Forceclosure and optimal stability of the lumbopelvic region

Andry Vleeming, Frank Willard

We have chosen to make this contribution based on the latest evidence on the force closure of the lumbopelvic region. As the anatomy and biomechanics session in this congress describes; *"This anatomy session of the congress will focus at the coherence of the passive connective tissues and active muscular structures and the relevance of their mutual interactions in relation to low-back and pelvic pain. Muscular forces are transmitted to the skeletal system through passive connective tissue structures such as tendons. The mechanical properties of this tissue thus co-determine the dynamic effects of muscle action. This is of importance as training and disuse have substantial effects on the properties of connective tissues".*

"Moments and reaction forces generated by muscles and by passive structures, such as ligaments, combine to provide equilibrium at the multiple kinematical degrees of freedom of the SI joints and lumbar intervertebral joints. The use of passive tissue contributions by allowing some movement at the joints until equilibrium is reached, might greatly simplify control of this multi-joint system. However, this strategy would imply that muscle activation patterns need to be adjusted when changes in passive stiffness occur due to movements of the joint, prolonged loading and injury.

The passive tissues interact with the muscular system in addition through their role as sensory organs, adding feedback to the control of the system. Again this function may be impaired through sustained loading or injury (van Dieen J, Vleeming A, moderators)".

General outline of the anatomy and biomechanics of the pelvis

In all quadrupeds and bipeds, the pelvic girdle forms a firm connection between the spine and the lower extremities. In bipeds, the pelvis has to serve as a basic platform with three large levers acting on it (the spine and the legs). To allow bipedal gait in humans, evolutionary adaptations of the pelvis have been necessary, i.e. changing the shape of the ilia, flaring out into the sagittal plane, providing a more optimal lateral attachment site for the gluteus medius as an important muscle for hip pelvic stability. In particular, a dramatically increased attachment site for the gluteus maximus muscle has changed this muscle – a relatively minor muscle in the chimpanzee – into one of the largest muscles of the human body (Lovejoy 1988). Thus the human pelvis evolved quite differently to that of the chimpanzee.

The human pelvis has both *external* and *internal* movements. This implicates external movement of the pelvic platform relative to the hip joints. Because of the more limited movement of the pelvis relative to the lumbar spine, the large external pelvic movements through the hip joints (like flexion and extension ab-and adduction), subsequently could force the lumbar spine also in flexion / extension and lateral flexion and rotation. Internal motion occurs both in the SIJ and in the symphysis. Additional evolutionary changes in humans are the muscular and ligamentous connections between the sacrum and ilia: (1) muscles, like the lower lumbar multifidi, that insert into the sacrum and also into the medial cranial aspects of the ilium; (2) changes in the position of the coccygeus and the piriformis muscles, and of the gluteus maximus muscle originating from the sacrum and sacrotuberous ligaments; (3) extensive fibrous connections adapted to the typical human anatomy of the SIJ, like the vast interosseous SI- ligaments, surrounding an iliac protrusion fitting in a dorsal sacral cavity, called the axial joint just behind the auricular surfaces of the SIJ (Bakland & Hansen 1984); (4) ventral and especially strong dorsal SIJ ligaments, like the sacrotuberous,sacrospinous, long dorsal and deep dorsal SIJ ligaments between sacrum and ilium. In addition, direct fibrous connections exist between the iliac bone and L4 and L5, the iliolumbar ligaments and the anterior longitudinal ligament bridging the anterior lower vertebrae. Due to the above-mentioned muscular and ligamentous connections, movement of the sacrum with respect to the iliac bones, or vice versa, affects the joints between L5–S1 and between the higher lumbar levels. Anatomical and functional impairments of the pelvis or lumbar region, influence each other. Due to the tightness of the fibrous connections and the specific architecture of the SIJ, mobility in the SIJ is normally very limited, but movement does occur and has not been scientifically challenged (Egund et al 1978, Lavignolle et al 1983, Miller et al 1987, Solonen 1957, Sturesson et al 1989, 2000a, 2000b, Vleeming et al 1990a, 1990b, 1996, Weisl 1955). The main movements in the SIJ (internal pelvic motion) are forward rotation of the sacrum relative to the iliac bones (nutation) and backward rotation of the sacrum relative to the ilia (counter nutation). It was shown that even at advanced age (> 72 years) the combined movement of nutation and counternutation can amount up to 4°; normally movements are less than 2° (Vleeming et al. 1992a). In the latter study, the SIJ with the lowest mobility showed radiologically marked arthrosis. Ankylosis of the SIJ was found to be an exception, even at advanced age. This finding is in agreement with studies of Stewart (1984) and Miller et al (1987). Nutation is increased in load-bearing situations, e.g. standing and sitting. In lying prone, nutation is also increased compared to supine positions (Egund et al 1978, Sturesson et al 1989, 2000a, 2000b, Weisl 1955). Counternutation normally occurs in unloaded situations like lying down (supine). Counter nutation in supine positions can be altered to a relative nutation by maximal flexion in the hips, using the legs as levers to posteriorly rotate the iliac bones relative to the sacrum, as in a labour position, creating space for the head of the baby during delivery. The SIJ in humans serve a purpose: Besides the very large external movement of the pelvic platform on the hips, internal movement as SIJ and symphyseal motion function as a point of transfer between the pelvis and its three levers (spine and both legs) to economize gait, to allow shock and shear absorption, and to alleviate birth of (in the evolutionary sense) abnormally large babies. The principal function of the SIJ is to act as a stress reliever, ensuring that the pelvic girdle is not a solid ring of bone that could easily crack under the stresses to which it is subjected (Adams et al 2002).

