The Sacro-iliac Joint

A clinical-anatomical, biomechanical and radiological study

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Het sacro-iliacale gewricht

Een klinisch-anatomische, biomechanische en radiologische studie

PROEFSCHRIFT

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	Prof. Dr. J. Voogd
Overige leden:	Prof. Dr. H.E. Schütte
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To my parents,
to Nora, Barynia & Lauranne, and to
Rob Stoeckart

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Figure 1:
Brooke, R. The sacro-iliac joint. J. Anat. 1924; 58: 299-305;
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Stewart, T.D. Pathologic changes in aging sacroiliac joints. Clin. Orthop. and Rel. Res. 1984; 183: 188-196;
Figures 9 and 10:
Bakland, O., Hansen, J.H. The "axial sacroiliac joint". Anat. Clin. 1984; 6: 29-36;
Figures 11 and 12:
Egund, N., Ollsson, T.H., Schmid, H., Selvik, G. Movements in the sacroiliac joints demonstrated with roentgen stereophotogrammetry. Acta Rad. Diagn. 1978; 19: 833-846;
Figure 13:
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Figure 14:
Lavignolle, B., Vital, J.M., Senegas, J., Destandau, J.,Toson, B., Bouyx, P., Morlier, P., Delorme, G., Calabet, A. An approach to the functional anatomy of the sacroiliac joints in vivo. Anat. Clin. 1983; 5: 169-176;
Figure 15:
Walheim, G.G., Olerud, S., Ribbe, T. Mobility of the pubic symphysis. Acta Orthop. Scand. 1984; 55: 203-208;
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Contents

People will do anything, no matter how absurd,
in order to avoid facing their own souls
(C.G. Jung, in *Psychology and Alchemy*,
Princeton University Press,
Princeton NJ, 1978, p. 99).

Preface

Low back pain may be due to anatomical, biomechanical and other causes (e.g., Oosterhuis, 1982; Verkes & Megchelen, 1985). There exists, for instance, a correlation between emotional suffering on the one hand, and pain in rather specific areas of the low back on the other—a fact which reminds one of the old metaphor of the back as the 'mirror of the soul'.

Low back pain may be caused by a large variety of anatomical 'deviations'; *vice versa*, afflictions of the low back may present themselves as pain in a large variety of areas; the phenomena themselves are often part of complex patterns, the complexity of which may transcend the limitations of analytical science. Nevertheless, analytical reduction is of considerable importance in reaching an adequate understanding of complex patterns. Our understanding of the low back region has improved significantly by dividing the area into small units and by analysing the functional role these units play in the organism as a whole.

In general, those who propose schemes for analytical reduction, have a firm grasp of the complex whole to be analysed. Students and practitioners, however, who are confronted with the units, are at risk of losing the overview. It is difficult, for instance, to understand that restriction of the range of motion in one segment may lead to enhancing the range of motion in another.

This lack of overview also concerns kinematic relationships of the sacrum. Even those with only some crude knowledge of the spinal column are aware of the fact that the sacrum is connected with the right and left ilium. It is often recognized that the sacrum can move with respect to the iliac bones, i.e., in the sacro-iliac joints. However, many fail to see that such movement influences the other joints of the sacrum. The latter, being the (lumbosacral) joints between the sacrum and the vertebral arch of the fifth lumbar vertebra as well as that between the sacrum and the body of the fifth lumbar vertebra, through the intervertebral disc. Of course, also ligaments and muscles play a role in connecting these skeletal structures. It would be appropriate, we[1] argue, to introduce the notion of 'sacral joints', referring to both the sacro-iliac and the lumbosacral joints.

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[1] By using the plural 'we', the author wishes to express his indebtedness to the large group of people involved in the research presented in this Thesis. Of course, the responsibility for the present text resides with the present author alone.

In this respect, the sacrum effects the functional possibilities of other parts of the kinematic chain, e.g., lumbar vertebrae. It is possible that an abnormal position of the sacrum leads to problems with the intervertebral disc connecting L5 with the sacrum.

It turns out to be difficult to teach the functional role of the sacro-iliac joints. This problem may derive from a fundamental lack in our basic knowledge concerning sacro-iliac anatomy, mobility and diagnostics.

> The more uncertainty reigns in a specific realm, the more heated the debates, a circumstance which often leads to the formation of opposing factions. Following Schumacher (1977), we want to distinguish between convergent and divergent problems.
> A 'convergent problem' is one where adequate discussions within a large community will lead to a specific solution, provided that relevant information is sufficiently available. In the case of a convergent problem, consensus is often within reach—as occurs so often in the natural sciences.
> A 'divergent problem' is one where the solution appears to be at hand whenever the problem is first knowledgeably discussed within a large community. In the long run, however, opinions diverge and will continue to do so—as occurs so often with problems where emotional and/or moral aspects are involved.

It is our opinion that the problem of understanding the morphology and function of the sacro-iliac joints and the lower spine, will turn out to be a convergent one as soon as enough basic information is provided to the discussants.

In his 1962 book on "Die Wirbelsäuleleiden und ihre Differentialdiagnose" [Afflictions of the Spinal Column and their Differential Diagnostics], Brochner states:

> Allgemein wird im Sprachgebrauch des Klinikers und Röntgenologen als Wirbelsäule nur derjenige Teil des Achsenskelettes bezeichnet, welcher zwischen dem ersten Hals und dem letzten Lendenwirbel liegt. Diese Einstellung hat sich in praktischer Hinsicht dahin ausgewirkt, daß wir wohl über eine stattliche Zahl von Wirbelsäulenbüchern verfügen, daß jedoch unseres Wissens noch kein Autor eine Zusammenfassende Arbeit aller Affektionen des Sakrums geschaffen hat[2].

2 In the jargon of the clinician and the radiologist, the term 'spinal column' usually refers to that part of the axial skeleton that extends between the first cervical and the last lumbar

Brochner's concern may suggest that the sacro-iliac joints have remained enigmatic due to lack of adequate research. This lack is certainly related to the fact that the sacro-iliac joints are hard to reach for anatomical study or X-ray analysis due to the very complexity of their construction.

Finally, how difficult it is to classify sacro-iliac problems on the basis of presently available knowledge, may be illustrated by the work of Richter et al. (1983) concerning patients with isolated tuberculosis of a sacro-iliac joint. The time needed to reach the correct diagnoses was, on the average, 1 year and 9 months. Many patients had first been treated for "ischialgia caused by disc problems."

In order to obtain a better potential for treatment, we need a better understanding of the morphology and function of the literal basis of the spine, i.e., the sacrum and its joints.

It is our hope that this Thesis may contribute to the discussing of low back pain within a wider context.

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vertebra. The practical consequence of this attitude has been that we have an impressive number of books about the spinal column at our disposal, whereas no author yet, as far as we know, has created an overview of the afflictions of the sacrum.

GENERAL INTRODUCTION

A short history of sacro-iliac research

Sacro-iliac afflictions used to be treated both conservatively and surgically by a variety of methods.

The results of treating what was called 'ischialgia' were clinically regarded as being satisfactory (e.g., Smith-Peterson, 1921; Jackson, 1934).

The work of Mixter and Barr (1934), in particular, suggested that prolapse or protrusion of the intervertebral disc plays an important, if not the most important, role in the emergence of ischialgic complaints.

It is of relevance to ask whether such a 'hernia' occurs in isolation or in relation to other, insufficiently understood, afflictions. In this respect, one may wonder how it was possible that the therapies of former days, such as sacro-iliac arthrodesis, were at all effective.

There is a possibility that 'historical knowledge' concerning the sacro-iliac joint may contain important information.

It has been shown that sacro-iliac surgery was sometimes effective in treating ischialgia (Smith-Peterson, 1921; Freiberg & Vinke, 1934). It is conceivable that such surgery resulted in a change of ligamentous and muscular tensions, thereby possibly changing the position of the sacrum with respect to the sacro-iliac joints and, thus, reducing the pressure on the intervertebral disc.

Chronology[1]

Fifth century B.C.

Hippocrates states that the sacro-iliac joint is immobile. The relevant information is probably derived from animal experiments.
Hippocrates is of the opinion that the joint acquires some form of mobility during pregnancy.

1543

Vaesalius describes the sacro-iliac joint as a fixed, immobile connection.

1643

Researching corpses, Paré confirms the observation that the sacro-iliac joint is mobile during pregnancy.

[1] Only literature with specific historical impact is discussed in this Section. See also: General conclusions from the literature.

1689

Diemerbroch states that the sacro-iliac joint also has some form of mobility in subjects who are not pregnant.

1789

Thouret describes that the ventral aspects of the joint (both the ilium and the sacrum) consist of special cartilage, surrounded by a joint capsule with ligaments.

1803

Portal regards the dorsal ligaments as extra-articular and proposes a new nomenclature for the sacro-iliac fibrous apparatus.

1841

Barkow describes the interosseous ligaments of the joint.

1864

Following Albinus and Hunter, Von Luschka categorizes the joint as a 'diarthrosis'.

1889, 1896, 1899 & 1929

Walcher, Fothergill, Pinzani, and Jarcho use different techniques with living subjects and embalmed corpses to determine the *conjugata vera* (anterior-posterior diameter) and the *conjugata diagonalis* (oblique diameter). It is concluded that the conjugata vera becomes between 0.1—1.3 cm smaller while movement takes place from a supine position with maximal hip and trunk extension towards the normal supine position.
It is brought to the fore that lessening the conjugata vera leads to enlarging the distal pelvic aperture, i.e., a small pelvic inlet implies a large pelvic outlet.
Eventually, this leads to the conception that movement in the sacro-iliac joint takes place around a fixed, horizontal axis—supposedly piercing the iliac tuberosity, the bony enlargement dorsal to the auricular surface of the ilium.

1905

Goldthwaith and Osgood claim that ischialgia results from sacro-iliac overuse or hypermobility, leading to irritation of the lumbar plexus.

1909

Using a specific staining technique, Albee demonstrates the synovial nature of the sacro-iliac joint. This research confirms that the joint is mobile to a certain degree.

1910

The construction of the first Aswan Dam allowed Smith and Jones to perform an archeological anatomical investigation of human skeletons found in old cemeteries. Although many are examined (several hundreds are mentioned), only 9 of them show signs of sacro-iliac ankylosis.

1920

Research on embalmed corpses leads Halladay to conclude that asymmetrical movements in the sacro-iliac joints lead to movements in the pubic symphysis. Symmetrical sacro-iliac movements, on the other hand, hardly lead to any movement in the symphysis.
It is reported that hyperextension of the back leads to angular displacement of the sacrum with respect to the fifth lumbar vertebra.

