheless, the use of transabdominal ultrasound is limited due to anatomical restrictions like different abdominal tissues and oblique direction of the intervertebral discs as the major boundaries against ultrasonographic pulses at the level of L3-L4 and L5-S1 (37).

Finally, well-controlled, prospective studies demonstrated that although spinal canal size might be a risk factor for LBP, ultrasound measurement of spinal canal size has no practical role in prediction and/or estimation of the prognosis of LBP, neither in workers nor in general population (38, 39). It seems that small spinal canal diameter only plays as a facet of a multifactorial matrix in development of LBP. In addition, spinal canal size measurement using ultrasound has not gained wide attention since it requires quite a lot of expertise of the operator and the proficiency of the operator is the major determinant of the accuracy of measurements.

3.2. Ultrasonography and Paraspinal Muscles

Osseoligamentous lumbar spine is inherently unstable (40, 41) and is dependent on the integrated function of the muscles (especially paraspinal muscles) and neural subsystems for stability and movement (42, 43). Among the paraspinal muscles lumbar multifidus (LM) has a unique role in spinal stabilization and contributes to almost 2/3 of lumbar spine stability especially in the lower lumbar section (44) and is the predominantly affected paraspinal muscle in patients with LBP (45). In healthy subjects, the LM muscles are round or oval in shape, symmetrical between sides and increase in size cephalocaudally (46-49).

The most commonly used imaging studies for evaluation of paraspinal muscles are CT, MRI and rehabilitative ultrasound imaging (RUSI). Important aspects of muscles assessed using RUSI are muscle size, density and muscle contraction (50). The reliability of using RUSI to measure size of paraspinal musculature has been shown to be fair to excellent (ICC = 0.72-0.98), which is acceptable for clinical application (47, 51-53). It also has shown to have a reasonable inter-rater reliability among novice raters (54). Many authors reported muscle cross-sectional area (CSA) as the indicator of

muscle size; if RUSI measurements are performed utilizing strict criteria, there is no significant difference regarding CSA measurements between RUSI and MRI (55). However, measuring CSA is a time consuming task; instead the greatest depth and the greatest width are usually measured (46). Linear measurements, especially when two dimensions are multiplied by each other, have a very high correlation (r = 0.93-0.98) with CSA in healthy individuals (46-48). However, this correlation is much smaller when muscle becomes atrophied (r = 0.75-0.85) (47). Therefore application of linear measurements is limited in clinical practice; as in most cases the objective is to compare atrophied and healthy muscles.

LM atrophy is a common finding (around 80%) in patients with chronic LBP (56). LM muscle atrophy in chronic LBP is localized to the lower region of the spine and asymmetry occurs in those with unilateral pain (57). The pattern of LM atrophy seen in the chronic LBP patients using RUSI appears to be specific and localized in nature (58). Using RUSI, it has also been shown that the pattern of the multifidus CSA change in various postures differs in healthy subjects from patients with LBP; in healthy subjects multifidus CSA increases from prone lying to upright standing, then gradually decreases during forward flexion while; in patients with chronic LBP forward flexion produces a further increase in CSA (59). The altered function of LM might be due to failure of a neuromuscular self-regulatory mechanism to regulate muscle contraction in order to meet the postural demands, which may in turn predispose the patient to LBP

(59, 60). Table 1 provides details of the studies that evaluated paraspinal muscles employing US.

Patients with chronic LBP may also show changes in the density and appearance of damaged paraspinal muscles (47, 61). Infiltration of fat into the muscle and replacement of muscle fibers with fat cells results in decreased muscle density (56, 62-64). Increased muscle echogenicity has been reported in afflicted LM in patients with chronic LBP (47). The validity and reliability of USI for this purpose, however, remains to be specified in future studies; achievement of this goal might require sticking to strict criteria, as image brightness is affected by gain setting on the ultrasound machine.

Measurement of changes in muscle activation associated with LBP can lead to development of selective interventions to reverse the identified impairment. Pursuing this goal, USI was used to evaluate functional impairments in muscle contraction. It was demonstrated that there is a linear relation (r = 0.79 P = 0.001) between LM thickness change and EMG activity across a narrow span of activation range (19-34% of maximum voluntary isometric contraction (MVIC)) (52). USI was able to show that patients with LBP were not able to voluntarily contract the LM at the vertebral level with muscle atrophy (65, 66). It was demonstrated that the ability of patients with chronic LBP to activate the LM at the affected lumbar section is reduced, as evidenced by smaller increases in thickness on RUSI images during contraction compared to contralateral normal side muscle or asymptomatic control subjects (58, 67).

Table 1. Details of Studies Using Ultrasound for Evaluation of Paraspinal Muscles [a]

Author	Year	Subject (No.)	Measuring Elements (Muscle)	Probe Position	Subjects Position	Results
Hides et al. (46)	1992	Healthy (48)	Linear dimensions and CSA of LM	The transducer was placed transversely over the spinous process and moved directly laterally.	Prone with the head in the midline position with a small roll placed under the forehead and two rolls under the shoulders. The lower lumbar spine was made flat by placing pillows under the hips.	US showed to have a good repeatability for measuring CSA of LM muscle. US is a feasible way to assess CSA, size and shape of LM muscle in young adults.
Kennelly et al. (68)	1993	Scoliosis (20)	Linear dimensions and CSA of LM	The transducer was placed transversely over the spinous process and was held against the skin surface at 90° and moved laterally.	Prone with a rolled towel under their forehead and shoulder. A pillow was placed under the hips to eliminate the lumbar lordosis.	It was shown that for different curve types in lumbar scoliosis, a pattern of asymmetry in LM exists.
Hides et al. (47)	1994	Healthy/LBP (51/26)	Linear dimensions and CSA of LM	The transducer was placed transversely over the spinous process and moved directly laterally.	Prone with the head in the midline position with a small roll placed under the forehead and two rolls under the shoulders. The lower lumbar spine was made flat by placing pillows under the hips.	Most of the patients showed greatest wasting at the level of L5. Asymmetry of CSA in patients was significantly different from between-side differences in control group. This asymmetry was greater in female patients.
Hides et al. (49)	1995	Healthy (10)	Linear dimensions and CSA of LM	The transducer was located adjacent to demarcated spinous process of the level to be examined.	Subjects were positioned in a comfortable and relaxed prone position, with their hips flexed to 35°.	In terms of LM muscle CSA no significant differences were found between MRI and US in young female adults.
Hides et al. (65)	1996	LBP (41)	CSA of LM	The transducer was placed transversely over the spinous process and moved directly laterally.	Prone with the head in the midline position with a small roll placed under the forehead and two rolls under the shoulders. The lower lumbar spine was made flat by placing pillows under the hips.	In the group that only received medical treatment LM muscle recovery was not spontaneous on remission of painful symptoms in patients. After 10-week follow-up examination patients in this group still had decreased LM muscle size.