What specific adaptations are available to prevent shear in the SIJs?

The SIJs are abnormal compared to other joints because of cartilage changes that are present already before birth. These occur especially at the iliac side of the joint and were misinterpreted as degenerative arthrosis (Bowen & Cassidy 1981, Sashin 1930). These cartilage changes are more prominent in men than in women and according to Salsabili et al (1995), the sacral cartilage is relatively thick in females. This gender difference might be related to childbearing and possibly to a different localization of the center of gravity in relation to the SIJ (Dijkstra et al 1989, Vleeming et al 1990a, 1990b). Vleeming et al (1990a, 1990b) considered these changes to reflect a functional adaptation. The features seem to be promoted by the increase in body weight during the pubertal growth spurt and concern a boost of more coarse cartilage texture (especially on the iliac side) and a wedge and propeller-like form of the joint surfaces. Studies of frontal slides of intact joints of embalmed specimens show the presence of cartilage- covered bone extensions protruding into the joint. These protrusions seemed irregular but are in fact complementary ridges and grooves. Joint samples taken from normal SIJ with both coarse texture and complementary ridges and grooves were characterized by high-friction coefficients (Vleeming et al 1990b).

All these features are expected to reflect adaptation to human bipedality, contributing to a high coefficient of friction and enhancing the stability of the joint against shear (Vleeming et al 1990a). As a consequence, less muscle and ligament force is required to bear the upper part of the body. The specific architecture of the sacrum further contributes to its stability within the pelvic ring. The bone is wider cranially than caudally; wider anteriorly than posteriorly and the joint at the level of S1 converges posteriorly and S3 converges anteriorly. Such a configuration helps the sacrum to become 'compressed or forceclosed' cranially and dorsally into the ilia within the pelvic ring (Vleeming et al 1990a, 1990b).

The SIJ has evolved from a relatively flat joint into a much more stable construction in humans. To illustrate the importance of friction and compression in the SIJ, the principles of *form and force closure* were introduced (Vleeming et al 1990a, 1990b). *Form* closure refers to a theoretical stable situation with closely fitting joint surfaces, where no extra forces are needed to maintain the state of the system, given the actual load situation. If the sacrum would fit in the pelvis with perfect form closure, no lateral forces would be needed. However, such a construction would make mobility practically impossible. With *force* closure (leading to joint compression) both a lateral force and friction are needed to withstand vertical load. Shear in the SIJ is prevented by the combination of the specific anatomical features and the compression generated by muscles and ligaments that can be accommodated to the specific loading situation (force closure). Force closure is the effect of changing joint reaction forces generated by tension in ligaments, fasciae, and muscles and ground reaction forces. Force closure of the SIJ ideally generates a perpendicular reaction force to the SIJ to overcome the forces of gravity (Vleeming et al 1990b). This shear prevention system was named the self-bracing mechanism and such a mechanism is present elsewhere in the body, e.g. in the knee, foot, and shoulder. When a larger lever is applied and/or coordination time becomes less, the general effect in the locomotor system will be closure or reduction of the degrees of freedom of the kinematic chain, leading to a reduction of the chain's mobility or a gain of stability by increasing force closure (Huson 1997). In self-bracing of the pelvis, nutation of the sacrum is crucial. This movement can be seen as an anticipation for joint loading. Hodges et al (2003) use the terminology 'preparatory motion' for a comparable phenomenon in the lumbar spine. Therefore, nutation is seen as a movement to prepare the pelvis for increased loading by tightening most of the SIJ ligaments, among which are the vast interosseous and short dorsal sacroiliac ligaments. As a consequence the posterior parts of the iliac bones are pressed together, enlarging compression of the SIJ.