1921

Smith-Peterson suggests that chronic sacro-iliac hypermobility leads, eventually, to instability. Anterior-posterior radiological analysis may serve to reveal the resulting degenerative changes in the joints, i.e., proliferation of the caudal parts of the joint.
It is claimed that sacro-iliac arthrodesis is effective in treating ischialgia, already before the final ossification of the joint takes place.

1923

Kajava researches patients who did not, or hardly, load their hip joints during a considerable amount of time.
According to Solonen (1957), this research led to the conclusion that sacro-iliac ankylosis occurs at the non-affected side, particularly when the lessening of the load has occurred during adolescence[2].

1924

Brooke states that sacro-iliac ankylosis is more often a male than a female affliction, male joints relatively often showing extra-articular tubercles. Among 105 female preparations of different ages, no, or hardly any, signs of ankylosis are found.
It is observed that sexual differences with respect to the anatomy of the joint come to the fore at the beginning of puberty.

1928

Yeoman states that 36% of all ischialgia is caused by sacro-iliac arthritis.

1929

Schubert performs a radiological analysis of the conjugata vera. A reduction of between 0.5 and 0.7 cm is observed upon changing from a supine position to standing upright.

1930

Chamberlain demonstrates that child birth may lead to sacro-iliac lesions. These lesions are caused by laxity of the ligaments, depending upon

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2 It remains unclear what criteria were used in this study to diagnose 'ankylosis'.

hormonal changes. Chamberlain states that laxity of the ligaments may also occur during menstruation.

1930

Sashin, having investigated 257 preparations, states that, in the young adult, the sacro-iliac joint is a true diarthrosis.
He regards the joint in older age groups as an 'amphi-arthrosis' with hardly any mobility, due to the ankylosis occurring in men as well as in women.

1933

Abramson et al. demonstrate sacro-iliac changes before and after child birth. Among other techniques, the researchers make use of radiological analysis of the mobility of the pubic symphysis in women who are 8 months pregnant.
A distinction is made between sacro-iliac complaints and problems of the pubic symphysis.

1934

Mixter and Barr claim ischialgia to be due to rupture of the intervertebral disc.

1934

Freiberg and Finke state that bilateral ischialgia coincides with bilateral afflictions of the sacro-iliac joints.

1934

Jackson indicates that, at the end range of sacro-iliac motion, only minor forces are needed to produce abnormal translational movements. According to the author, ischialgic complaints may be caused by sacro-iliac malfunctioning.
Jackson treated patients with a large dose of an anesthetic, strongly reducing muscular tension. After this medication, the affected leg is slowly flexed in the hip. This whole procedure takes about half an hour, at the end of which the knee of the patient reaches up as far as the head.
According to Jackson, one may hear a loud snap during this procedure, which is reported to often result in complete cure[3].

1934

E.F. Cyriax regards sacro-iliac subluxation as 'malrotation' to be measured by comparing left and right leg lengths. He states that leg length differences may be the prime cause of sacro-iliac complaints.

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[3] At first sight, these data are ridicule. Assuming, however, that the author reports truthfully, we wonder about the underlying mechanisms. It is possible that Jackson's observations derive from an extremely tilted position of the sacro-iliac joint, resulting in such overloading of the discs L4—L5 that ischialgia resulted. It is conceivable that the forces exerted on the lumbar spine, the sacro-iliac joint, and the fibrous apparatus, led to sacro-iliac displacements with a positive effect on the alleged protrusion or prolapse.

1937
Having examined 958 human skeletons, Trotter concludes that in 36% of the skeletons, one or more accessory sacro-iliac joints are present. About 50% of these 'accessory joints' are found bilaterally, at the level of the second sacral foramen[4].

1938
Schuncke states that the sacro-iliac joint can be recognized as a typical joint from the 2nd month *in utero* onwards, and that the development of the joint cavity is completed by month 7—8.
Examination of 200 preparations leads to the conclusion that the bony surfaces of the joint are smooth until puberty. At a later age, all kinds and combinations of bony ridges and grooves occur. The most frequent localization of the ridges appears to be on the ilium. Schuncke does not classify these bony irregularities under the general heading of 'arthrosis'.

1938
Strachan investigates preparations which have their iliac bones fixed to a block of concrete. The trunk is moved with respect to the pelvis and the effects on the sacrum are studied.
Strachan concludes the following: trunk traction leads to tilting of the sacrum towards dorsal ('contranutation'). This may be understood on the basis of the fact that the sacrum is under less load and takes, therefore, a position as if the person is supine (Weisl, 1955). Trunk compression leads to tilting of the sacrum towards ventral ('nutation').
Flexion of the spine results in tilting towards ventral, whereas the ilium tends to somewhat follow the movements of the sacrum. Extension of the spine results in tilting towards dorsal, the ilium, again, somewhat following the sacrum. Lateral flexion of the lumber spine results in ipsilateral flexion of the sacrum. Rotation of the lumbar spine results in ipsilateral rotation.

1939
In the context of clinical investigations, Abel concludes that sacro-iliac problems are the major cause of low back pain.

1939
Gray remarks that sacro-iliac pain, in the context of movement restriction, may be caused by minor movements in mutually corresponding ridges and grooves.

1940, 1944
Rauber and Kopsch state that the sacro-iliac joint is intermediate between a synarthrosis and a diathrosis.

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[4] It remains somewhat unclear what exactly is meant by 'accessory', and, *per exclusionem*, what it is that characterizes the normal joint. No information is given as to the question whether these accessory joints are covered with cartilage.

This is followed by the proposition, in Gray's Anatomy, that the sacro-iliac joint be an amphi-arthrosis, thus, hardly allowing any movement.

1949

Testut and Latarjet describe the sacro-iliac joint as a diarthro-amphiarthrosis. The joint capsule is supposed to be part of the diarthrosis, the interosseous ligaments part of the synarthrosis.

1948, 1951

Platt and Ghormley deny all mobility to the sacro-iliac joint. It is their contention that low back pain cannot result from sacro-iliac pathology.

1950

On the basis of a general investigation of joints, Gardner concludes that movement is necessary for the development and self-maintenance of a joint.

1952

Howarth is of the opinion that sacro-iliac joints do not exist, let alone their 'subluxations'.

1954

J. Cyriax states: "Lesions of the sacro-iliacal joints are as rare as pain felt at the inner aspect of the buttock is common".

1954

Weisl investigates the sacro-iliac fibrous apparatus and concludes that the iliolumbar, sacrotuberous and sacrospinous ligaments have to be regarded as 'accessory ligaments' of the sacro-iliac joints.

1955

Watson describes sacro-iliac subluxations, accessible to both manual and radiological examination.

1957

Solonen reports on an extensive clinical, anatomical, biomechanical, and radiological study of the sacro-iliac joint and concludes the following.
The sacro-iliac articular surfaces are rather asymmetrical, with great interindividual variability.
If the ventral aspect of the joint narrows from cranial towards caudal, the ligaments are under less tension than in the opposite case.
Furthermore, the investigation suggests that a larger part of the joint surface carries the load when the position of the sacrum is vertical rather than horizontal.
In view of the strongly developed ligaments and the irregular form of the articular surfaces, Solonen concludes that sacro-iliac movement is not, or hardly, possible, except in the case of pregnancy.

Concerning sacro-iliac innervation, Solonen demonstrates that the ventral aspect of the joint is innervated from L3—S2, the dorsal aspect from S1—S2. Solonen concludes that this situation explains the pattern of referred pain, i.e., pain in the buttock or the leg.
Solonen states that sacro-iliac arthrography is practically impossible since the joint cavity 'opens' under such an angle that injection is extremely difficult. The mobility of the joint can be investigated by using the Chamberlain method (1930).
Upon surveying 6895 patients with low back pain, Solonen reports that only 2.4% of them have real sacro-iliac pathology. Due to the similarity of lumbar and sacro-iliac innervation patterns, the possibility to differentiate between the two must be regarded with some scepsis. Since, however, sacro-iliac pathology does not result in abnormal reflexes or sensibility, differentiation from complete disc prolapse is often possible. Solonen fails to discuss possible relationships between sacro-iliac pathology and disc problems.
In case of serious sacro-iliac afflictions, Solonen advises arthrodesis.

1957

Moffet states that both the temporomandibular and the sacro-iliac joint show a relatively late ontogenetic maturation of the synovial membrane.

Developmental biology of the sacro-iliac joint

Development *in utero*

Around week 8 of intra-uterine development, a three-layered structure develops in the pelvic mesenchyme—sacral cartilage, iliac cartilage and the interposed zone of mesenchyme, containing a slit which is the early articular cavity. Out of this structure, the sacro-iliac joint will develop (Schuncke, 1938).

In week 10, cavities emerge centrally as well as peripherally—whereas in other diarthroses only a central cavity is formed. The formation of the central cavity is supposed to take place under the influence of minor movements (Gardner, 1950) since neonatal paralysis of the lower body coincides with anomalies in both the sacrum and the sacro-iliac joint (DeCuveland, Grand, Eichenberger & Jacobson, as discussed by Brochner, 1962)[5].

Fibrous septa protrude into the cavity of the joint, both from its sacral and iliac sides, the latter ones gradually developing into a delicate transversal ridge on the auricular aspect of the ilium. Globally speaking, this ridge divides the cartilage in a cranial and a caudal part. On the auricular cartilage of the sacrum, the septa remain separate. It is said that they usually disappear during the first postnatal year while remaining present in exceptional cases (Schuncke, 1938; Drachman et al., 1966).

Normally, the joint cavity is fully developed in the eighth month. At that time, the general contour of the joint can clearly be recognized, and the joint has acquired the potential to move (Schuncke, 1938; Bowen & Cassidy, 1981).

The synovial membrane of the sacro-iliac joint develops shortly before birth out of the mesenchyme surrounding the edge of the primordial central cavity. Such late development also takes place in the temporomandibular joint (Moffet, 1957), another joint that hardly moves before birth.

During intra-uterine development, conspicuous differences can be seen between the auricular cartilage of the ilium and that of the sacrum. The sacral cartilage is glossy and white, whereas the iliac cartilage is dull and striped (partly due to irregularities in the underlying bone tissue). Sacral

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[5] In fact, the sacrum does not exist during the intra-uterine period. The coalescence of the five separate vertebrae starts after birth (Töndury, 1970), not to be finished until the age of 25—30 years.

cartilage is two to three times thicker than iliac cartilage (Sashin, 1930; Schuncke, 1938; Bowen & Cassidy, 1981).