Eisele et al. (69)	1998	Health/ Lumbar Disk Disorder/ Unknown (30/20/40)	Texture analysis and CSA of paraspinal lumbar muscle	Not Stated	Not Stated	Using US all patients with lumbar spinal history were detected. LM texture analysis can be a good and rapid investigation in patients with discogenic and structural disorders.
Coldron et al. (70)	2003	Healthy (20)	CSA of LM	The transducer was placed longitudinally over the skin marking for spinous process and then moved directly laterally.	1: Prone: the subject lay with the head in the midline position, with one pillow under the lower legs and another under the hips to reduce the lumbar lordosis. 2: Side lying position: subjects lay on their left side and the transducer was placed behind the subject. One pillow was placed under the head and another between the knees, with the hips and knees positioned in sufficient flexion. A rolled towel was placed under the waist.	Assessing CSA of LM muscle at the level of L5 can be made at both prone and side lying positions.
Stokes et al. (48)	2005	Healthy (120)	Linear dimensions and CSA of LM	The transducer was first placed longitudinally over the lower lumbar spine, in the mid-line. The transducer was then rotated through 90° to lie transversely in the midline and the spinous processes and laminae were identified on a cross-sectional scan. The transducer was then moved laterally to each side.	Prone with the forehead resting just above the breathing hole in the plinth, the head in the midline and the arms supported on the plinth's armrests. One or two pillows were placed under the hips.	It was found that CSA of LM is larger in males and age didn't have any effect. Both in males and females the CSA was larger in L5 than L4. Linear measurements multiplied (A × Lat) correlated highly with CSA.
Lee et al. (59)	2006	Healthy/LBP (19/16)	CSA of LM	The transducer was held perpendicular to the skin surface of the subjects' lower back.	1: Subjects were prone and a small pillow was inserted below their abdomen. 2: Subjects were upright standing, and 25° and 45° forward stooping.	In different positions, CSA changes in LBP group had a reverse pattern in comparison to healthy subjects.
Pressler et al. (71)	2006	Healthy (30)	Linear dimensions and CSA of LM	The transducer was held orthogonal to the surface of the body and moved slowly from the left or right PSIS to the S1 spinous process.	Prone with 35° of hip flexion and no lumbar lordosis. A manually adjusted treatment table with the hip joints placed along the hinge was used.	US seems to be a reliable way for imaging LM at the level of S1 by newly trained assessors.
Vasseljen et al. (72)	2006	Healthy (10)	LM muscle activity onset	The probe was transversally oriented to the fiber direction and placed on a line running from the PSIS to the L1/L2 interspinous space.	Subjects stood relaxed with their arms beside the body.	US can detect muscle activity onset accurately but it has a small systematic delay that should be corrected for determining activity onset.
Kiesel et al. (52)	2007	Healthy (5)	Thickness of LM	Transducer was placed along the spine with the mid-point over the L4 spinous process. It was moved laterally and angled slightly medially until the L4/5 zygapophyseal joint could be identified.	Prone position. An inclinometer was placed longitudinally over the lumbosacral junction and pillows were used to flatten the lumbar curve to less than 10°.	In a narrow range of LM muscle contraction RUSI showed to be a valid method of measurement.
Wallwork et al. (51)	2007	Healthy (10)	Thickness of LM	The transducer was placed longitudinal where the zygapophyseal joints, the overlying multifidus muscle bulk at 2 to 3 vertebral levels, and the thoracolumbar fascia could be visualized.	Prone, with a pillow placed under the abdomen to minimize the lumbar lordosis.	Reliable evaluations of CSA of LM muscle at two vertebral levels were performed by both novice and experienced assessors.
Hides et al. (73)	2008	Athletes (26)	CSA of LM	The transducer placed transversely over the spinous process of the vertebral level being measured.	Prone with a pillow placed under the abdomen to minimize lumbar lordosis.	Even in highly active individuals with LBP atrophy of LM can exist. Improvement in CSA of LM was concomitant with a decrease in pain.
Hides et al. (74)	2008	Healthy/LBP (40/50)	CSA of LM	The transducer placed transversely over the spinous process of L2 to L5.	Prone with pillows under the hips to eliminate the lumbar lordosis.	Level of L5 was the greatest site of asymmetry in LM in patients with unilateral pain. The reported side of pain was the side that LM was smaller.
Wallwork et al. (58)	2009	Healthy/LBP (17/17)	Thickness and CSA of LM	The transducer placed transversely over the spinous process of L2 to L5.	Prone, with a pillow placed under the abdomen to minimize the lumbar lordosis.	At the level of L5, smaller CSA of LM muscle was reported for subjects of CLBP group than control group and percent thickness contraction was smaller in CLPB group.
Dickx et al. (75)	2010	Healthy (15)	Thickness of LM	The transducer was placed on the spinous processes and then moved lateral allowing visualization of the zygapophyseal joints, multifidus muscle and thoracolumbar fascia.	Prone with pillows under the abdomen to minimize the lumbar lordosis. An inclinometer ensured that the lumbar curve was less than 10°.	Muscle thickness increase during contraction decreased when unilateral pain was induced at a segmental level.

| Worsley et al. (76) | 2012 | LBP (81) | Thickness, linear dimensions and CSA of LM | Transducer was first placed longitudinally over the mid-line at L3 level. The transducer was then rotated 90° to produce a transverse image of the bilateral multifidus muscles. | Prone, with a pillow under the pelvis to reduce the lumbar lordosis. | In terms of thickness and CSA there were small differences between curvilinear and linear transducers. For width, linear transducer gave larger measures. There was a significant correlation between both transducers for linear dimensions and CSA measurements. |

a Abbreviations: AP, anteroposterior; CLBP, chronic low back pain; CSA, cross-sectional area; Lat, lateral; LBP, low back pain; LM, lumbar multifidus muscle; PSIS, posterior superior iliac spine; RUSI, rehabilitative ultrasound imaging; US, ultrasound.

3.3. Ultrasonography and Sacroiliac Joint Dysfunction

SIJ has been implicated as the primary source of pain in 10% to 25% of the patients with LBP (77, 78). Abnormal biomechanics of the SIJ is considered a potential source of LBP (79-81); however, evaluation of SIJ dysfunction is still a challenge to clinicians. Intra-articular injection of steroids and analgesics to the SIJ is the gold standard in the diagnosis of SIJ dysfunction (82, 83). Nevertheless, the technique is invasive and requires specialized equipment and expertise. Neither the SIJ clinical presentation nor diagnostic procedures like X-rays and MRI are accurate enough for evaluation of SIJ dysfunction (82, 84, 85). Thus, a non-invasive objective method, which can be routinely applied in the clinic, was needed. Buyruk et al. (86) developed a technique called Doppler imaging of vibrations (DIV), to objectively measure the laxity of the SIJ. The laxity of the SIJ is quantified as threshold units (TU) which is assumed to be representative of the degree of vibration intensity attenuation through the SIJ, measured by color Doppler ultrasound (CDUS). TU is directly related to the density of the tissue that the vibrations pass through; for instance, a large difference in TU between sacrum and ilium indicates a lax joint and a small difference or an absence of it is an indicator of a stiff joint (87-92). The laxity measurements of the SI joint with DIV, after specific training of the operator, seems to be reliable and accurate (92). Moreover, DIV has proven to be of clinically relevant in evaluation of the patients with pregnancy related pelvic pain (88-91).

3.3.1. Pregnancy

According to different studies, twenty to eighty percent of women complain of some sort of back pain during pregnancy (93-99). This pain may persist, or arise, after delivery (100), and will, in some patients, leads to severe disability (97, 101-105). Two major patterns of back pain during pregnancy have been identified; pregnancy-related lumbar pain (PRLP) and pregnancy-related posterior pelvic pain (PRPPP) (106).

These mechanisms of back pain during pregnancy have been a matter of debate (107-112) and the precise mechanism of pregnancy back pain development is not fully understood (113). Studies have suggested that both PRLP and PRPPP might be related to sacroiliac joint (SIJ) dysfunction (89, 114). Recent introduction of DIV has made the evaluation of SIJ laxity feasible (115). DIV was first used in a cross-sectional study to compare SIJ stiffness in patients with peripartum pelvic pain including both PRPPP and PRLP patients and healthy subjects. No significant difference in the stiffness of SIJ was found between pelvic pain group and healthy subjects. Nevertheless, asymmetry in stiffness of the SIJ was significantly higher in patients with pelvic pain (88). These findings were further confirmed in succeeding studies (113, 116) where the authors showed the asymmetry in laxity rather than stiffness in SIJ is related to moderate to severe PRPPP (116). It was also demonstrated that asymmetric laxity during pregnancy measured using DIV, can predict persistence of pelvic pain to the postpartum period in patients with moderate to severe PRPPP; patients with asymmetrical laxity of SIJ during pregnancy had a three-fold increase in moderate to severe pain persisting into the postpartum period compared with subjects with symmetrical laxity. The sensitivity, specificity, and positive predictive value of SIJ asymmetric laxity during pregnancy for PRPPP persisting postpartum were 65%, 83%, and 77%, respectively (113).

3.4. US in Sacroiliac Joint Inflammation

Sacroiliitis is a frequent and early manifestation of the spondylarthropathies (SpA) (117). Inflammatory back pain (IBP) due to sacroiliitis is the key symptom of axial involvement in SpA and is present in the majority of patients with SpA (118-120). Diagnosis of sacroiliitis is mainly based on clinical findings and X-ray studies, which lack specificity and are poorly reproducible (121). MRI can demonstrate early pre-destructive alterations of SIJ, and thus provide an early diagnosis of sacroiliitis (122-126). The availability of MRI, however, is limited, and the technique is time consuming and costly (123, 125, 127).

Color Doppler ultrasonography (CDUS), a technology that is widely used for detection of blood flow, has been used for diagnosis of sacroiliitis. Early studies found a high sensitivity (100%) for CDUS to detect vascularity around and/or inside SIJ in patients with active sacroiliitis (128); but this finding lacks specificity as vascularity was also present in some of the patients with osteoarthritis and in the control subjects. However, in sacroiliitis the resistive index (RI) of the vasculature was significantly lower than those in osteoarthritis (P < 0.001) and volunteers (P < 0.001) (128). Nevertheless, not all the studies using CDUS showed such a high sensitivity for detection of sacroiliitis. Klauser et al. (129) could only detect sacroiliitis in 18% of the patients who had MRI confirmed inflammation of SIJ

which is likely to be explained by the flow signal criteria that was used to detect SIJ involvement. Microbubble contrast agents have been shown to improve the detection of increased vascularity in inflamed synovium by CDUS (130-132). In sacroiliitis contrast enhanced CDUS had dramatically improved *sensitivity* (18% before contrast *vs.* 94% after contrast administration) and negative predictive value (72% before contrast *vs.* 97% after contrast administration) to a level that is comparable with MRI (129). Clustered receiver operating curve (ROC) analysis also demonstrated that enhanced CDUS was significantly better than unenhanced CDUS for the diagnosis of active sacroiliitis (Az = 0.89 *vs.* Az = 0.61, P < 0.0001) (129). The high sensitivity and negative predictive value of contrast-enhanced CDUS may obviate the need for MRI in screening of the IBP patients for SIJ involvement (129). An advantage of CDUS is that it can be used to quantitate response to therapy; the increase of the RI value and the decrease of symptoms are indicative of response to medical treatment (34, 129). This method, however, has its own limitations; false negative results may arise when inflammation is at the anterosuperior portion only or when there is prominent spur formation dorsally, because of limited ultrasound beam penetration (129).