With reference to a loading mode in the frontal plane, friction in the SIJ could be theoretically increased by the use of a pelvic belt. In this model the location of the belt, and not the load, appeared to be crucial (Vleeming et al 1992 b). In this study the influence of pelvic belts on the stability was evaluated by measuring the effect on the nutation and counternutation in SIJ of human pelvic spine specimen/preparations. This study showed that on average, with a load not more then 50 N, that overall rotation of the SIJ was reduced by 18.8 %. A pelvic belt has to be applied with a small force in patients, like the effect of tensing the laces of a shoe. The model indicates that normally the belt must be positioned just cranial to the greater trochanters. The study advises not to use pelvic belts as a monotherapy because stability of the lumbopelvic area has to established by proper motor control and coordination.

Based on these studies new research was initiated to analyse forceclosure and selfbracing. Buyruk et al. (1995a) applied unilateral oscillations to the anterior superior iliac spine to assess laxity of the pelvic joints. With sonoelasticity, using Doppler imaging of vibrations (DIV), they measured the stiffness/laxity ratio of artificially unstabilized versus stabilized pelvices. The new method was objective and repeatable. In vivo studies followed with the same technology used in healthy subjects (Damen et al 2002a and b). It was shown that pelvic belts are effective to alter the laxity of the SIJ with an applied force of maximally 50 N. Subsequently, they showed that the laxity values of the SIJ decreased after application of a belt in patients with pelvic pain (Damen et al. 2002a). In another study (Damen et al. b), patients with asymmetric SIJ laxity reported significantly more pain during pregnancy compared when compared with patients with symmetric laxity. Increased laxity of the pelvis in itself is not associated with pelvic girdle pain. According to these studies, the *asymmetry* of laxity correlates with the symptomatic individual with PGP.

In 1999, Mens et al developed a new diagnostic test. They studied the relation between impaired active straight leg raising (ASLR) and the mobility of pelvic joints with and without the application of a pelvic belt (testing the hypothesis that the pelvis is the basic bony platform that has to be stabilized before levers, like the legs and spine, can be used effectively). They conclude that impairment of the ASLR test correlates highly with the level of laxity of the pelvis, because application of a pelvic belt generally reduces the impairment of the ASLR test. The sensitivity and specificity of the test is high for PGP (pelvic girdle pain) and the test is suitable to discriminate between PGP patients and healthy individuals (Mens et al 2002). The same authors (Mens et al 1999) showed – by means of X-rays taken after pregnancy – that the pubic bone on the symptomatic side shifts in a caudal direction relative to the other side when the symptomatic leg is freely hanging down in a standing position. This procedure differs from the classical Chamberlain X- ray method, which screens the symptomatic loaded side. The authors conclude that this symphyseal shift is the result of an anterior rotation of the iliac bone relative to the sacrum on the symptomatic side (counternutation in the SIJ). Hungerford et al (2001) came to the same conclusion. Using an external motion analysis system, they studied (three dimensionally) the angular and translational displacements in patients with SIJ problems and in healthy persons. They concluded that posterior rotation of the iliac bones relative to the sacrum (nutation) occurs in healthy individuals on the weight bearing side. By contrast, the iliac bones rotated anteriorly relative to the sacrum (counter- nutation) in the patient group. They found the same in the standing flexion test. Only in the loaded (standing) symptomatic side did an anterior rotation of the iliac bone occur. The conclusion of these recent studies is that a relation exists between pelvic asymmetric laxity and the severity of complaints (Buyruk et al 1999, Damen et al 2002b). Damen et al. state that subjects with asymmetric laxity of the SIJ during pregnancy have a threefold higher risk of moderate to severe pelvic pain persisting into the postpartum period, compared to subjects with symmetric laxity during pregnancy. They also conclude that pelvic belt application can diminish the laxity and stiffen the pelvis and influence an impaired ASLR test with application of the DIV method. Based on the studies mentioned here a dysfunctional SIJ is not related to a subluxated position of the joint, but to an altered positional compression-forceclosure within the normal range of motion due to asymmetric forces acting on the joint.