Microscopically, iliac cartilage is usually characterized as fibrocartilage (Bowen & Cassidy, 1981), sacral cartilage as hyaline cartilage. Histological-biochemical research of Paquin et al. (1983), however, appears to contradict this distinction, that is, the authors conclude that iliac cartilage is a special form of hyaline cartilage.

First decade

The joint capsule has two layers. The outer, fibrous layer consists of firm connective tissue containing many fibroblasts, blood vessels, and collagenous fibres. The synovial membrane, a so-called 'intima', has two to three cellular layers. Synovial villi may reach down deep into the joint.

Immediately after birth, the general orientation of the human sacro-iliac joint is very similar to that of quadrupeds. The articular surfaces have the same direction as the joints of the arches of the lumbar vertebrae. Change begins as soon as the child starts to locomote (Schuncke, 1938; Solonen, 1975). The sacrum enlarges towards lateral and the articular surfaces 'fold' in the direction of the adult curvature, i.e., craniocaudally as well as ventrodorsally (Solonen, 1957).

Comparative anatomy and paleontological research indicate that these changes are brought about by mechanical factors such as the supine position, body weight, load on the femur and strain on the pubic symphysis (Solonen, 1957).

The most important process in the development of the sacro-iliac joint is the torsion between the iliac bones and the sacrum (Solonen, 1957). The mobility of the joint can be revealed by manual examination of first decade preparations (Brooke, 1924; Sashin, 1930; Schuncke, 1938; Bowen & Cassidy, 1981).

Second decade

Although pelvic sexual differences in general become recognizable as early as the fourth month *in utero* (Schuncke, 1938), sacro-iliac differences do not emerge until puberty.

Male sacro-iliac development seems to be a functional adaptation in order to cope with major forces. This results in a thickening of the ligaments and a decrease in mobility.

Initially, also female sacro-iliac development reveals a restriction of mobility (around the age of 14), but, according to Brooke (1924), it begins to increase again in the later part of the second decade (Figure 1).

In the study of the relationships between sacro-iliac architecture, gender, and age, one is usually referred to Brooke's (1924) data. However, due to sampling problems inherent to that investigation, the data can be used as a general guide-line only.

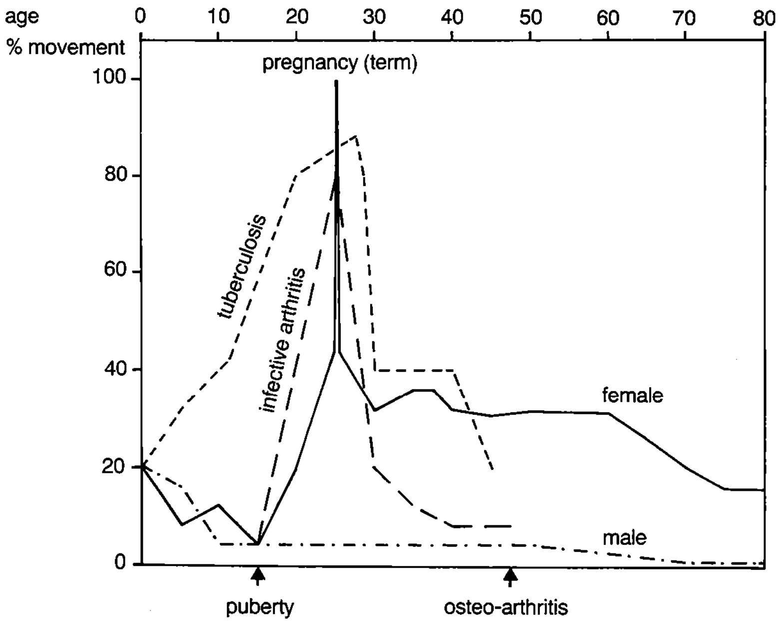


Figure 1. Age and mobility in the sacro-iliac joint (after Brooke, 1924).

Brooke mentions that in 88% of 55 male preparations of diverse ages, an intra-articular bony tubercle is present, ventrally in the middle aspect of the auricular surface of the sacrum.

This small tubercle, covered with cartilage, is said to be present as early as at the age of 14. In 75% of male preparations, this tubercle was clearly pronounced. In 15% of 95 female preparations, only a rather small tubercle could be shown.

Brooke reports that sometimes a second tubercle is present, directly dorsal to the first. If no tubercle is present, the whole auricular surface of the sacrum is convex. Brooke suggests that the tubercle shows stronger development in males because of the large forces that play a role. Allegedly, the tubercles enhance stability, thereby allowing for large forces.

Particularly in women, an accessory protrusion may occur on the dorsocaudal aspect of the sacral auricle (Brooke, 1924). This protrusion probably derives from the third sacral element.

Women in the second decade also develop a groove in the iliac bone, the paraglenoidal sulcus, usually absent in men. This small but conspicuous groove can be found ventrally and caudally to the iliac articular surface. Often, a pronounced bony edge is present at the ventral end of the groove. To this edge, part of the anterior joint capsule is connected.

Third decade

The characteristics that emerged during the second decade, are now clearly present, with the above mentioned exception of the mobility of the female sacro-iliac joint, which, according to Brooke, increases. During pregnancy, this increase is much more pronounced (Figure 1).

Investigating a female corpse from this age group, with pregnancy of 8—9 months, Brooke reports that mobility had increased by a factor two and a half, in comparison to non-pregnant women of comparable age. In one case of a deceased women with acute inversion of the uterus, the sacro-iliac ligaments had such laxity that the ventral edges of the articular surfaces yielded more than 0.6 cm. Figure 1 shows that mobility may, in extreme cases, increase twenty-fold between puberty and the end of pregnancy.

Sashin (1930) remarks:

> The relaxation of the ligaments surrounding the SI-joints was found in four instances, all females.
> Two of these, one a young woman of 23 and the other of 26, had normal deliveries just before death. In the third case, a woman of 27 had delivered an eight month premature foetus shortly before death, while the fourth, a twenty year old girl, died of septic abortion in the fourth month of pregnancy. In these cases the capsule was found loose, thinned out, and relaxed. A separation of the joint surfaces of over 6 mm. was easily obtained by manual traction. Di Gaspero reports that the anatomist, F.V. Müller, obtained a separation of 4 centimetres in a girl dying late in pregnancy.

One has to note that the observations of Brooke and Sashin were made in specimens where the fibrous and muscular apparatus were adapted to pregnancy.

Fourth decade

Around the age of thirty, a bony ridge is often found in the auricular surface of the ilium, and a central groove in the auricular surface of the sacrum.

It has to be emphasized that left-right symmetry is an exception rather than the rule. Even if pelves appear, at first sight, to be exactly symmetrical, detailed analysis of the sacro-iliac articular surfaces will reveal clear differences (Brooke, 1924; Schuncke, 1938; Bowen & Cassidy, 1981).

According to Brooke, hypermobility complaints become less frequent in women after the age of thirty, for which a hormonal mechanism appears to be responsible (Abramson et al., 1937).

There is an increased tendency of capsular thickening, both in men and women. Thick strands of collagen can be observed. Also the synovial membrane thickens, its vascularization diminishing (Sashin, 1930; Schuncke, 1938; Bowen & Cassidy, 1981).

The iliac cartilage roughens increasingly; sacral cartilage becomes more and more yellow and dull, and also somewhat rougher (Brooke, 1924; Sashin, 1930; Schuncke, 1938; Bowen & Cassidy, 1981; Stewart, 1984; Dijkstra et al., 1989).

Below the age of 50—general data

Upon analysis of 88 radiographs of people without low back pain, Cohen et al. (1967) report that 6% of those under 50 had articular and subarticular sacro-iliac erosion.

During routine autopsies, Resnick et al. (1975) investigated, radiologically as well as pathologically, 46 male and female sacro-iliac joints. They discriminated between para- and intra-articular arthrosis. In only one person below the age of 50, para-articular arthrosis was found, according to the authors a typical sign of osteoarthrosis.

In Brooke's (1924) investigation, 37% of 105 male preparations of diverse ages revealed complete ankylosis. In 105 female preparations, no ankylosis could be found.

It appears, therefore, justified to conclude that sacro-iliac ankylosis seldom occurs in women below 50, and not very often in men below 50. Of course, ankylosis may occur in the context of ankylosing spondylitis, i.e., Bechterew's disease (Resnick et al., 1975).

Above the age of 50

Around the age of 50, para-articular osteophytes usually arise at several places around the sacro-iliac joint. In men they are localized, in particular, around the cranial aspect of the joint, in women around its ventrocaudal aspect (Brooke, 1924; Stewart, 1984). In some cases, the osteophytes bridge the cleft of the joint. The articular surface erodes, leading, in rare cases, to the surfacing of subchondral bone.

In a study of our own (Vleeming et al., in press-a), we have observed that the iliac and sacral grooves and ridges are usually complementary. The cartilage covering the ridges is usually of about the same thickness as that on places without ridges.

According to Resnick et al. (1975), using conventional X-ray techniques, the joint cleft narrows at high ages. In people between 50—70 years of age, the cleft is usually between 0.1—0.2 cm, in people above 70 between 0—0.1 cm. One has to note that there exists a tendency to underestimate the width of the cleft because of the projection of the curvatures (Dijkstra et al., 1989).

According to Brooke (1924), progressive cartilaginous degeneration may present itself with local intercartilaginous connections, the joints of many patients containing *débris*. Both Stewart (1984) and we ourselves failed to observe such intercartilaginous connections. Brooke states to have found no ankylosis in female preparations, and indicates that ankylosis could be observed in 76% of the investigated male pelves above the age of 50. This is not in keeping with data from Stewart (1984) and Vleeming et al. (in press-a).

It may be of relevance that Brooke investigated people who lived before 1925. Their way of life and environment may have influenced the sacro-iliac joints. A more likely explanation for the differences between the data may derive from Brooke's methodology. In our own research, we found that male pelves, with their strong ligaments, are difficult to mobilize *post mortem*. Detailed analysis, however, usually reveals the pelves to be intact, without ankylosis. Brooke did not mention how 'ankylosis' was measured. It also remains unclear in how far the alleged ankylosis was caused by para- or intra-articular pathology.

In the study of Sashin (1930), which used 51 male and female preparations (> 60 years) it was observed that 82% of sacro-iliac joints in men above 60 showed local or global osteophytic pathology. In women this was 30%. McDonald and Hunt (1952) observed real intra-articular sacro-iliac ankylosis in no more than 2 out of 59 preparations. We ourselves investigated 24 female and 13 male preparations of different ages, both under embalmed and non-embalmed conditions. We found ankylosis in only 2 of the male preparations, one of which intra-articularly; both these preparations were over 60 years of age (Vleeming et al., in press-a).