Most recently, ultrasound had been implemented for detecting sacroiliac joint effusion in spandyloarthropathies (SpA). US showed joint effusion in 38.9% of SIJs of patients with SpA and only in 1.7% SIJ of the controls (P < 0.0001). SIJ effusion assessed by US had a positive likelihood ratio of 2.67 for the presence of IBP (133). This implies that high resolution US might be useful in the assessment of SIJ involvement in SpA especially when IBP is present. Ultrasonographic detection of SIJ effusion is easy to perform, requires only standard and not sophisticated US equipment, and is an inexpensive tool suggesting that this diagnostic method could represent a relevant tool in clinical practice. Nevertheless, the value of US as a routine diagnostic tool for IBP due to sacroiliitis has to be further confirmed by future studies.

3.5. Ultrasonography in Spondylolisthesis

Spondylolisthesis refers to slipping of a vertebra relative to an adjacent vertebra. Early detection of progressive disease by repeated radiologic evaluation is a key factor in the successful management of this entity (134, 135). However, the relatively high cumulative radiation dose of long-term follow-up is of concern especially in pediatric patients (134). Ultrasound has the advantage of being devoid of harmful effects of radiation and could be easily used by the physician for repetitive follow-ups of spondylolisthesis. It was shown that ultrasonic measurement of vertebral dislocation has a mean error of only 1.3 mm (range 0-3 mm) and a high correlation (r = 0.976, P < 0.001) with X-ray in the measurement of degree of slip (134). Therefore, it appears that the accuracy of ultrasonography should be sufficient for clinical use. However, at the moment there is only limited evidence to support the use of ultrasound

in serial follow-up of spondylolisthesis. Future studies will elucidate the role of ultrasound in the management of spondylolisthesis.

3.6. Ultrasonography and Transabdominal Muscles

The role of transverse abdominal muscle (TrA) in LBP has been thoroughly investigated over the past decade. The first clues to biomechanical involvement of TrA in patients with LBP were reports that demonstrated TrA muscle contracts prior to limb movement in asymptomatic subjects (66, 136, 137), while such response was delayed in patients with LBP (138). Alteration in motor control of the abdominal muscles, particularly TrA, in patients with LBP was reported to cause the delay (139). It was therefore concluded that TrA may play an essential role in the stability of spinal column, and thereby in LBP (140). These findings were further confirmed by finding that TrA strengthening exercises reduce the pain intensity in patients with LBP (141, 142). Moreover, an asymmetric pattern for TrA muscle thickness (143) and an asymmetric increase in TrA thickness in patients with LBP (144) provided additional evidence of TrA derangements in development of LBP. Studies that investigated transabdominal muscles using US are presented in Table 2.

The reliability of US in measuring TrA thickness in LBP has been extensively tested (145); according to Hodges et al. (146) US has an acceptable reliability in the measurement of TrA thickness if the transducer is positioned in the right place using a belt. This method of transducer fixation has also shown to have reasonable intra-class correlation co-efficient for measurement of abdominal muscle thickness during active tasks (147). Furthermore, it was found that US is also a reliable way in measuring the controlled contraction of TrA thickness (51, 148-150). It was demonstrated that there is a linear relation between level of contraction (measured by EMG) and thickness of TrA in up to 30-40% of MVIC of TrA (151, 152).

In a nutshell, it appears that the TrA dysfunction plays a major role in development and increase of severity of LBP. Ultrasound proved to be a reliable tool in the measurement of TrA thickness and contraction. However, well-controlled and better designed prospective studies are required to understand the role of ultrasound measurement of TrA thickness and/activity in prediction of LBP in predisposed patients.

4. Conclusions

Ultrasonography has been used widely in diagnosis and even rehabilitation of patients with LBP; however, lack of conclusive evidence to generalize the use of ultrasonography in clinical setting cannot be dismissed. While the first researches on employing ultrasound in diagnosis of patients with LBP had been focused on spinal canal diameter, recent studies have been mostly performed to evaluate the role of transabdominal and paraspinal muscles on core stability and thereby LBP occurrence.

Table 2. Details of Studies Using Ultrasound for Evaluation of Abdominal Wall Muscles [a]

Author	Year	Subject (No.)	Measuring Elements (Muscle)	Probe Position	Subjects position	Results
Bunce et al. (145)	2002	Healthy (22)	TrA	The transducer was located between the 12th rib and the iliac crest over the antero-lateral abdominal wall.	1: Supine 2: Standing 3: Walking on treadmill	US was found as a reliable way for measurement of TrA thickness.
Critchley (142)	2002	Healthy (28)	EO, IO, TrA	Transducer was located at a point 2.5 cm anterior to the midpoint between the ribs and ilium between on the mid-axillary line.	Low abdominal hollowing in four-point kneeling with and without pelvic floor contraction.	Co-contraction of pelvic floor with abdominal hollowing-in maneuver may lead to greater increase of TrA thickness compared to abdominal hollowing-in maneuver alone.
Kidd et al. (148)	2002	Healthy (11)	TrA	Not Stated	Lying and standing; no more details are described.	US imaging provides a reliable measure of controlled contraction of TrA.
Hodges (151)	2003	LBP (3)	EO, IO, TrA	The transducer was placed transversely midway between the iliac crest and inferior border of the rib cage and with the medial edge 10 cm from the midline.	The subjects had to sit in a reclining chair when their hips were flexed to approximately 30°.	In terms of muscle activity US seems to detect low levels of muscle activity. Moderated and high muscle activity cannot be distinguished employing US.
Ferreira et al. (144)	2004	Healthy/LBP (10/10)	EO, IO, TrA	The transducer was placed transversely across the abdominal wall along a line midway between the inferior angle of the rib cage and the iliac crest.	Supine with arms crossed over the chest, the hips flexed to 50°, and knees flexed to 90°.	A positive correlation between EMG and US findings in those with and without LBP was found. Also changes in TrA control in patients with LBP comparing to other group was concluded.
McMeeken et al. (152)	2004	Healthy (13)	TrA	25 mm antero-medial to the midpoint between the ribs and ilium on the mid axillary line and parallel to transversus abdominis.	Supine with a pillow under the head and the knees bent to approximately 20° over two pillows.	Reliability of US measurements as well as a positive correlation between US and EMG findings were reported in this study.
Teyhen et al. (149)	2005	LBP (30)	EO, IO, TrA	The transducer was placed in a transverse plane just superior to the left iliac crest along the axillary line.	1: Quadruped. 2: Seated.3: Supine.4: Hook-lying.	A high inter-reliability for transabdominal muscle measurement of those with and without LBP was achieved. Short-term abdominal drawing in maneuver did not influence the thickness of TrA.
Ainscough-Potts et al. (153)	2006	Healthy (30)	IO, TrA	The transducer was placed on the skin halfway between the anterior or superior or iliac spine and the lower rib cage in the anterior axillary line.	1: Supine lying. 2: Relaxed sitting on a chair.3: Relaxed sitting on a gym ball with both feet on the ground. 4: sitting on a gym ball lifting the left foot.	There was no difference in muscle thickness between relaxed sitting on chair and sitting on a gym ball. At the end of aspiration the muscles were thicker.
Hides et al. (150)	2006	Healthy (13)	IO, TrA	A transverse image of the anterolateral abdominal wall was obtained just inferior to the level of the umbilicus for left and right sides.	Supine	There was a positive correlation between MRI and US findings in measurement of IO and TrA. Anterior abdominal fascia of TrA moved laterally during weight bearing.
Rankin et al. (154)	2006	Healthy (123)	EO, IO, TrA, RA	1: Immediately below the rib-cage in direct vertical alignment with the ASIS. 2: Halfway along a line joining the ASIS to just below the ribcage in the mid-axillary line.	Subjects lay supine with two pillows under their knees	In terms of relative thickness of the muscles the pattern was as follows: RA > IO > EO > TrA. There was no asymmetry for all muscles relative thickness.
Springer et al. (143)	2006	Healthy (32)	EO, IO, TrA	The center of the transducer was placed in a transverse plane just superior to the iliac crest, in line with the mid-axillary line.	Bilaterally while the subjects were at rest, and while they performed the abdominal drawing-in maneuver.	Bilateral symmetry in the lateral abdominal muscles in those without LBP.
Hides et al. (155)	2007	Healthy (19)	IO, TrA	The transducer was along a line midway between the inferior angle of the rib cage and the iliac crest for left and right sides.	Supine with their right heel against a footplate linked to a force transducer. Each subject performed a static simulated weight-bearing task of the right lower extremity.	A greater TrA than IO thickness was found. There was no significant differences between right and left abdominal muscles.
Hides et al. (156)	2007	Healthy (19)	IO, TrA	The transducer was along a line midway between the inferior angle of the rib cage and the iliac crest.	Supine hook-lying position, with their hips in 45° of flexion.	RUSI showed a high reliability in three measurements and also a fair to high reliability was stated across two days.