Overall conclusions on stability of the lumbopelvic a spine

The following model could help to explain the relationship between optimal stability and laxity. Living on earth requires a constant response to gravity and displacement is possible, albeit small, and therefore stabilization during loading the pelvic joints is required. This is achieved by increasing compression across the joint surface at the moment of loading. The anatomical structures responsible for this are the ligaments and muscles, together with their fascia. Ligaments are tensed when bones move in directions that lengthen them and when muscles that attach to them contract. When the joint is compressed, friction increases (Vleeming et al 1990b) and consequently augments, what is coined self-bracing of the joint (Snijders et al 1993a, 1993b, Vleeming et al 1990a, 1990b). This is seen as a prerequisite in all joints and the effective application of tailored compression is the decisive factor, besides the anatomical factors, for joint stabilization. Compression reduces the size of the joint's neutral zone and increases the stiffness value of the joint. Shear forces are thereby controlled, facilitating stabilization of the joint. In all joints, it is the combination of regional and local ligaments, muscles, fascial systems, and gravity that contribute to force closure (Snijders et al. 1993a, 1993b, Vleeming et al. 1990a, 1990b), and not only the deep stabilizing muscles. Muscles with a bigger lever arm to the joint also add to joint reaction forces. When this mechanism works efficiently in the pelvis, the shear forces between the iliac bones and sacrum are adequately controlled and loads can be transferred between the trunk, pelvis, and legs (Snijders et al. 1993a, 1993b). Van Wingerden et al. (2004) studied several muscles that could contribute to force closure of the pelvis and influence the stiffness characteristics of the joint. In six healthy women, SIJ stiffness was measured using DIV. SIJ stiffness was measured both in a relaxed situation and during EMG-recorded isometric voluntary contractions. The biceps femoris, gluteus maximus, erector spinae, and contralateral latissimus dorsi muscles were included in this study, where as deeper muscles such as the internal obliques, the transversus abdominis, and the multifidus muscle were omitted. Pelvic stiffness significantly increased when the individual muscles were activated. This held especially for activation of the erector spinae, the biceps femoris, and the gluteus maximus. During some tests, significant co-contraction of other muscles occurred. The study concludes that SIJ stiffness increased even with slight muscle activity, supporting the notion that effective load transfer from spine to legs is possible when muscle forces actively compress the SIJ, preventing shear. This is in agreement with the work of Cholewicki et al. (2000), showing that sufficient stability of the spine is achieved in most people with modest levels of co-activation of the paraspinal and abdominal wall muscles. Furthermore, Hodges et al (2003) demonstrated in porcine experiments that contractions of both the transversus abdominis muscle and the diaphragm increased the stiffness of the spine. Van Wingerden et al (2004) also mention that during manual test procedures, the influence of muscle activation patterns must be considered, because both inter and intra-tester reliability can be directly altered by muscle activity. Richardson et al (2002) further elaborated on the force closure model by showing that contractions of the transversus abdominis and multifidus muscles significantly increase SIJ stiffness. However, in their study influences of other muscles were not measured or controlled. O'Sullivan et al (2002) showed elegantly how the pelvic floor and diaphragm can directly influence the active straight leg raise test by a different strategy of motor control of the pelvis and diaphragm, influencing force closure and stabilizing the pelvis.

Sturesson et al (1999) note that SIJ movement in most patients can be reduced by applying an external Hoffman Slatis frame and that this will, in all probability, reduce the pain. This is in line with studies on pelvic belts; use of a pelvic belt normalizes the ASLR test (Mens et al 1999) and influences, the amount of laxity in the joint (Damen et al 2002a).