In a study by Resnick et al. (1975), only in 4 out of 46 preparations real intra-articular ankylosis was found. Resnick et al. state that these were all cases of ankylosing spondylitis (Bechterew's disease), i.e., a pathological degeneration. Para-articular ankylosis was observed in 24% of the cases.

Differences in the experimental data concerning ankylosis derive, according to Resnick et al., from the lack of clear-cut criteria in these studies. They suggest to systematically discriminate between different aspects of the pathological process leading to ankylosis, i.e., para-/ intra-articular osteophytosis and/or the presence of osteophytes type II, i.e., osteophytes which completely bridge the joint, thereby causing real fusion.

The following scheme by Resnick et al. displays characteristics of the two most common sacro-iliac afflictions (Table 1).

Table 1. The two most common sacro-iliac afflictions (after Resnick et al., 1978).

	OSTEOARTHROSIS	**ANKYLOSING SPONDYLITIS**
AGE	OLDER PATIENTS	YOUNGER PATIENTS
BONY ANKYLOSIS	PARA-ARTICULAR	INTRA-ARTICULAR
SCLEROSIS	MILD, FOCAL	MAY BE EXTENSIVE
EROSIONS	ABSENT	MAY BE EXTENSIVE
LIGAMENT OSSIFICATION	RARE	FREQUENT

According to Resnick et al. (1975), who consider every change in the appearance of sacro-iliac cartilage to be pathological, changes of cartilage are, in the elderly, mostly due to osteoarthrosis.

Brooke (1924) states, concerning ankylosis:

> In males of late middle or of advanced age, the joints are usually amphi-arthrodial; in many cases complete ankylosis is present; but the number forms much too small a percentage of the whole to form the basis of a description of the normal state of affairs. In fact there is every reason to believe that such joints are not normal at all but the result of senile pathological changes.

We wonder if this small group of patients did, indeed, suffer from sacro-iliac ankylosis, as Brooke suggests. We argue that manually established immobility, if possible at all, is not sufficient to establish ankylosis. The joints may present extreme stiffness due to the presence of grooves and ridges but this does not exclude the possibility that the cartilage has remained intact (Vleeming et al., in press-a).

It is of relevance to describe Brooke's observations concerning the relationship between sacro-iliac ankylosis and changes in the lumbar spine. In 38 preparations, it was demonstrated that sacro-iliac ankylosis directly affects lumbosacral mobility.

Of these 38 cases of 'ankylosis', in our opinion to be interpreted as large resistance against movement and not as ossification per se, 81% had increased lumbosacral mobility; 19%, on the other hand, presented lumbosacral ankylosis. In the latter subgroup, mobility between the other lumbar vertebrae had increased. Moreover, it was observed that in the case of sacro-iliac ankylosis, the iliolumbar ligaments were rather thick. If one realizes that the alleged ankylosis occurs above the age of 50, these data become more important since they suggest functional adaptation to occur even at high age (Brooke, 1924).

Authors appear to agree in the description of histological changes in the sacro-iliac joint of the elderly. There is an increasing tendency of cartilaginous change, with irregularities on the articular surfaces, particularly at the iliac aspect of the male joint. Resnick et al. (1975) speculate that osteophytes may easily penetrate the thin iliac cartilage—sometimes through clefts in it, whether pathological or not.

They regard 'partial fibrous ankylosis' as a separate pathological entity, i.e., collagenous ankylosis rather than ossification. It occurs above the age of 50, particularly in men above 70, and includes progressive cartilaginous degeneration with thickening and sometimes dystrophic calcification of the joint capsule.

Stewart's 1984 study

To conclude this Section, we will comment on Stewart's 1984 study which described the sacro-iliac development per decade, making use of a large amount of material (1986 pelves), investigating racial and gender differences, and distinguishing between para- and intra-articular ankylosis.

According to Stewart, differences in gender render it very difficult to trace the osteophytic process that may lead to para- and/or intra-articular ankylosis. Possibly, Stewart refers in this respect to the interpretation of older literature in which the gender of the described material is often omitted. The differences in question have to do with the intensity of the osteophytic process as well as its localization. Following others (Brooke, 1924; Sashin, 1930; Schuncke, 1938; Bowen & Cassidy, 1981), Stewart observes that the most important sacro-iliac changes occur at the ilium, a fact which we have been able to confirm (Dijkstra et al., 1989).

Generally speaking, both para- and intra-articular formation of osteophytes is more rare in women than in men.

Concerning female ankylosis, Stewart gives the following quantitative data, without distinguishing between para- and intra-articular causes. Upon examination of 227 pelves of Caucasian women, 4% was found to be ankylotic, 2 of which unilaterally; 3% was ankylotic out of 167 American Negroid female pelves, all of them unilaterally; and also 3% of 100 African Negroid female pelves, again all of them unilaterally.

Stewart states that the (rare) occurrence of osteophytes—the possible cause of female ankylosis—may be due to intra-articular hemorrhage during pregnancy precipitated by the stretching of the ligaments.

In men, the osteophytic process occurs especially at the cranial aspect of the joint. Concerning male ankylosis, Stewart gives the following data. Upon examination of 347 American Caucasian male pelves, 11.2% was found to be ankylotic, 7.2% of which unilaterally, and the remaining 4% bilaterally; 24.9% was ankylotic out of 241 American Negroid male pelves, 15.8% of which unilaterally, 9.1% bilaterally; 8.6% of 335 African Negroid male pelves, 3.6% of which unilaterally and 5% bilaterally.

Table 2 summarizes Stewart's data on para-articular osteophytosis. A graphical display of para-articular osteophytosis, specified according to race, is found in Figure 2.

The classification of the osteophytic process takes place by using a system of weighted points, based on ten stages:

1.	bridging osteophyte, small, unilaterally,	2.	bilaterally,
3.	bridging osteophyte, large, unilaterally,	4.	bilaterally,
5.	osteophytic fusion, small, unilaterally,	6.	bilaterally,
7.	osteophytic fusion, large, unilaterally,	8.	bilaterally,
9.	total fusion, unilaterally,	10.	bilaterally.

Table 2. Distribution and intensity of para-articular osteophytosis (after Stewart, 1984).
The composition of the Table is best illustrated by an example. For the sixth decade 99 male pelves are available. From left to right, one reads that 22 right and 27 left sacro-iliac preparations had para-articular osteophytes. In the next columns, the amount of osteophytosis is weighted (on a ten point scale) by determining the stage of every individual pelvis. The average stage in the example under discussion, is around 2 (Stewart gives 41 points for the 22 right, and 46 for the 27 left preparations). The maximum for 99 preparations would be 990, i.e., in the case of bilateral total fusion in all of them. The 'percentage' in the last columns is calculated as actual points divided by maximally possible points—concerning the right column, (41/990) × 100 = 4.14.

		No. with Lip or Fusion		Osteophytosis Weighted		Percentage Involvement	
Decade	Paired Innominates	Right	Left	Right	Left	Right	Left
Males							
20-29	-	-	-	-	-	-	-
30-39	28	-	2	-	3	-	1.07
40-49	68	12	9	21	20	3.04	2.94
50-59	99	22	27	41	46	4.14	4.64
60-69	137	26	25	127	94	9.27	6.86
70-79	95	9	11	97	79	10.21	8.32
80-89	19	4	4	23	16	12.10	8.42
Totals	446	73	78	309	258	6.93	5.78
Females							
20-29	2	-	-	-	-	-	-
30-39	16	-	-	-	-	-	-
40-49	21	1	-	4	-	1.90	-
50-59	47	-	-	-	-	-	-
60-69	70	1	3	5	11	0.71	1.57
70-79	64	2	3	15	20	2.34	3.12
80-89	43	1	2	5	12	1.16	2.79
90+	4	1	1	6	6	15.00	15.00
Totals	267	6	9	35	49	1.31	1.34

It may be observed that at no age and in no subpopulation the ankylotic process ever exceeds 22%.

Stewart also reports on intra-articular sacro-iliac changes. He focuses on the ilium, where the changes are most pronounced. He concludes, as was to be expected, that this intra-articular change occurs more frequently at higher ages.

Upon examination of 308 Caucasian pelves (male as well as female), only 3 were found to be both para- and intra-articularly ankylotic; in 392 Negroid pelves, only one case of intra-articular ankylosis was found.

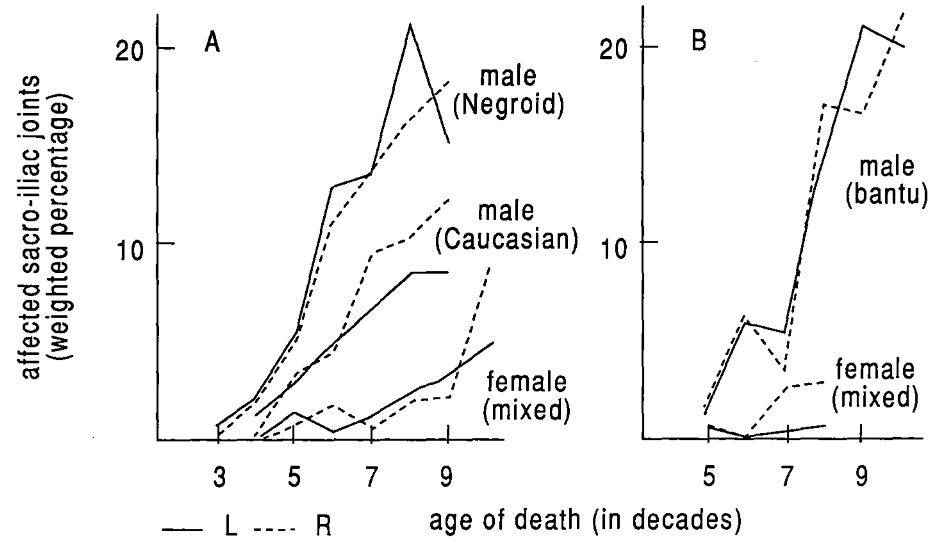


Figure 2. Distribution of para-articular osteophytosis (after Stewart, 1984).
A. America
B. Africa.

Table 3 summarizes Stewart's intra-articular data, using a four-point scale, from 'mild' to 'major' changes in the joint.

It has to be regretted that only the iliac side was taken into account. Symmetrical/complementary changes were left out of the analysis, and we may, therefore, have to do with the description of a physiological process.