Kiesel et al. (157)	2007	Healthy/LBP (20/56)	TrA	The transducer placed along the lateral abdominal wall, just superior to the iliac crest, along the midaxillary line.	Supine hook-lying position	TrA muscle thickness significantly changed during the abdominal drawing-in maneuver.
Raney et al. (158)	2007	LBP (9)	IO, TrA	The transducer was superior to the iliac crest, along the right mid-axillary line in the transverse plane.	Cases were positioned in the supine hook-lying position.	In 6 of 9 patients increased ability to improve TrA thickness during draw-ing-in maneuver was demonstrated. The thickness of TrA at rest decreased in 5 patients. This decrease was also noted in IO muscle in 4 of the patients.
Kiesel et al. (159)	2008	Healthy (6)	TrA	the transducer was placed just superior to the iliac crest along the axillary line.	Supine hook lying position	TrA thickness changed during the abdominal draw-in activity. In terms of thickness changes, control group with pain was significantly different to no pain group.
Mannion et al. (160)	2008	Healthy/LBP (14/14)	EO, IO, TrA	The transducer was positioned 2.5 cm anteromedial to the mid-point between the iliac crest and the costal margin on the mid-axillary line.	Supine hook-lying position (hips in 30° flexion)	Using US there was no significant between-day differences in thickness of any muscle during rest and hollowing.
Hides et al. (139)	2009	Healthy/LBP (20/20)	IO, TrA	Midway between the inferior angle of the rib cage and the iliac crest of both sides.	Supine, lying on a near-frictionless surface with the heel of the test limb resting on a foot plate.	Impairment of TrA and IO contraction in those without LBP in comparison to those with LBP.
Koppen-haver et al. (161)	2009	LBP (30)	TrA	The transducer positioned just superior to the iliac crest along the midaxillary line.	Supine, with hips and knees extended at rest and were instructed to "raise your leg off of the table approximately 8 inches (20 cm) without bending your knee".	RUSI showed to be a reliable method to measure TrA thickness based on the mean of two measures. A high reliability was demonstrated when the measures were taken by a single examiner, and the reliability employing different examiners was also adequate.
Reeve and Dilley (140)	2009	Healthy (20)	TrA	between the iliac crest and the lowest rib along the anterior axillary line.	1: supine lying, 2: erect sitting, 3: slouched sitting, 4: erect standing, 5: sway-back standing.	Posture may influence the measured thickness of TrA using US.
Kordi et al. (162)	2011	Healthy (63)	EO, IO, TrA	1: A point 25 mm anteromedial at the midpoint between the inferior rib and the iliac crest to the mid-axillary line. 2: A point immediately under the rib cage in direct vertical alignment with the ASIS.	Subjects were positioned in a crook-lying position with pillows under the head and the knees.	After food consumption thickness values significantly reduced in all measured abdominal muscles.
Noormo-hammad-pour et al. (163)	2012	Healthy (19)	EO, IO, TrA	Transducer was at A point 25 mm anteromedial to the mid-point between the inferior rib and the iliac crest on the mid-axillary line.	Crook lying position while pillows were placed under their head and knees.	After 12 weeks of concurrent energy restricted diet and abdominal resistance training increase in muscle thickness during drawing-in maneuver was demonstrated.
Rostami et al. (164)	2013	Healthy (90)	EO, IO, TrA	The point of probe position was set at 25 mm anteromedial to the midpoint between the inferior rib and the iliac crest on the mid-axillary line, as it was previously used in other studies.	Supine hook lying position (supine position with hips flexes to almost 30°) where small pillows were laid under their knees and head.	A significant positive relation was found between EO thickness and weight, mass index, waist circumference and skin fold thickness. IO muscle thickness decreased with higher values of mass index, waist circumference and skin fold thickness but weight did not have a significant correlation with IO thickness. These measurements of fatness showed no significant relation to TrA thickness.

^a Abbreviations: ASIS, anterior superior iliac spine; EO, external oblique muscle; IO, internal oblique muscle; LBP, low back pain; RA, rectus abdominis muscles; RUSI, rehabilitative ultrasound imaging; TrA, transverse abdominis muscles; US, ultrasound.

Use of ultrasonography in the measurement of transabdominal muscles particularly TrA has led to findings which can be employed in rehabilitation of patients as a curative procedure. The rehabilitation would be established for the patients via biofeedback. It seems more controlled imaging studies should be carried out to recommend strengthening of transabdominal muscles in LBP treatment.

RUSI assessment of LM as the predominantly affected muscle in LBP is of clinical importance in diagnosis of LBP. Impaired morphology of LM has been investigated both in acute and chronic LBP. Atrophy and infiltration of fatty tissue into the muscle are seen in LM of individuals suffering LBP. The validity and reliability of US for this purpose, however, remains to be specified in future studies. US can also be used to evaluate functional impairments in muscle contraction in addition to morphological abnormalities. The use of USI for observation of contraction of paraspinal muscles which is reduced during chronic LBP has been recently validated.

On the other side, Doppler ultrasonography has recently played an important role in objective measurement of joint laxity as a common etiology for LBP. It was proposed that large difference in TU, obtained by DIV, between sacrum and ilium indicates a joint laxity and a smaller space in obtained view or an absence of it is an

indicator of a stiff joint. However conclusions based on measurements with DIV should be made with great care until future studies further validate the technique. There are also studies implying usefulness of US in assessment of SIJ in SpA especially when IBP is present. CDUS with microbubble contrast agent has been recently shown to be beneficial in diagnosis of sacroiliitis in light of detection of increased vascularity in inflamed joints. Nevertheless, in case of using Doppler ultrasonography easiness and inexpensiveness of usage cannot be well mentioned.

Doppler imaging also in pregnant patients with LBP has been recommended as a safe and sensitive method. However, it should be noted that there is only limited evidence regarding the use of US in spondylolisthesis and this method has not yet been widely used in clinical practice. As conclusion, according to recent and most prestigious studies, focusing more on transabdominal muscle thickness can be considered as future approach in investigations.