Recent studies on the ASLR test

New studies on the active straight leg raise test by Beales et al. focus on motor control strategies during the active straight leg raise test, under various loading conditions in pain free and nulliparous patients and female patients with chronic PGP. Scores on the ASLR test diminished by adding manual compression to the anterior pelvis. This is consistent with a pain disorder associated with an impaired force closure mechanism. Beales et al. conclude that pain free subjects adopt a predominant pattern of greater motor activation ipsilateral to the side of the leg lift, also under additional load situations. Chronic patients adopt a bilateral bracing/splinting motor control pattern during the ASLR test. The authors conclude that the aberrant motor patterns in Chronic PGP patients may be maladaptive in nature and highlight the need for looking for individualized patterns that attempt to normalize motor control strategies.

Hu Hai (2009) et al. also studied the ASLR test. Muscle activity during ASLR was assessed, and how this changes with a pelvic belt. In healthy nulligravidae (N = 17) the ASLR test was performed, and they walked on a treadmill at increasing speeds, without and with a belt. Fine-wire Electromyography (EMG) was used to record activity of the mm. psoas, iliacus, and transversus abdominis, while other hip and trunk muscles were recorded with surface EMG. In the ASLR test, all muscles were active. In both tasks, walking and raising the leg, transverse and oblique abdominal muscles were less active with the application of the belt. Hu hai et al. described that hip flexors normally exert a forward rotating torque on the ilium. They conclude that apparently, the abdominal wall was active to prevent such forward rotation. The fact that transverse and oblique abdominal muscles were less active in conditions with a pelvic belt, suggests that the belt provides "force closure", as described in the literature and in the same way as the external fixator in severe pelvic girdle patients.

When we compare this study to former studies of Hungerford et al. and Mens et al., it is interesting to see that the described counternutated position of the SIJ (anterior displacement of the ilium relative to the sacrum) in patients with PGP could be the effect of especially the iliacus muscle pulling the ilium forward relative to the sacrum. In other words, using both the data from Hu hai and Beales, maladaptive motorcontrol strategies can minimize the function of muscles like the IO and transversus and therefore impede the bracing of the pelvic joints. This will lead to insufficient forceclosure of the pelvis. Hence, especially the iliacus muscle, among others, stops lifting the leg but instead pulls the ilium anteriorly leading counternutation in the SIJ in an open kinematic chain movement. As has been shown, counternutation of the SIJ is not supported by many ligaments and especially depends on the proper function the long dorsal ligament of the SIJ.The same authors (Hu Hai et al. 2010), also concluded that the psoas muscle is bilaterally active in normal healthy individuals when performing the ASLR test. They conclude that the bilateral recruitment of the muscle is necessary to stabilize the lumbosacral spine probably in the frontal plane

The thoracolumbar fascia and related muscles and forceclosure of the lumbopelvic area

As discussed, the thoracolumbar fascia plays a central role in transferring forces between spine, pelvis and legs, in relation to stabilization of lower lumbar spine and SI-joints. The gluteus maximus and the latissimus dorsi merit special attention since they can conduct forces contralaterally, via the posterior layer (Vleeming et al. 1995, Mooney et al. 2001). Also through especially the MLF (Barker et al.) the transverse and internal oblique muscles tense the MLF and partially the dorsal layer of the TLF. However, reality seems more complex. Directly anterior to the deep layer of the PLF lies the very strong erector spinae aponeurosis, overlying both the longissimus and the lumbar part of the iliocostal muscle and the deeper lying multifidus muscles. This aponeurosis blends together with the multifidus to the dorsal side of the sacrum and partially to the ilia. Contraction of both the erector muscle, the iliocostalis and the multifidus will not only increase the tension to the blended fascia and aponeurosis by pull and indirectly by dilating the complete posterior layer of the thoracolumbar fascia, but also by effecting the tension of the middle layer. If the transverses and the internal oblique fire earlier than other muscles in healthy individuals, the "floor" (MLF) of the thoracolumbar fascial envelope will be tensed. In that case, erector and multifidus contractions will become more efficient and directed because the slack of the fascial envelope is diminished. For that reason we have to realize that within the envelope of the TLF (posterior, middle and anterior layer) this strong aponeurotic tendon is present. Furthermore often the simple fact is missed that any external movement of the pelvis through the hip joints, influences the tension in the TLF. Also the relative flexion or extension position of the trunk with or without lateroflexion and rotation strongly influences the tension of the TLF envelope. All these factors described here, will change the external and internal dynamics-force and pressure of the fascial envelope.