Stewart's study contains important information. Obviously, the incidence of ankylosis is much lower than it had been thought formerly (Brooke, 1924; Sashin, 1930). This may be due to way of life and environment of the investigated, to criteria for the definition of ankylosis, or to errors in the observation, sampling or classification of ankylosis.

The very low frequency of female sacro-iliac changes shows that ankylosis, especially in women, is extremely rare. The possible difference between para-articular osteophytes and intra-articular changes was not analysed, which has to be regretted. It might be possible that intra-articular changes are physiological and para-articular osteophytes are pathological. It must be noted that Stewart described the intra-articular process (contrary to the para-articular situation) as 'change' rather than arthrosis. Stewart shows that para-articular ankylosis rarely occurs in both joints at the same time, and that the process has some preference for the right side. Finally, it appears that the localization of osteophytosis is different in men and women.

Table 3. Distribution of intra-articular sacro-iliac changes (after Stewart, 1984).

Age	Paired Innominates	Changes "Weighted" (+ to ++++)		Percentage Involvement	
		Right	Left	Right	Left
White males					
30-39	8	–	1	-	3.1
40-49	36	17	15	11.8	10.4
50-59	55	26	25	11.8	11.4
60-69	80	38	51	11.9	15.9
70-79	43	27	33	15.7	19.2
80-89	10	4	2	10.0	5.0
Totals	232	112	127	12.2 (5.5	13.8 6.9)*
White females					
30-39	5	2	2	10.0	10.0
40-49	5	1	1	5.0	5.0
50-59	12	5	8	10.4	16.7
60-69	20	21	21	26.2	26.2
70-79	21	21	23	25.0	27.4
80 & up	14	17	17	30.4	30.4
Totals	77	67	72	21.8 (12.0	23.4 14.9)*
Black males					
30-39	55	30	30	13.6	13.6
40-49	58	36	35	15.5	15.1
50-59	66	59	57	22.3	21.6
60-69	57	50	41	21.9	18.0
70-79	20	29	28	36.2	35.0
80-89	9	10	10	27.8	27.8
Totals	265	214	201	20.2 (14.0	19.0 13.7)*
Black females					
30-39	29	1	3	0.9	2.6
40-49	32	18	16	14.1	12.5
50-59	20	7	11	8.8	13.8
60-69	18	9	12	12.5	16.7
70-79	15	11	12	18.3	20.0
80 & up	13	13	16	25.0	30.8
Totals	127	59	70	11.6 (6.7	13.8 7.5)*

* Grade + omitted.

Regional anatomy of the sacro-iliac joint

Introduction

The spinal column can be seen as a flexible rod that keeps the body in the upright position. The pelvic girdle forms the connection with the supporting legs. The connection with the pelvic girdle is formed by, practically, the most caudal part of the spinal column, i.e., the sacrum. The intervertebral disc between L5—S1 protrudes towards ventral as does the basis of the sacrum (promontory).

Considerable forces are exerted in the area of the caudal intervertebral discs. The ventrally directed angle between L5 and the sacrum tends to become more acute under load since the sacrum will tilt towards ventral (Egund et al., 1978; Lavignolle et al., 1981). Accordingly, the strong ventral ligament of the spinal column, i.e., the anterior longitudinal ligament, is connected to the sacrum.

Fibrous connections are extensive between the sacrum and the surrounding bone structures (interosseous sacro-iliac ligaments in the sacro-iliac joint cavity, ventral and dorsal sacro-iliac ligaments, sacrotuberous and sacrospinous ligaments). In addition, the iliolumbar ligament connects the ilium with L4—L5 without direct involvement of the sacrum.

Both the tightness of the well developed fibrous apparatus and the specific architecture of the sacro-iliac joint result in limited mobility.

Intervertebral mobility is limited by, among other factors, ligaments. Since ligamentous and muscular connections exist that span non-adjacent vertebrae, movement between adjacent vertebrae affects non-adjacent ones. Similarly, tilting of the sacrum between the iliac bones affects the joints between L5—S1, and probably also the joints at the higher levels. Sacral movement does not only involve the sacro-iliac joints but also the disc between L5—S1 and the joint between the arch of L5 and the sacrum.

Anatomy textbooks tend to separate the fibrous apparatus of the lower spine from that of the sacro-iliac connection. This may serve a didactic purpose, but some information is lost in the process. In the present Section, the anatomy of the region is treated as a whole from dorsal towards ventral, with the exception of neuro-vascular topography, which is treated separately.

The anatomical description is based on our own observations, and on Bakland and Hansen's (1984) data, which we could confirm.

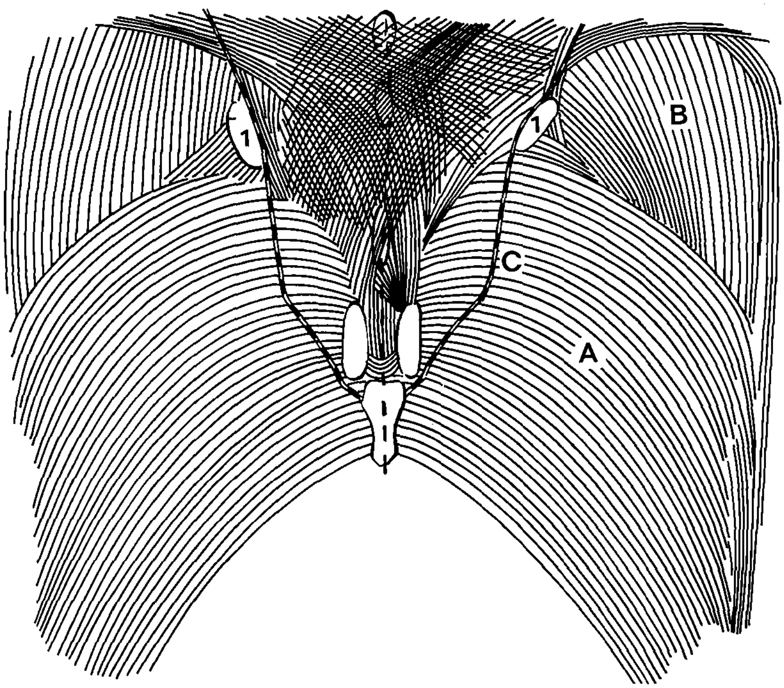


Figure 3[6]. Layers of the external fascia superficial to the sacrum with connections to the thoracolumbar fascia.
1. Posterior superior iliac spine
A. Fascia of the gluteus maximus
B. Fascia of the gluteus medius and the iliotibial tract
C. Lateral sacral crest.

The dorsal region

After removing the skin and the subcutaneous connective tissue, the fascia of the gluteus and of the erector spinae can be inspected (Figure 3). Obliquely crossing fibres of the thoracolumbar fascia are conspicuous. The fascia of the gluteus maximus inserts, in part, into this fascia, allowing the muscle to stretch it.

[6] Figures 3—8 have been produced in our department.

In Figure 3, *B* represents the fascia of the gluteus medius and the iliotibial tract. Forces exerted on these structures may somewhat deform the fascia that covers the iliac crest. Some fibres of the gluteus medius fascia and the iliotibial tract are connected with the thoracolumbar fascia.

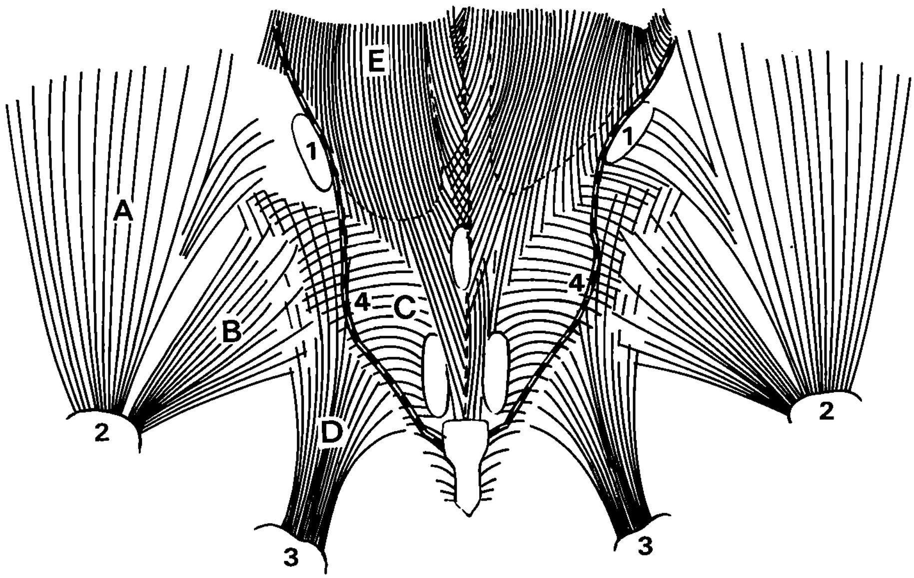


Figure 4. After removing the superficial layers of connective tissue.
1. Posterior superior iliac spine
2. Greater trochanter
3. Ischial tuberosity
4. Lateral sacral crest
A. Gluteus medius
B. Piriformis, with dorsal continuation in sacrotuberous ligament
C. Connection of gluteus maximus with sacrum and back muscles
D. Sacrotuberous ligament
E. Aponeurosis of the erector spinae.

Figure 4 displays the region after the removal of the superficial layers of connective tissue. Tendinous structures of the erector spinae have become visible by now (*E*). It is impossible to separate the superficial fascia from the underlying tendinous structures around the spinous processes: fibres of the superficial layer insert in the deep layer and deep fibres insert superficially.