References

1. Bressler HB, Keyes WJ, Rochon PA, Badley E. The prevalence of low back pain in the elderly. A systematic review of the literature. *Spine (Phila Pa 1976)*. 1999;**24**(17):1813–9.
2. Walker BF. The prevalence of low back pain: a systematic review of the literature from 1966 to 1998. *J Spinal Disord*. 2000;**13**(3):205–17.
3. Horvath G, Koroknai G, Acs B, Than P, Illes T. Prevalence of low back pain and lumbar spine degenerative disorders. Questionnaire survey and clinical-radiological analysis of a representative Hungarian population. *Int Orthop*. 2010;**34**(8):1245–9.
4. Manchikanti L. Epidemiology of low back pain. *Pain Physician*. 2000;**3**(2):167–92.
5. Dunn KM, Croft PR. Epidemiology and natural history of low back pain. *Eura Medicophys*. 2004;**40**(1):9–13.
6. Licciardone JC. The epidemiology and medical management of low back pain during ambulatory medical care visits in the United States. *Osteopath Med Prim Care*. 2008;**2**:11.
7. Freburger JK, Holmes GM, Agans RP, Jackman AM, Darter JD, Wallace AS, et al. The rising prevalence of chronic low back pain. *Arch Intern Med*. 2009;**169**(3):251–8.
8. Urquhart DM, Bell R, Cicuttini FM, Cui J, Forbes A, Davis SR. Low back pain and disability in community-based women: prevalence and associated factors. *Menopause*. 2009;**16**(1):24–9.
9. Pellise F, Balague F, Rajmil L, Cedraschi C, Aguirre M, Fontecha CG, et al. Prevalence of low back pain and its effect on health-related quality of life in adolescents. *Arch Pediatr Adolesc Med*. 2009;**163**(1):65–71.
10. Ansari NN, Hasson S, Naghdi S, Keyhani S, Jalaie S. Low back pain during pregnancy in Iranian women: Prevalence and risk factors. *Physiother Theory Pract*. 2010;**26**(1):40–8.
11. Louw QA, Morris LD, Grimmer-Somers K. The prevalence of low back pain in Africa: a systematic review. *BMC Musculoskelet Disord*. 2007;**8**:105.
12. Oksuz E. Prevalence, risk factors, and preference-based health states of low back pain in a Turkish population. *Spine (Phila Pa 1976)*. 2006;**31**(25):E968–72.
13. Barrero LH, Hsu YH, Terwedow H, Perry MJ, Dennerlein JT, Brain JD, et al. Prevalence and physical determinants of low back pain in a rural Chinese population. *Spine (Phila Pa 1976)*. 2006;**31**(23):2728–34.
14. Gilgil E, Kacar C, Butun B, Tuncer T, Urhan S, Yildirim C, et al. Prevalence of low back pain in a developing urban setting. *Spine (Phila Pa 1976)*. 2005;**30**(9):1093–8.
15. Chou R, Qaseem A, Snow V, Casey D, Cross JT, Jr., Shekelle P, et al. Diagnosis and treatment of low back pain: a joint clinical practice guideline from the American College of Physicians and the American Pain Society. *Ann Intern Med*. 2007;**147**(7):478–91.
16. Carragee EJ, Hannibal M. Diagnostic evaluation of low back pain. *Orthop Clin North Am*. 2004;**35**(1):7–16.
17. Chhem RK, Kaplan PA, Dussault RG. Ultrasonography of the musculoskeletal system. *Radiol Clin North Am*. 1994;**32**(2):275–89.
18. Barnett SB, Ter Haar GR, Ziskin MC, Rott HD, Duck FA, Maeda K. International recommendations and guidelines for the safe use of diagnostic ultrasound in medicine. *Ultrasound Med Biol*. 2000;**26**(3):355–66.
19. Vasseljen O, Fladmark AM, Westad C, Torp HG. Onset in abdominal muscles recorded simultaneously by ultrasound imaging and intramuscular electromyography. *J Electromyogr Kinesiol*. 2009;**19**(2):e23–31.
20. Costa LO, Maher CG, Latimer J, Hodges PW, Shirley D. An investigation of the reproducibility of ultrasound measures of abdominal muscle activation in patients with chronic non-specific low back pain. *Eur Spine J*. 2009;**18**(7):1059–65.
21. Costa LO, Maher CG, Latimer J, Smeets RJ. Reproducibility of rehabilitative ultrasound imaging for the measurement of abdominal muscle activity: a systematic review. *Phys Ther*. 2009;**89**(8):756–69.
22. Hebert JJ, Koppenhaver SL, Parent EC, Fritz JM. A systematic review of the reliability of rehabilitative ultrasound imaging for the quantitative assessment of the abdominal and lumbar trunk muscles. *Spine (Phila Pa 1976)*. 2009;**34**(23):E848–56.
23. Langevin HM, Stevens-Tuttle D, Fox JR, Badger GJ, Bouffard NA, Krag MH, et al. Ultrasound evidence of altered lumbar connective tissue structure in human subjects with chronic low back pain. *BMC Musculoskelet Disord*. 2009;**10**:151.
24. Porter RW, Wicks M, Ottewell D. Measurement of the spinal canal by diagnostic ultrasound. *J Bone Joint Surg Br*. 1978;**60-B**(4):481–4.
25. Chovil AC, Anderson DJ, Adcock DF. Ultrasonic measurement of lumbar canal diameter: a screening tool for low back disorders? *South Med J*. 1989;**82**(8):977–80.
26. Porter RW, Hibbert CS, Wicks M. The spinal canal in symptomatic lumbar disc lesions. *J Bone Joint Surg Br*. 1978;**60-B**(4):485–7.
27. Porter RW, Hibbert C, Wellman P. Backache and the lumbar spinal canal. *Spine (Phila Pa 1976)*. 1980;**5**(2):99–105.
28. Porter RW, Drinkall JN, Porter DE, Thorp L. The vertebral canal: II. Health and academic status, a clinical study. *Spine (Phila Pa 1976)*. 1987;**12**(9):907–11.
29. Macdonald EB, Porter R, Hibbert C, Hart J. The relationship between spinal canal diameter and back pain in coal miners. Ultrasonic measurement as a screening test? *J Occup Med*. 1984;**26**(1):23–8.
30. Anderson DJ, Adcock DF, Chovil AC, Farrell JJ. Ultrasound lumbar canal measurement in hospital employees with back pain. *Br J Ind Med*. 1988;**45**(8):552–5.
31. Macdonald EB, Anderson JA, Dales JL. Ultrasonic measurement of spinal canal. *Br Med J (Clin Res Ed)*. 1984;**288**(6422):1010.
32. Legg SJ, Gibbs V. Measurement of the lumbar spinal canal by echo ultrasound. *Spine (Phila Pa 1976)*. 1984;**9**(1):79–82.
33. Macdonald EB. Ultrasonic measurement of the lumbar spinal canal. *J Occup Med*. 1984;**26**(6):412.
34. Howie DW, Chatterton BE, Hone MR. Failure of ultrasound in the investigation of sciatica. *J Bone Joint Surg Br*. 1983;**65**(2):144–7.
35. Battie MC, Hansson TH, Engel JM, Zeh J, Bigos SJ, Spengler DM. The reliability of measurements of the lumbar spine using ultrasound B-scan. *Spine (Phila Pa 1976)*. 1986;**11**(2):144–8.
36. Missere M, Natale S, Maria AC, Sicuranza G, Raffi GB. Use of ultrasound in occupational risk assessment of low-back pain. *Arh Hig Rada Toksikol*. 1999;**50**(2):189–92.
37. Tervonen O, Koivukangas J. Transabdominal ultrasound measurement of the lumbar spinal canal. Its value for evaluation of lumbar spinal stenosis. *Spine (Phila Pa 1976)*. 1989;**14**(2):232–5.
38. Battie MC, Hansson T, Bigos S, Zeh J, Fisher L, Spengler D. B-scan ultrasonic measurement of the lumbar spinal canal as a predictor of industrial back pain complaints and extended work loss. *J Occup Med*. 1993;**35**(12):1250–5.
39. Porter RW, Bewley B. A ten-year prospective study of vertebral canal size as a predictor of back pain. *Spine (Phila Pa 1976)*. 1994;**19**(2):173–5.
40. Lucas DB. *Bresler, Stability of the ligamentous spine.* University of California San Francisco Biomechanics Laboratory Report; 1961.

41. Panjabi M, Abumi K, Duranceau J, Oxland T. Spinal stability and intersegmental muscle forces. A biomechanical model. *Spine (Phila Pa 1976).* 1989;**14**(2):194–200.

42. Panjabi MM. The stabilizing system of the spine. Part I. Function, dysfunction, adaptation, and enhancement. *J Spinal Disord.* 1992;**5**(4):383–9.

43. Quint U, Wilke HJ, Shirazi-Adl A, Parnianpour M, Loer F, Claes LE. Importance of the intersegmental trunk muscles for the stability of the lumbar spine. A biomechanical study in vitro. *Spine (Phila Pa 1976).* 1998;**23**(18):1937–45.

44. Wilke HJ, Wolf S, Claes LE, Arand M, Wiesend A. Stability increase of the lumbar spine with different muscle groups. A biomechanical in vitro study. *Spine (Phila Pa 1976).* 1995;**20**(2):192–8.

45. Bierry G, Kremer S, Kellner F, Abu Eid M, Bogorin A, Dietemann JL. Disorders of paravertebral lumbar muscles: from pathology to cross-sectional imaging. *Skeletal Radiol.* 2008;**37**(11):967–77.

46. Hides JA, Cooper DH, Stokes MJ. Diagnostic Ultrasound Imaging for Measurement of the Lumbar Multifidus Muscle in Normal Young Adults. *Physiother Theory and Pract.* 1992;**8**(1):19–26.

47. Hides JA, Stokes MJ, Saide M, Jull GA, Cooper DH. Evidence of lumbar multifidus muscle wasting ipsilateral to symptoms in patients with acute/subacute low back pain. *Spine (Phila Pa 1976).* 1994;**19**(2):165–72.

48. Stokes M, Rankin G, Newham DJ. Ultrasound imaging of lumbar multifidus muscle: normal reference ranges for measurements and practical guidance on the technique. *Man Ther.* 2005;**10**(2):116–26.

49. Hides JA, Richardson CA, Jull GA. Magnetic resonance imaging and ultrasonography of the lumbar multifidus muscle. Comparison of two different modalities. *Spine (Phila Pa 1976).* 1995;**20**(1):54–8.

50. Stokes M, Hides J, Elliott J, Kiesel K, Hodges P. Rehabilitative ultrasound imaging of the posterior paraspinal muscles. *J Orthop Sports Phys Ther.* 2007;**37**(10):581–95.