It seems clear that for understanding effective force closure of the SIJ and lumbar spine, we need to include in our models both the fascia, ligaments, layers of "loose connective tissue" and muscles. Indeed a true composite fabric, to better understand the dynamic stability in vertebrates under constantly changing conditions. In other regions of the body the same anatomical constructs can be found and stability needs integrated anatomical study. In an anatomical biomechanical study of the pelvis it was clarified that force closure and compression of joints can be produced by muscles forces in combination with forces in ligaments and fascia that cross the SIJ surfaces and the lower lumbar spine (Snijders Vleeming et al.).

Muscles with an appropriate direction are indicated in figure 1. A special effect of the oblique and transverse muscles can be noted anteriorly. The abdominal force results in a higher SIJ force closure because of the different lever arms of muscles and fascia and the reaction force to the deep dorsal ligaments (6). This magnification of abdominal force resembles the mechanism of a nutcracker. Optimal function needs stiff interosseous ligaments but also the very strong composite structure of fascia, ligaments and aponeurosis in combination with the dorsal spine muscles. In a study by Vleeming et al. 1995 it was noticed that the TLF fascia over the L5 and S1, S2, indeed becomes thicker and stronger over this region. In figure 1, we can see in a transverse cross section of the pelvis at the level of the SIJ that forces generated by the anterior oblique and transverse abdominals create a vector *F*o. In combination with stiff interosseous ligaments and the dense "composite" of the TLF erector/ aponeurosis/ fascia/ muscle complex, (*F*i,) a joint reaction force *F*j is the result. The lever arms of the active anterior force Fo and the much stronger relatively "passive" dorsal force *F*i , results in a joint reaction force *F*j, which actually becomes much bigger. Please realize that any action of the transverse and obliques muscles automatically increases the tension also dorsally through mainly the middle layer of the fascia but also the dorsal layer and this is part of the vector Fi, representing the dorsal ligaments of the SIJ and the dorsal ligaments around the lower lumbar spine.

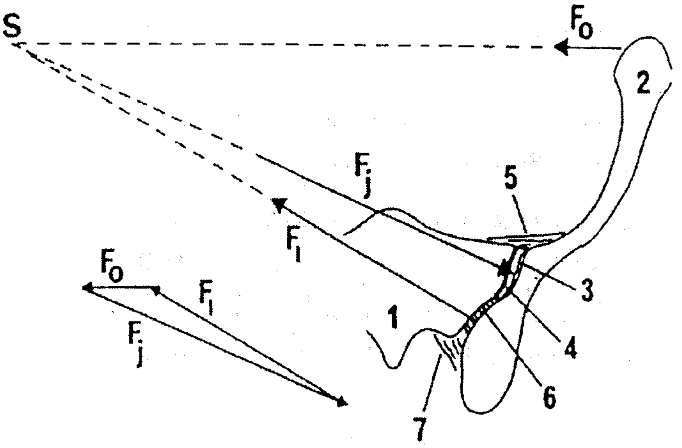

Fig.1. From Snijders Vleeming et al. Reprinted with permission of Spine

References

1. Adams MA, Dolan P, Burton K, Bodguk N 2002. The biomechanics of back pain. Churchill Livingstone,Edinburgh
2. Bakland O, Hansen JH 1984 The axial sacroiliac joint.Anatomica Clinica 6:29–36
3. Barker J 2005 The thoralumbar fascia. Thesis. Universityof Melbourne, Australia
4. The role of the pelvic girdle in coupling the spine and the legs joint: pain referral maps upon applying a new injection/arthrography technique. 2: Clinical evaluation. Spine 19:1483–1489
5. Beales D 2009. Motorcontrol during an active straight leg raise in pain free and chronic pelvic girdle patients. Thesis Curtin University of Perth Australia.
6. Bowen V, Cassidy JD 1981 Macroscopic and microscopic anatomy of the sacroiliac joints from embryonic life until the eighth decade. Spine 6:620
7. Buyruk HM, Stam HJ, Snijders CJ et al 1995a. The use of colour Doppler imaging for the assessment of sacroiliac joint stiffness: a study on embalmed human pelvices. European Journal of Radiology 21:112–116
8. Buyruk HM, Snijders CJ, Vleeming A et al 1995b. The measurements of sacroiliac joint stiffness with colourDoppler imaging: a study on healthy subjects. European Journal of Radiology 21:117–121
9. Buyruk HM, Stam HJ, Snijders CJ et al 1999 Measurement of sacroiliac joint stiffness in peripartum pelvic pain patients with Doppler imaging of vibrations (DIV). European Journal of Obstetrics, Gynecology and Reproductive Biology 83(2):159–163
10. Cholewicki J, Simons APD, Radebold A 2000 Effects of external trunk loads on lumbar spine stability. Journal of Biomechanics 33(11):1377–1385