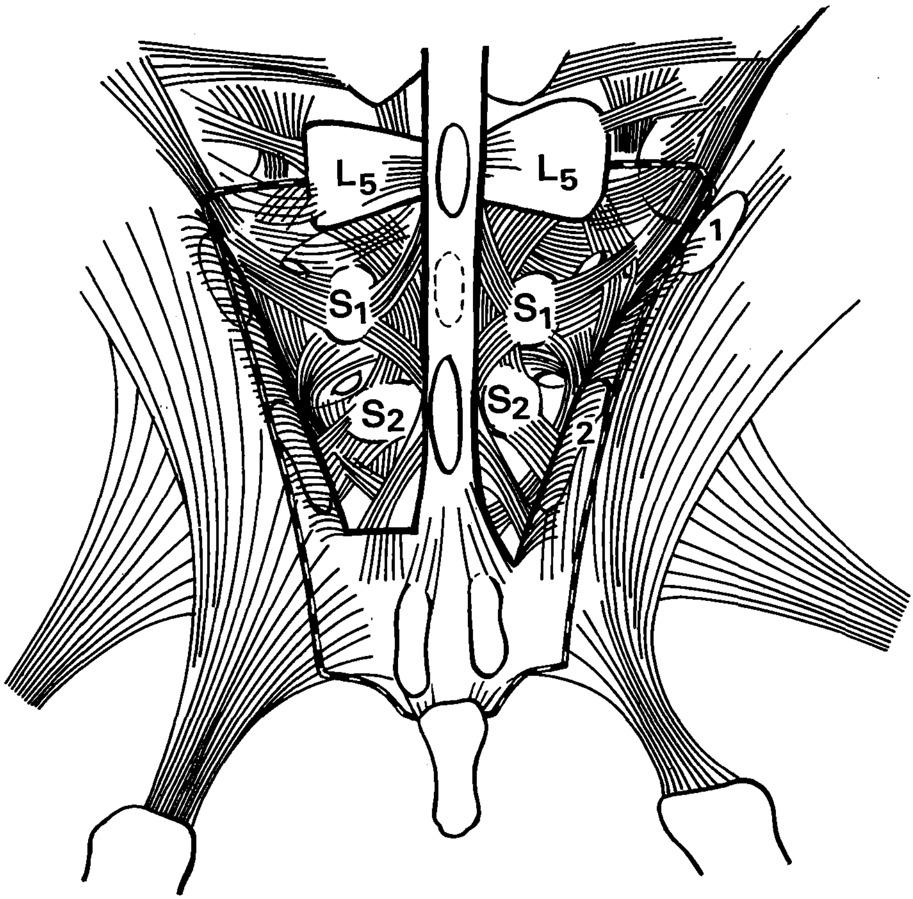


Figure 5. Intertransverse, dorsal sacro-iliac and iliolumbar ligaments, visible after removing the ligaments connected to the erector spinae.
1. Posterior superior iliac spine
2. Lateral sacral crest (only globally indicated).

The most caudal part of the erector spinae is localized in the depression between the median sacral crest and the posterior superior and inferior iliac spines. The muscular and tendinous tissue in this area is two-layered, a superficial layer (mostly iliocostal) and a deep one (multifidus). Contractions of these muscles will stretch the fascia. The external fascial layer is in part continuous with the fascia glutea, covering the gluteus muscles, and with cranial muscle fibres of the gluteus maximus. The erector spinae and the gluteus maximus, therefore, are functionally interdependent in controlling the force that is mutually exerted by the ilium and the sacrum.

The sacrotuberous and sacrospinous ligaments become visible after removing the gluteus maximus. Due to the tightness of the connections with the ischial tuberosity, they may be difficult to remove.

In all preparations (N = 12), the thin dorsal fascia of the piriformis was continuous with the sacrotuberous ligament.

In two cases, the dorsal fascia of the piriformis was bilaterally aponeurotic. In these cases, the ventrolateral border of the ligament was continuous with the dorsal fascia of the muscle.

Forces exerted on the muscle can slightly deform the ligament.

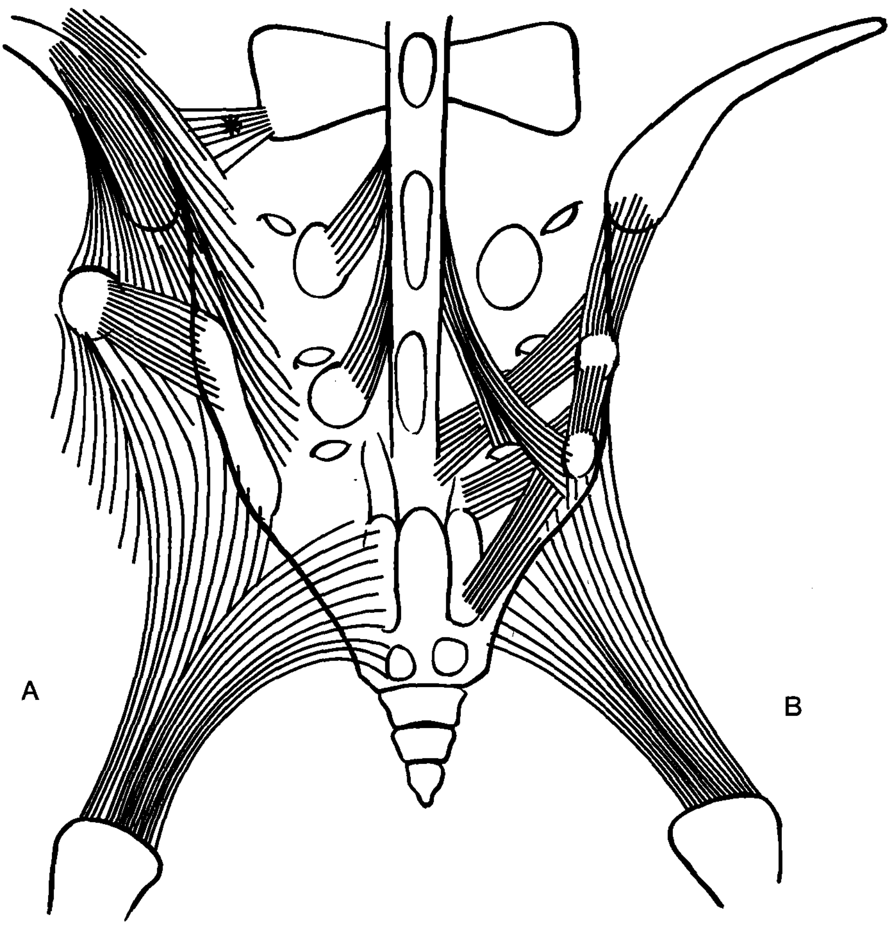


Figure 6. After removing the remaining parts of the gluteus maximus.
A. First (more superficial) view; note the iliolumbar ligament (*)
B. Second view (after removing the ligaments visible in A).

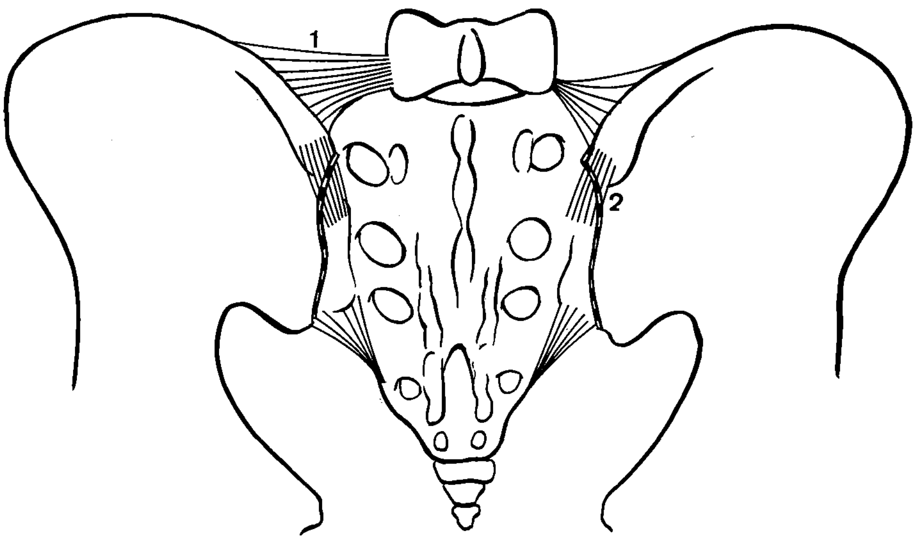


Figure 7. The fibrous apparatus at the deepest level.
The dotted line refers to the dorsal border of the sacro-iliac joints.
1. Iliolumbar ligament
2. Thick part of dorsal sacro-iliac ligament.

In 5 female and 1 male preparations (N = 23), the biceps femoris bilaterally radiated out into the sacrotuberous ligament without being connected directly to the ischial tuberosity. In 5 other preparations, the biceps femoris, unilaterally, was partly connected to the corresponding sacrotuberous ligament and ischial tuberosity. In all these cases, the biceps femoris is able to stretch the ligament (Vleeming et al., 1989-a & b).

After freeing the erector spinae and its fibrous sheath from the ligaments connected with the muscle, the intertransverse, dorsal sacro-iliac and iliolumbar ligaments can be seen (Figure 5). The intertransverse ligaments are usually depicted only in the lumbar region but do exist lumbosacrally as well. Centrally, covering the spinous processes, one may see a superficial fascia connecting the sacrum with L5—L4.

> If one takes the extensiveness and localization of the fibrous apparatus into account, one comes to the conclusion that we have to do with an important functional link between L5—L4. A sitting position with pronounced kyphosis, evokes tension in all dorsal muscles and ligaments.

One is reminded of the fact that keeping the shoulder for a longer period of time at the end range of motion may result in pain, usually attributed to overstretching the ligaments. The fibrous apparatus under discussion, therefore, deserves more attention in cases of patients with non-radiating low back pain related to sitting positions with kyphosis.

After removal of the remaining parts of the gluteus maximus, the deep aspect of the dorsal sacro-iliac ligament becomes visible (Figure 6A), at several places tightly connected to the gluteus maximus.

Forces exerted on this muscle stretch the fibrous apparatus. Most textbooks of anatomy only discuss functional relationships between muscles and bones, omitting the above-mentioned functional relationships between muscles and the fibrous apparatus.

After the removal of ligaments, resulting in Figure 6A, deeper strands of connective tissue become visible, the fibres having a different orientation, as in Figure 6B.