51. Wallwork TL, Hides JA, Stanton WR. Intrarater and interrater reliability of assessment of lumbar multifidus muscle thickness using rehabilitative ultrasound imaging. *J Orthop Sports Phys Ther.* 2007;**37**(10):608–12.

52. Kiesel KB, Uhl TL, Underwood FB, Rodd DW, Nitz AJ. Measurement of lumbar multifidus muscle contraction with rehabilitative ultrasound imaging. *Man Ther.* 2007;**12**(2):161–6.

53. Portney LG, Watkins MP. *Foundations of Clinical Research: Applications to Practice.* London: Prentice Hall Health; 2000.

54. Teyhen DS, George SZ, Dugan JL, Williamson J, Neilson BD, Childs JD. Inter-rater reliability of ultrasound imaging of the trunk musculature among novice raters. *J Ultrasound Med.* 2011;**30**(3):347–56.

55. Hides J, Richardson C, Jull G, Davies S. Ultrasound imaging in rehabilitation. *Aust J Physiother.* 1995;**41**(3):187–93.

56. Kader DF, Wardlaw D, Smith FW. Correlation between the MRI changes in the lumbar multifidus muscles and leg pain. *Clin Radiol.* 2000;**55**(2):145–9.

57. Barker KL, Shamley DR, Jackson D. Changes in the cross-sectional area of multifidus and psoas in patients with unilateral back pain: the relationship to pain and disability. *Spine (Phila Pa 1976).* 2004;**29**(22):E515–9.

58. Wallwork TL, Stanton WR, Freke M, Hides JA. The effect of chronic low back pain on size and contraction of the lumbar multifidus muscle. *Man Ther.* 2009;**14**(5):496–500.

59. Lee SW, Chan CK, Lam TS, Lam C, Lau NC, Lau RW, et al. Relationship between low back pain and lumbar multifidus size at different postures. *Spine (Phila Pa 1976).* 2006;**31**(19):2258–62.

60. Pope MH, Bevins T, Wilder DG, Frymoyer JW. The relationship between anthropometric, postural, muscular, and mobility characteristics of males ages 18-55. *Spine (Phila Pa 1976).* 1985;**10**(7):644–8.

61. Mengiardi B, Schmid MR, Boos N, Pfirrmann CW, Brunner F, Elfering A, et al. Fat content of lumbar paraspinal muscles in patients with chronic low back pain and in asymptomatic volunteers: quantification with MR spectroscopy. *Radiology.* 2006;**240**(3):786–92.

62. Kjaer P, Bendix T, Sorensen JS, Korsholm L, Leboeuf-Yde C. Are MRI-defined fat infiltrations in the multifidus muscles associated with low back pain? *BMC Med.* 2007;**5**:2.

63. Mayer TG, Vanharanta H, Gatchel RJ, Mooney V, Barnes D, Judge L, et al. Comparison of CT scan muscle measurements and isokinetic trunk strength in postoperative patients. *Spine (Phila Pa 1976).* 1989;**14**(1):33–6.

64. Parkkola R, Rytokoski U, Kormano M. Magnetic resonance imaging of the discs and trunk muscles in patients with chronic low back pain and healthy control subjects. *Spine (Phila Pa 1976).* 1993;**18**(7):830–6.

65. Hides JA, Richardson CA, Jull GA. Multifidus muscle recovery is not automatic after resolution of acute, first-episode low back pain. *Spine (Phila Pa 1976).* 1996;**21**(23):2763–9.

66. Hodges PW, Richardson CA. Feedforward contraction of transversus abdominis is not influenced by the direction of arm movement. *Exp Brain Res.* 1997;**114**(2):362–70.

67. Zedka M, Prochazka A, Knight B, Gillard D, Gauthier M. Voluntary and reflex control of human back muscles during induced pain. *J Physiol.* 1999;**520 Pt 2**:591–604.

68. Kennelly KP, Stokes MJ. Pattern of asymmetry of paraspinal muscle size in adolescent idiopathic scoliosis examined by real-time ultrasound imaging. A preliminary study. *Spine (Phila Pa 1976).* 1993;**18**(7):913–7.

69. Eisele R, Schmid R, Kinzl L, Kramer M, Katzmaier P, Hartwig E. Soft tissue texture analysis by B-mode-ultrasound in the evaluation of impairment in chronic low back pain. *Eur J Ultrasound.* 1998;**8**(3):167–75.

70. Coldron Y, Stokes M, Cook K. Lumbar multifidus muscle size does not differ whether ultrasound imaging is performed in prone or side lying. *Man Ther.* 2003;**8**(3):161–5.

71. Pressler JF, Heiss DG, Buford JA, Chidley JV. Between-day repeatability and symmetry of multifidus cross-sectional area measured using ultrasound imaging. *J Orthop Sports Phys Ther.* 2006;**36**(1):10–8.

72. Vasseljen O, Dahl HH, Mork PJ, Torp HG. Muscle activity onset in the lumbar multifidus muscle recorded simultaneously by ultrasound imaging and intramuscular electromyography. *Clin Biomech (Bristol, Avon).* 2006;**21**(9):905–13.

73. Hides JA, Stanton WR, McMahon S, Sims K, Richardson CA. Effect of stabilization training on multifidus muscle cross-sectional area among young elite cricketers with low back pain. *J Orthop Sports Phys Ther.* 2008;**38**(3):101–8.

74. Hides J, Gilmore C, Stanton W, Bohlscheid E. Multifidus size and symmetry among chronic LBP and healthy asymptomatic subjects. *Man Ther.* 2008;**13**(1):43–9.

75. Dickx N, Cagnie B, Parlevliet T, Lavens A, Danneels L. The effect of unilateral muscle pain on recruitment of the lumbar multifidus during automatic contraction. An experimental pain study. *Man Ther.* 2010;**15**(4):364–9.

76. Worsley PR, Smith N, Warner MB, Stokes M. Ultrasound transducer shape has no effect on measurements of lumbar multifidus muscle size. *Man Ther.* 2012;**17**(2):187–91.

77. Bernard TN, Jr., Kirkaldy-Willis WH. Recognizing specific characteristics of nonspecific low back pain. *Clin Orthop Relat Res.* 1987(217):266–80.

78. Fortin JD, Aprill CN, Ponthieux B, Pier J. Sacroiliac joint: pain referral maps upon applying a new injection/arthrography technique. Part II: Clinical evaluation. *Spine (Phila Pa 1976).* 1994;**19**(13):1483–9.

79. Pool-Goudzwaard A, Hoek van Dijke G, Mulder P, Spoor C, Snijders C, Stoeckart R. The iliolumbar ligament: its influence on stability of the sacroiliac joint. *Clin Biomech (Bristol, Avon).* 2003;**18**(2):99–105.

80. Sims JA, Moorman SJ. The role of the iliolumbar ligament in low back pain. *Med Hypotheses.* 1996;**46**(6):511–5.

81. Snijders CJ, Vleeming A, Stoeckart R. Transfer of lumbosacral load to iliac bones and legs Part 1: Biomechanics of self-bracing of the sacroiliac joints and its significance for treatment and exercise. *Clin Biomech (Bristol, Avon).* 1993;**8**(6):285–94.

82. Schwarzer AC, Aprill CN, Bogduk N. The sacroiliac joint in chronic low back pain. *Spine (Phila Pa 1976).* 1995;**20**(1):31–7.

83. van der Wurff P, Meyne W, Hagmeijer RH. Clinical tests of the sacroiliac joint. *Man Ther.* 2000;**5**(2):89–96.

84. Dreyfuss P, Michaelsen M, Pauza K, McLarty J, Bogduk N. The value of medical history and physical examination in diagnosing sac-

roiliac joint pain. *Spine (Phila Pa 1976)*. 1996;**21**(22):2594–602.

85. Slipman CW, Sterenfeld EB, Chou LH, Herzog R, Vresilovic E. The predictive value of provocative sacroiliac joint stress maneuvers in the diagnosis of sacroiliac joint syndrome. *Arch Phys Med Rehabil*. 1998;**79**(3):288–92.

86. Buyruk HM, Stam HJ, Snijders CJ, Vleeming A, Lameris JS, Holland WP. The use of color Doppler imaging for the assessment of sacroiliac joint stiffness: a study on embalmed human pelvises. *Eur J Radiol*. 1995;**21**(2):112–6.

87. Buyruk HM, Snijders CJ, Vleeming A, Lameris JS, Holland WP, Stam HJ. The measurements of sacroiliac joint stiffness with colour Doppler imaging: a study on healthy subjects. *Eur J Radiol*. 1995;**21**(2):117–21.

88. Buyruk HM, Stam HJ, Snijders CJ, Lameris JS, Holland WP, Stijnen TH. Measurement of sacroiliac joint stiffness in peripartum pelvic pain patients with Doppler imaging of vibrations (DIV). *Eur J Obstet Gynecol Reprod Biol*. 1999;**83**(2):159–63.