11. Damen L, Spoor CW, Snijders CJ, Stam HJ 2002a. Does a pelvic belt influence sacroiliac laxity? Clinical Biomechanics 17(7):495–498
12. Damen L, Buyruk HM, Guler Uysal F et al 2002b. The prognostic value of asymmetric laxity of the sacroiliac joint in pregnancy related pelvic pain. Spine 27(24): 2820–2824
13. Dijkstra PF, Vleeming A, Stoeckart R 1989 Complex motion tomography of the sacroiliac joint: an anatomical and roentgenological study. Fortschritte auf dem Gebiete der Rontgenstrahlen und der Nuklearmedizin 150:635–642
14. Egund N, Ollson TH, Schmid H, Selvik G 1978 Movements in the sacroiliac joints demonstrated with roentgen stereophotogrammetry. Acta Radiologica, Diagnosis 19:833
15. Hodges PW, Kaigle A, Holm S et al 2003. Intervertebral stiffness of the spine is increased by evoked contraction of transversus abdominus and the diaphragm; in vivo porcine studies. Spine 28(23):2594–2601
16. Hu H, Onno G. Meijer, Jaap H. van Dieën, Paul W. Hodges, Sjoerd M. Bruijn, Rob L. Strijers, Prabath W. Nanayakkara, Barend J. vanRoyen, Wenhua Wu, Chun Xia 2009. Muscle activity during the Active Straight Leg Raise (ASLR), and the effects of a pelvic belt on the ASLR and on treadmill walking. J Biomech. 2010 Feb 10;43(3):532-9. Epub 2009 Nov
17. Hu H, Meijer OG, van Dieen JH, Hodges PW, Bruin SM, Strijers RL, Nanayakara PW van Royen BJ, Wu WH, Xia C 2010. Is the psoas a hipflexor in the active straight leg raise test? Eur Spine J. Jul 13 (pre publication)
18. Hungerford B, Gilleard W, Lee D 2001 Alteration of sacroiliac joint motion patterns in subjects with pelvic motion asymmetry. In: Proceedings from the Fourth World Interdisciplinary Congress on Low Back andPelvic Pain. Montreal, Canada
19. Hungerford B, Gilleard W, Hodges PW 2003 Evidence of altered lumbo–pelvic muscle recruitment in the presence of sacroiliac joint pain. Spine 28(14):1593–1600
20. Huson A 1997 Kinematic models and the human pelvis. In:Vleeming A et al (eds) Movement stability and low back pain. Churchill Livingstone, Edinburgh, p123–131
21. Lavignolle B, Vital J M, Senegas J et al 1983 An approach to the functional anatomy of the sacroiliac joints in vivo.Anatomica Clinica 5:169
22. Lovejoy CO 1988 Evolution of human walking. Scientific American 259:118–125
23. MacIntosh JE, Bogduk N 1986 The biomechanics of the lumbar multifidus. Clinical Biomechanics 1:205–213 Barker J, Briggs CA 1999 Attachments of the posterior
24. layer of the lumbar fascia. Spine 24(17):1757–1764
25. 23. Mens JMA, Vleeming A, Snijders CJ et al 1999.The active straight leg raising test and mobility of the pelvic joints. European Spine 8:468–473
26. 24. Mens JM, Vleeming A, Snijders CJ, Koes BW, Stam HJ 2002. Validity of the active straight leg raise test for measuring disease severity in patients with posterior pelvic pain during pregnancy. Spine 15;27(2):196-200
27. 25. Miller JA, Schultz AB, Andersson GB 1987 Load displacement behaviour of sacroiliac joint. Journal of Orthopaedic Research 5:92 Mooney V, Pozos R, Vleeming A et al 2001 Exercise treatment for sacroiliac joint pain. Orthopedics 24(1):29–32
28. 26. O'Sullivan PB, Beales DJ, Beetham JA et al 2002 Altered motor control strategies in subjects with sacroiliac pain during the active straight leg raise test. Spine 27(1):E1–E8
29. 27. Richardson CA, Snijders CJ, Hides JA et al 2002. The relationship between the transversus abdominus muscle, sacroiliac joint mechanics and LBP. Spine 27(4):399–405
30. 28. Salsabili N, Valojerdy MR, Hogg DA 1995 Variations inthickness of articular cartilage in the human sacroiliac joint. Clinical Anatomy 8:388–390
31. 29. Sashin D 1930 A critical analysis of the anatomy and the pathological changes of the sacroiliac joints. Journal of Bone and Joint Surgery 12:891
32. 30. Snijders CJ, Vleeming A, Stoeckart R 1993a Transfer of lumbosacral load to iliac bones and legs. 1: Biomechanics of self-bracing of the sacroiliac joints and its significance for treatment and exercise. Clinical Biomechanics 8:285–294
33. 31. Snijders CJ, Vleeming A, Stoeckart R 1993b Transfer of lumbosacral load to iliac bones and legs. 2: Loading of the sacroiliac joints when lifting in a stooped posture. Clinical Biomechanics 8:295–301
33. Solonen KA 1957 The sacroiliac joint in the light of anatomical, roentgenological and clinical studies. Acta Orthopaedica Scandinavica 27:1–127
34. Stewart TD 1984 Pathologic changes in aging sacroiliac joints. Clinical Orthopaedics and Related Research 183:188
35. Sturesson B, Udén A 1999 Can an external frame fixation reduce the movements in the sacroiliac joints? A radiostereometric analysis of 10 patients. Acta Orthopedica Scandinavica 70(1):42–46
36. Sturesson B, Selvik G, Udén A 1989 Movements of the sacroiliac joints. A roentgen stereophotogrammetric analysis. Spine 14:162–165
37. Sturesson B, Udén A, Vleeming A 2000a A radiostereometric analysis of movements of the sacroiliac joints during the standing hip fl exion test. Spine 25(3):364–368
38. Sturesson B, Udén A, Vleeming A 2000b A radiostereometric analysis of the movements of the sacroiliac joints in the reciprocal straddle position. Spine 25(2): 214–217