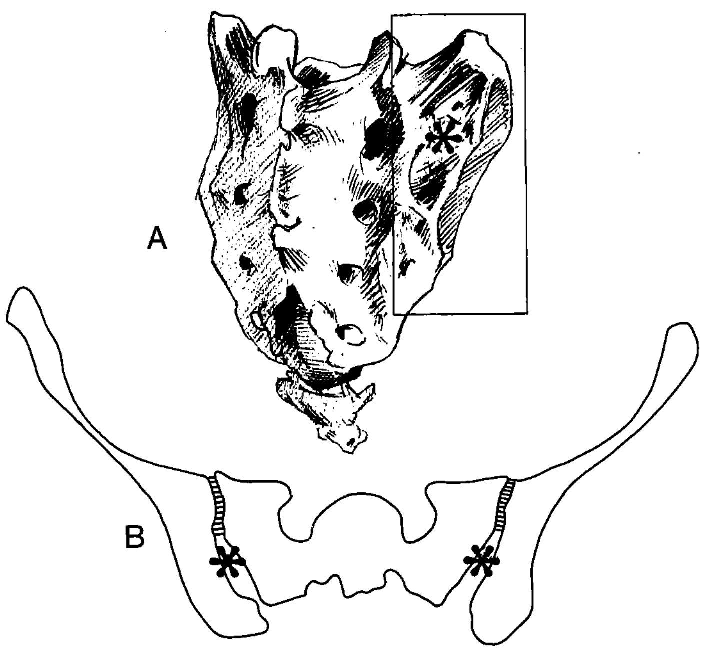
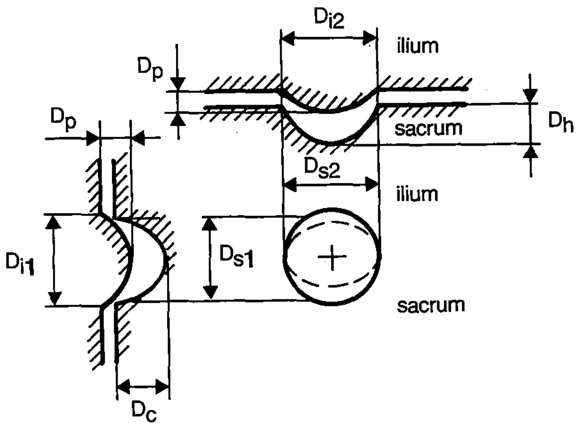


Figure 8. The 'axial' joint (*) shown from latero-dorsal (A) and in transverse section (B).
The shaded area in Figure B represents the auricular surface.



D_h = depth of cavity
D_p = height of prominence
D_{i1} = craniocaudal expansion ilium
D_{s1} = craniocaudal expansion sacrum
D_{i2} = anteriorposterior expansion ilium
D_{s2} = anteriorposterior expansion sacrum

Figure 9. Technical drawing of ball-and-socket relationships in the axial joint (after Bakland & Hansen, 1984).

Figure 7 summarizes the relationships as they are usually described in anatomical textbooks. This Figure, as well as the preceding ones, illustrates how difficult it is to manually investigate the sacro-iliac joint directly (dotted line in Figure 7). The fibrous apparatus connecting the posterior superior iliac spine with the sacrum, belonging to the dorsal sacro-iliac ligaments, may have an anterior-posterior diameter of as much as 1 cm.

Concluding remark
The biceps femoris, the gluteus maximus and the erector spinae are able to stretch the rather complex dorsal fibrous apparatus in the area of L4—S1 and of the sacro-iliac joints. Major interindividual differences exist.

The 'axial' joint

Although many investigators have reported 'extra-articular' joints in the sacro-iliac area, Bakland and Hansen (1984) were the first to offer a detailed description of the area dorsal to the auricular surfaces (Figure 8). Bakland and Hansen coined their extra-articular joint as the 'axial' joint because of what they suppose to be the localization of the axis for sacro-iliac tilting movements (nutation and contranutation). The authors report that the axial joint presents very little congruence; in most of the preparations the convexity of the ilium is too large for the concavity of the sacrum (Figure 9). The function of a plate of fibrous cartilage, usually present at the iliac side, may be adaptive.

Using a system of coordinates (see coordinate lines of auricular and axial sacro-iliac joint in Figure 10A), Bakland and Hansen classified intra- and interindividual differences (Figure 10B).

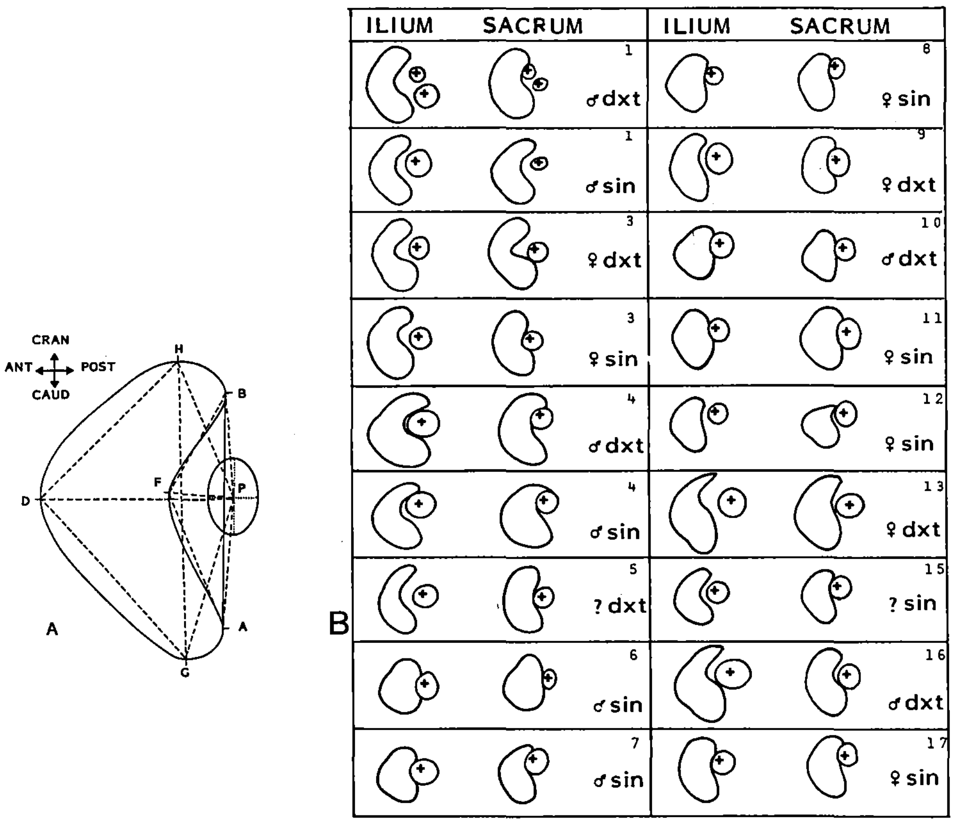


Figure 10. Intra- and interindividual sacro-iliac differences (after Bakland & Hansen, 1984).
10A. Coordinate system
10B. Differences in the geometry of the auricular and axial areas.

Because of the multitude of intra- and interindividual differences the interpretation of the results of manual investigation of sacro-iliac mobility, requires extreme care.

In view of the importance of Bakland and Hansen's research, we have tried to confirm their observations, using 5 preparations. It turned out to be extremely difficult to assess the 'axial' joint due to both the irregular bony contours and the extensive fibrous apparatus. Between ilium and sacrum, we found a funnel-shaped complex of interosseous ligaments, the apex of which is connected to the sacrum. The iliac cartilage of the 'axial' joint is localized in the middle of the funnel.

Because of the difficulty to establish exactly the border between fibrous apparatus and cartilage, confirmation of the details of Bakland and Hansen's observations is not possible. In general terms, however, we have confirmed their morphological results. We agree that the 'axial' joint requires more attention but we are of the opinion that coining the term 'axial' is hardly justified since so little is known regarding the exact axes of sacro-iliac movement.

The ventral region

A short description of the general topographical relationships of the ventral fibrous apparatus may be sufficient.

In the area between the psoas major and the cranial insertion of the obturator internus, a rather unimpressive ventral sacro-iliac ligament relates closely to the lumbosacral trunc (fibres from L4—L5) and the nerve bundle of the obturator nerve. The psoas major is intimately related to the sacro-iliac joint. Major blood vessels can be found nearby (iliac artery and vein).

Neuro-vascular supply of the sacro-iliac joint

As is true in so many cases, the innervation of the sacro-iliac joint is taken care of by nerves which are responsible for muscles inserting into the joint capsule. More specifically:

- dorsally—in general, by end branches of the dorsal branches S1—S2;
- ventrally—fibres from the ventral branches L4—S1, sometimes also S2 and (rarely) L3; the most constant factors appear to be the involvement of L4—L5 and of the superior gluteus nerve (L4—S1).

Sacro-iliac vascularization obeys the same general principles, but blood vessels may also stem from the periost.

Investigating sacro-iliac mobility

The study by Egund et al. (1977)

Egund et al. (1977) made use of 'roentgen stereophotogrammetry' (Selvik, 1974; Suh, 1974). This methods offers the opportunity of an *in vivo* investigation without the need to exactly know the relative positions of the X-ray source, the film and the investigated object. In practice, this implies that sacro-iliac mobility can be investigated in the living, provided that a reference is also photographed; usually the object to be investigated is moved with respect to a visible reference system.

In order to analyse sacro-iliac mobility, radiograms are made in two different body positions. The system is tested and calibrated by using skeletons and preparations. Under local anesthesia, Egund et al. inserted 12 small tantalum balls (diameter 0.08 cm) as markers for the sacrum and the iliac bones. This technique has none of the disadvantages of externally registering movement by using thin steel rods which may slip off, due to fascia or muscle movements (Colachis et al., 1963).

Three female and one male patient were investigated by using the above method under several positional transitions such as the transition from a prone or supine position to standing. Earlier, these patients had undergone routine investigation of the low back because of problems in that area.

Two of the figures of Egund et al. are reproduced here (Figure 11), each derived from one patient. The effects of different positions are compared and the data are interpreted in terms of sacro-iliac movement.

'Positive rotation of the sacrum around a transversal axis' implies that the promontory tilts towards ventral and caudal (nutation). 'Positive rotation around a longitudinal axis' implies a rotation to the right of the anterior surface of the sacrum. 'Positive rotation around a sagittal axis' implies rotation of the cranial surface (the base of the sacrum) towards the right. 'Negative rotations' refer to the opposite movements.

It is assumed that the various axes of movement pierce the centre of the sacrum.

Discussion of this study

Inspection of the figures reveals that only small movements are registered; there is no rotation exceeding 2°.