89. Damen L, Buyruk HM, Guler-Uysal F, Lotgering FK, Snijders CJ, Stam HJ. Pelvic pain during pregnancy is associated with asymmetric laxity of the sacroiliac joints. *Acta Obstet Gynecol Scand*. 2001;**80**(11):1019–24.

90. Damen L, Buyruk HM, Guler-Uysal F, Lotgering FK, Snijders CJ, Stam HJ. The prognostic value of asymmetric laxity of the sacroiliac joints in pregnancy-related pelvic pain. *Spine (Phila Pa 1976)*. 2002;**27**(24):2820–4.

91. Damen L, Spoor CW, Snijders CJ, Stam HJ. Does a pelvic belt influence sacroiliac joint laxity? *Clin Biomech (Bristol, Avon)*. 2002;**17**(7):495–8.

92. Damen L, Stijnen T, Roebroeck ME, Snijders CJ, Stam HJ. Reliability of sacroiliac joint laxity measurement with Doppler imaging of vibrations. *Ultrasound Med Biol*. 2002;**28**(4):407–14.

93. Kristiansson P, Svardsudd K, von Schoultz B. Back pain during pregnancy: a prospective study. *Spine (Phila Pa 1976)*. 1996;**21**(6):702–9.

94. Larsen EC, Wilken-Jensen C, Hansen A, Jensen DV, Johansen S, Minck H, et al. Symptom-giving pelvic girdle relaxation in pregnancy. I: Prevalence and risk factors. *Acta Obstet Gynecol Scand*. 1999;**78**(2):105–10.

95. Noren L, Ostgaard S, Nielsen TF, Ostgaard HC. Reduction of sick leave for lumbar back and posterior pelvic pain in pregnancy. *Spine (Phila Pa 1976)*. 1997;**22**(18):2157–60.

96. Orvieto R, Achiron A, Ben-Rafael Z, Gelernter I, Achiron R. Low-back pain of pregnancy. *Acta Obstet Gynecol Scand*. 1994;**73**(3):209–14.

97. Ostgaard HC, Andersson GB, Karlsson K. Prevalence of back pain in pregnancy. *Spine (Phila Pa 1976)*. 1991;**16**(5):549–52.

98. Svensson HO, Andersson GB, Hagstad A, Jansson PO. The relationship of low-back pain to pregnancy and gynecologic factors. *Spine (Phila Pa 1976)*. 1990;**15**(5):371–5.

99. Turgut F, Turgut M, Cetinsahin M. A prospective study of persistent back pain after pregnancy. *Eur J Obstet Gynecol Reprod Biol*. 1998;**80**(1):45–8.

100. Mens JM, Vleeming A, Stoeckart R, Stam HJ, Snijders CJ. Understanding peripartum pelvic pain. Implications of a patient survey. *Spine (Phila Pa 1976)*. 1996;**21**(11):1363–9.

101. Endresen EH. Pelvic pain and low back pain in pregnant women-an epidemiological study. *Scand J Rheumatol*. 1995;**24**(3):135–41.

102. Fast A, Shapiro D, Ducommun EJ, Friedmann LW, Bouklas T, Floman Y. Low-back pain in pregnancy. *Spine (Phila Pa 1976)*. 1987;**12**(4):368–71.

103. Fast A, Weiss L, Ducommun EJ, Medina E, Butler JG. Low-back pain in pregnancy. Abdominal muscles, sit-up performance, and back pain. *Spine (Phila Pa 1976)*. 1990;**15**(1):28–30.

104. Mens JM, Vleeming A, Snijders CJ, Ronchetti I, Stam HJ. Reliability and validity of hip adduction strength to measure disease severity in posterior pelvic pain since pregnancy. *Spine (Phila Pa 1976)*. 2002;**27**(15):1674–9.

105. Wergeland E, Strand K. Work pace control and pregnancy health in a population-based sample of employed women in Norway. *Scand J Work Environ Health*. 1998;**24**(3):206–12.

106. Perkins J, Hammer RL, Loubert PV. Identification and management of pregnancy-related low back pain. *J Nurse Midwifery*. 1998;**43**(5):331–40.

107. Bogic LV, Mandel M, Bryant-Greenwood GD. Relaxin gene expression in human reproductive tissues by in situ hybridization. *J Clin Endocrinol Metab*. 1995;**80**(1):130–7.

108. Petersen LK, Vogel I, Agger AO, Westergard J, Nils M, Uldbjerg N. Variations in serum relaxin (hRLX-2) concentrations during human pregnancy. *Acta Obstet Gynecol Scand*. 1995;**74**(4):251–6.

109. Stewart DR, Celniker AC, Taylor CA, Jr., Cragun JR, Overstreet JW, Lasley BL. Relaxin in the peri-implantation period. *J Clin Endocrinol Metab*. 1990;**70**(6):1771–3.

110. MacLennan AH, Green RC, Grant P, Nicolson R. Ripening of the human cervix and induction of labor with intracervical purified porcine relaxin. *Obstet Gynecol*. 1986;**68**(5):598–601.

111. Ritchie JR. Orthopedic considerations during pregnancy. *Clin Obstet Gynecol*. 2003;**46**(2):456–66.

112. Fast A, Hertz G. Nocturnal low back pain in pregnancy: polysomnographic correlates. *Am J Reprod Immunol*. 1992;**28**(3-4):251–3.

113. De Troyer A, Estenne M, Ninane V, Van Gansbeke D, Gorini M. Transversus abdominis muscle function in humans. *J Appl Physiol (1985)*. 1990;**68**(3):1010–6.

114. Vleeming A, Buyruk HM, Stoeckart R, Karamursel S, Snijders CJ. An integrated therapy for peripartum pelvic instability: a study of the biomechanical effects of pelvic belts. *Am J Obstet Gynecol*. 1992;**166**(4):1243–7.

115. Whittaker J. Abdominal Ultrasound Imaging of Pelvic Floor Muscle Function in Individuals with Low Back Pain. *J Man Manip Ther*. 2004;**12**(1):44–9.

116. Ninane V, Rypens F, Yernault JC, De Troyer A. Abdominal muscle use during breathing in patients with chronic airflow obstruction. *Am Rev Respir Dis*. 1992;**146**(1):16–21.

117. Braun J, Bollow M, Remlinger G, Eggens U, Rudwaleit M, Distler A, et al. Prevalence of spondylarthropathies in HLA-B27 positive and negative blood donors. *Arthritis Rheum*. 1998;**41**(1):58–67.

118. Dougados M, van der Linden S, Juhlin R, Huitfeldt B, Amor B, Calin A, et al. The European Spondylarthropathy Study Group preliminary criteria for the classification of spondylarthropathy. *Arthritis Rheum*. 1991;**34**(10):1218–27.

119. Mau W, Zeidler H, Mau R, Majewski A, Freyschmidt J, Stangel W, et al. Clinical features and prognosis of patients with possible ankylosing spondylitis. Results of a 10-year followup. *J Rheumatol*. 1988;**15**(7):1109–14.

120. Brandt J, Bollow M, Haberle J, Rudwaleit M, Eggens U, Distler A, et al. Studying patients with inflammatory back pain and arthritis of the lower limbs clinically and by magnetic resonance imaging: many, but not all patients with sacroiliitis have spondyloarthropathy. *Rheumatology (Oxford)*. 1999;**38**(9):831–6.

121. Jarvik JG, Deyo RA. Diagnostic evaluation of low back pain with emphasis on imaging. *Ann Intern Med*. 2002;**137**(7):586–97.

122. Bollow M, Braun J, Hamm B, Eggens U, Schilling A, Konig H, et al. Early sacroiliitis in patients with spondyloarthropathy: evaluation with dynamic gadolinium-enhanced MR imaging. *Radiology*. 1995;**194**(2):529–36.

123. Braun J, Sieper J, Bollow M. Imaging of sacroiliitis. *Clin Rheumatol*. 2000;**19**(1):51–7.

124. Battafarano DF, West SG, Rak KM, Fortenbery EJ, Chantelois AE. Comparison of bone scan, computed tomography, and magnetic resonance imaging in the diagnosis of active sacroiliitis. *Semin Arthritis Rheum*. 1993;**23**(3):161–76.

125. Braun J, Bollow M, Eggens U, Konig H, Distler A, Sieper J. Use of dynamic magnetic resonance imaging with fast imaging in the detection of early and advanced sacroiliitis in spondylarthropathy patients. *Arthritis Rheum*. 1994;**37**(7):1039–45.

126. Oostveen J, Prevo R, den Boer J, van de Laar M. Early detection of sacroiliitis on magnetic resonance imaging and subsequent development of sacroiliitis on plain radiography. A prospective, longitudinal study. *J Rheumatol*. 1999;**26**(9):1953–8.