39. Vleeming A, Stoeckart R, Volkers ACW, Snijders CJ 1990a. Relation between form and function in the sacroiliac joint. 1: Clinical anatomical aspects. Spine 15:130–132
40. Vleeming A, Volkers ACW, Snijders CJ, Stoeckart R 1990b. Relation between form and function in the sacroiliac joint. 2: Biomechanical aspects. Spine 15(2):133–136
41. Vleeming A, Wingerden JP van, Dijkstra PF et al 1992a Mobility in the SI-joints in old people: a kinematic and radiologic study. Clinical Biomechanics 7:170–176
42. Vleeming A, Buyruk HM, Stoeckart R et al 1992b. The role of the pelvic girdle in coupling the spine and the legs for an integrated therapy for peripartum pelvic instability. American Journal of Obstetrics and Gynecology 166(4):1243–1247
43. Vleeming A, Pool-Goudzwaard AL, Stoeckart R et al 1995. The posterior layer of the thoracolumbar fascia: its function in load transfer from spine to legs. Spine 20:753–758
44. Vleeming A, Pool-Goudzwaard A, Hammudoghlu D et al. 1996. The function of the long dorsal sacroiliac ligament: its implication for understanding LBP. Spine 21(5): 556–562
45. Weisl H 1955 The movements of the sacroiliac joints. Acta Anatomica 23:80
46. Wingerden JP van, Vleeming A, Buyruk HM, Raissadat K 2004 Stabilization of the SIJ in vivo: verification of muscular contribution to force closure of the pelvis. European Spine Journal 13(3):199–205