127. Guglielmi G, De Serio A, Leone A, Cammisa M. Imaging of sacroiliac joints. *Rays*. 2000;**25**(1):63–74.

128. Arslan H, Sakarya ME, Adak B, Unal O, Sayarlioglu M. Duplex and color Doppler sonographic findings in active sacroiliitis. *AJR Am J Roentgenol*. 1999;**173**(3):677–80.

129. Klauser A, Halpern EJ, Frauscher F, Gvozdic D, Duftner C, Springer P, et al. Inflammatory low back pain: high negative predictive value of contrast-enhanced color Doppler ultrasound in

the detection of inflamed sacroiliac joints. *Arthritis Rheum.* 2005;**53**(3):440–4.

130. Carotti M, Salaffi F, Manganelli P, Salera D, Simonetti B, Grassi W. Power Doppler sonography in the assessment of synovial tissue of the knee joint in rheumatoid arthritis: a preliminary experience. *Ann Rheum Dis.* 2002;**61**(10):877–82.

131. Goldberg BB, Liu JB, Forsberg F. Ultrasound contrast agents: a review. *Ultrasound Med Biol.* 1994;**20**(4):319–33.

132. Klauser A, Frauscher F, Schirmer M, Halpern E, Pallwein L, Herold M, et al. The value of contrast-enhanced color Doppler ultrasound in the detection of vascularization of finger joints in patients with rheumatoid arthritis. *Arthritis Rheum.* 2002;**46**(3):647–53.

133. Spadaro A, Iagnocco A, Baccano G, Ceccarelli F, Sabatini E, Valesini G. Sonographic-detected joint effusion compared with physical examination in the assessment of sacroiliac joints in spondyloarthritis. *Ann Rheum Dis.* 2009;**68**(10):1559–63.

134. Cresswell AG. Responses of intra-abdominal pressure and abdominal muscle activity during dynamic trunk loading in man. *Eur J Appl Physiol Occup Physiol.* 1993;**66**(4):315–20.

135. Hu SS, Tribus CB, Diab M, Ghanayem AJ. Spondylolisthesis and spondylolysis. *J Bone Joint Surg Am.* 2008;**90**(3):656–71.

136. Hodges PW, Richardson CA. Contraction of the abdominal muscles associated with movement of the lower limb. *Phys Ther.* 1997;**77**(2):132–42.

137. Hodges PW. Is there a role for transversus abdominis in lumbo-pelvic stability? *Man Ther.* 1999;**4**(2):74–86.

138. Hodges PW, Richardson CA. Inefficient muscular stabilization of the lumbar spine associated with low back pain. A motor control evaluation of transversus abdominis. *Spine (Phila Pa 1976).* 1996;**21**(22):2640–50.

139. Hides JA, Belavy DL, Cassar L, Williams M, Wilson SJ, Richardson CA. Altered response of the anterolateral abdominal muscles to simulated weight-bearing in subjects with low back pain. *Eur Spine J.* 2009;**18**(3):410–8.

140. Reeve A, Dilley A. Effects of posture on the thickness of transversus abdominis in pain-free subjects. *Man Ther.* 2009;**14**(6):679–84.

141. O'Sullivan PB, Phyty GD, Twomey LT, Allison GT. Evaluation of specific stabilizing exercise in the treatment of chronic low back pain with radiologic diagnosis of spondylolysis or spondylolisthesis. *Spine (Phila Pa 1976).* 1997;**22**(24):2959–67.

142. Critchley D. Instructing pelvic floor contraction facilitates transversus abdominis thickness increase during low-abdominal hollowing. *Physiother Res Int.* 2002;**7**(2):65–75.

143. Springer BA, Mielcarek BJ, Nesfield TK, Teyhen DS. Relationships among lateral abdominal muscles, gender, body mass index, and hand dominance. *J Orthop Sports Phys Ther.* 2006;**36**(5):289–97.

144. Ferreira PH, Ferreira ML, Hodges PW. Changes in recruitment of the abdominal muscles in people with low back pain: ultrasound measurement of muscle activity. *Spine (Phila Pa 1976).* 2004;**29**(22):2560–6.

145. Bunce SM, Moore AP, Hough AD. M-mode ultrasound: a reliable measure of transversus abdominis thickness? *Clin Biomech (Bristol, Avon).* 2002;**17**(4):315–7.

146. Hodges PW. Changes in motor planning of feedforward postural responses of the trunk muscles in low back pain. *Exp Brain Res.* 2001;**141**(2):261–6.

147. Bunce SM, Hough AD, Moore AP. Measurement of abdominal muscle thickness using M-mode ultrasound imaging during functional activities. *Man Ther.* 2004;**9**(1):41–4.

148. Kidd AW, Magee S, Richardson CA. Reliability of real-time ultrasound for the assessment of transversus abdominis function. *J Gravit Physiol.* 2002;**9**(1):P131–2.

149. Teyhen DS, Miltenberger CE, Deiters HM, Del Toro YM, Pulliam JN, Childs JD, et al. The use of ultrasound imaging of the abdominal drawing-in maneuver in subjects with low back pain. *J Orthop Sports Phys Ther.* 2005;**35**(6):346–55.

150. Hides J, Wilson S, Stanton W, McMahon S, Keto H, McMahon K, et al. An MRI investigation into the function of the transversus abdominis muscle during "drawing-in" of the abdominal wall. *Spine (Phila Pa 1976).* 2006;**31**(6):E175–8.

151. Hodges PW, Pengel LH, Herbert RD, Gandevia SC. Measurement of muscle contraction with ultrasound imaging. *Muscle Nerve.* 2003;**27**(6):682–92.

152. McMeeken JM, Beith ID, Newham DJ, Milligan P, Critchley DJ. The relationship between EMG and change in thickness of transversus abdominis. *Clin Biomech (Bristol, Avon).* 2004;**19**(4):337–42.

153. Ainscough-Potts AM, Morrissey MC, Critchley D. The response of the transverse abdominis and internal oblique muscles to different postures. *Man Ther.* 2006;**11**(1):54–60.

154. Rankin G, Stokes M, Newham DJ. Abdominal muscle size and symmetry in normal subjects. *Muscle Nerve.* 2006;**34**(3):320–6.

155. Hides JA, Wong I, Wilson SJ, Belavy DL, Richardson CA. Assessment of abdominal muscle function during a simulated unilateral weight-bearing task using ultrasound imaging. *J Orthop Sports Phys Ther.* 2007;**37**(8):467–71.

156. Hides JA, Miokovic T, Belavy DL, Stanton WR, Richardson CA. Ultrasound imaging assessment of abdominal muscle function during drawing-in of the abdominal wall: an intrarater reliability study. *J Orthop Sports Phys Ther.* 2007;**37**(8):480–6.

157. Kiesel KB, Underwood FB, Mattacola CG, Nitz AJ, Malone TR. 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 Sports Phys Ther.* 2007;**37**(10):596–607.

158. Raney NH, Teyhen DS, Childs JD. Observed Changes in Lateral Abdominal Muscle Thickness After Spinal Manipulation: A Case Series Using Rehabilitative Ultrasound Imaging. *J Orthop Sports Phys Ther.* 2007;**37**(8):472–9.

159. Kiesel KB, Uhl T, Underwood FB, Nitz AJ. Rehabilitative ultrasound measurement of select trunk muscle activation during induced pain. *Man Ther.* 2008;**13**(2):132–8.

160. Mannion AF, Pulkovski N, Gubler D, Gorelick M, O'Riordan D, Loupas T, et al. Muscle thickness changes during abdominal hollowing: an assessment of between-day measurement error in controls and patients with chronic low back pain. *Eur Spine J.* 2008;**17**(4):494–501.

161. Koppenhaver SL, Hebert JJ, Fritz JM, Parent EC, Teyhen DS, Magel JS. Reliability of rehabilitative ultrasound imaging of the transversus abdominis and lumbar multifidus muscles. *Arch Phys Med Rehabil.* 2009;**90**(1):87–94.

162. Kordi R, Rostami M, Noormohammadpour P, Mansournia MA. The effect of food consumption on the thickness of abdominal muscles, employing ultrasound measurements. *Eur Spine J.* 2011;**20**(8):1312–7.

163. Noormohammadpour P, Kordi R, Dehghani S, Rostami M. The effect of abdominal resistance training and energy restricted diet on lateral abdominal muscles thickness of overweight and obese women. *J Bodyw Mov Ther.* 2012;**16**(3):344–50.

164. Rostami M, Abedi Yekta AH, Noormohammadpour P, Farahbakhsh F, Kordi M, Kordi R. Relations between lateral abdominal muscles thickness, body mass index, waist circumference and skin fold thickness. *Acta Med Iran.* 2013;**51**(2):101–6.