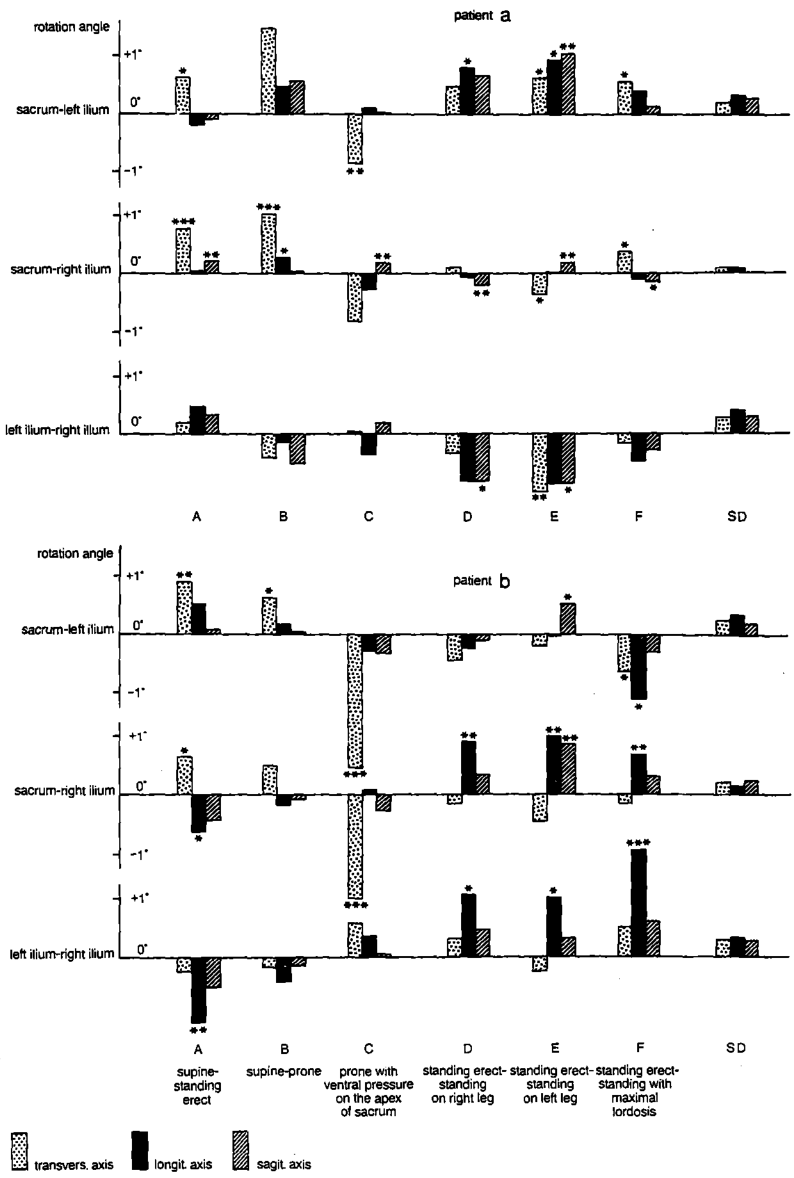


Figure 11. Sacro-iliac mobility in the study of Egund et al. (1977).
a—b refer to two different patients.
Note that positive and negative rotation is described with respect to transversal, longitudinal, and sagittal axes.
Per graph, the number of asterisks is related to the level of significance.

A point of critique is that the bony structures involved may deform when using the above method. For instance, 'C' in the figures refers to pressure on the apex of the sacrum. In corpses without *rigor mortis*, we ourselves observed considerable deformation of the sacrum. In this context, we removed some bony material from the posterior superior iliac spine. Steel rods were inserted into both the ilium and the sacrum, without destroying the integrity of the joint. Upon manual pressure (15 kg), hardly any, or no sacro-iliac movement occurred, but the sacrum deformed, the base yielding 0.5—1 cm with respect to the apex. Further analysis of these preparations revealed that the sacro-iliac joints did have some mobility, suggesting that bony deformation does not result from immobility of the joint.

The changes which Egund et al. did observe were interpreted in terms of sacro-iliac movement. However, the possibility of deformation should be taken into account. Of course, the markers were close together, not allowing for considerable yielding through deformation, but the range of motion was also extremely small.

According to Egund et al., their research supports the idea of sacro-iliac hypermobility, that had been suggested earlier by the manual comparison of right and left sides of the sacro-iliac joints of patients. To us, a real problem is the use of such an ill-defined term as 'hypermobility' in the context of an otherwise well designed experiment. What would 'hypermobility' imply for the sacro-iliac joints? Whenever one examines a patient, one does not know if 'deviations' are to be understood as normal anatomical variation, or as acute or chronic pathology. In our own research (Vleeming et al., in press-b), focusing on surface resistance in the sacro-iliac joint, none of the investigated joints was completely symmetrical. Bakland and Hansen (1984) observed the same lack of symmetry.

Given left-right asymmetry, different ranges of motion have to be expected. 'Hypermobility', *qua* comparison with the other joint, therefore, is a term which fails to acknowledge the fact that it remains unclear which of the two joints, if any, is abnormal. Probably, tests to diagnose 'hypermobility' are, in general, not specific enough.

Hence, we remain, uncertain as to the question whether 'hypermobility', as defined by Egund et al., is normal or abnormal and whether it is specific to the sacro-iliac joint. In order to be able to draw valid conclusions, simultaneous investigation of lumbar mobility would have been a precondition.

It is of particular interest that caudal pressure on the apex of the sacrum, as well as moving towards a position with maximal lordosis, apparently leads to sacro-iliac movement. If these procedures are painful, one may have to do with an affliction of the connections of the sacrum (sacro-iliac joint, intervertebral disc L5—S1, the joint between the arch of L5 and the sacrum, or the ligaments in this region). Of course, the above tests—caudal pressure and maximal lordosis—do not discriminate between sacral and lumbar pathology.

Egund et al. (1977) state that most sacro-iliac movement occurs around a generalized transversal axis, with a range of motion up to 2°. One may note that Egund et al. indicate that generalized rotation axes of the joint pass dorsal to the auricular surfaces (Figure 12).

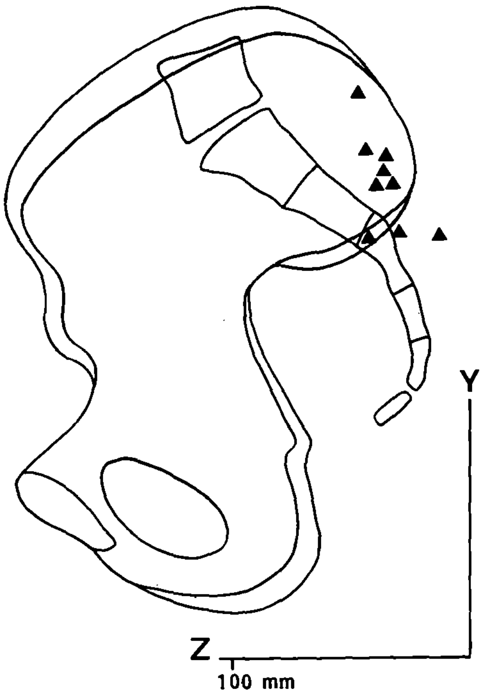


Figure 12. Possible positions of the transversal axis (after Egund et al., 1977).

Their study reveals that several positional transitions lead to movement between the left and right posterior superior iliac spines, with a range of motion of not more than 0.4 cm. The study suggests that the sacro-iliac joints may allow for more mobility of the sacrum than of the iliac bones which do not move much with respect to each other. This is of practical relevance since a number of standard manual tests explicitly rely on the posterior spines to measure left/right differences and sacro-iliac mobility.

The study by Frigerio et al. (1974)

The study by Frigerio et al. (1977) is also based on stereophotogrammetry. It is cited frequently, on the one hand because it speaks of large sacro-iliac mobility, on the other because it probably contains important experimental errors (Walheim et al., 1984). Only one test person is used, the other material for the study derives from one preparation and one skeleton.

As in the study of Egund et al. (1977), there are two X-ray devices. The only calibration is done on a preparation under complete control of movement. In this ideal situation, a shift of position is induced and monitored with stereophotogrammetry. The measurements revealed a standard error of 0.03 cm. Subsequently, the test person is investigated under three different positions, i.e., with the legs in a 'neutral' position, with 30° flexion in the right hip and maximal extension of the left hip, and *vice versa*. Among other data, the authors report deformation of 0.06 cm between a cranial and a caudal point of reference on the right iliac bone, and of 0.39 cm between similar reference points at the left side.

Discussion of this study

The observed difference in left and right ilium deformation, evokes questions as to the other data of this study. In our opinion, the results of the study by Frigerio et al. have to be interpreted with great care, also in view of the rather limited number of participants (N = 1) and the calibration method that was used.

Frigerio et al. conclude that sacro-iliac movement is possible up to several centimetres. This is in contradiction with data of other studies, reporting not more than 0.5 cm (around a generalized transversal axis). The test person in this study was lying on one side which hardly allows generalization to, e.g., the upright position.

Frigerio et al., however, use their data to draw general conclusions about 'normal' sacro-iliac mobility. They claim that their research 'end a long standing controversy regarding sacro-iliac mobility'.

The study by Colachis et al. (1963)

The studies discussed so far, used methods hard to apply in practice. Colachis et al. suggest to have solved this problem by inserting 0.15 cm diameter Kirscher steel rods into the posterior superior iliac spines of test persons.

The following rationale is presented. The insertion of two rods in the right, and one rod in the left posterior superior spine, and the marking of special points as ABC and A'B'C' (Figure 13A), brings two parallel planes into existence. With the exception of asymmetrical deformation of exclusively the rods on the right hand side, changes in these planes imply sacro-iliac movement.

Twelve test persons were used, eleven between 22—32 years, and one 44 years of age. No specifications as to gender are mentioned. In order to exclude skin and fascia movements as much as possible, the rods were inserted in the caudal aspects of the spines, directly accessible to manual examination. The test persons were investigated in a number of different positions (Figure 13B). Measurement of rod position was performed with an ill-defined instrument. If movements take place between the right two rods (BB'C'C), these data were excluded from the final material.

Specific results of this study are not given by the authors. Large inter-individual differences are reported. It was concluded that the largest range of motion in the rods could be observed during the transition from the standing position (*G*) towards flexion of the trunk (*I*, see Figure 13). The rods approach each other during this transition. The largest observed displacement, measured at the base of the rods, was reported to be 0.5 cm.

Discussion of this study

The researchers state that only limited results may be expected from the methodology used.

The most import conclusion appears to be that the left and right ilium can move 0.5 cm with respect to each other. Sacro-iliac movement, however, cannot be exactly measured by using this method. The interiliac movement that was reported only implies sacro-iliac movement in so far as no rod slipped off, and no bony deformation occurred.

It was tacitly assumed that (various) asymmetrical positions imply asymmetrical sacro-iliac movements. In and of itself this is correct, but this asymmetry cannot be measured by using the iliac bones exclusively.

The sacrum can move between the iliac bones which, in their turn, function as anchor points. Rotation of the sacrum around a generalized transversal axis does not have to lead to measurable corresponding movements of the iliac bones.

The observation that the rods approached each other upon flexion of the trunk, was to be expected: through the increasing tilt towards ventral, the sacrum stretches the dorsal sacro-iliac ligaments, which causes the iliac bones to approach each other (Solonen, 1957).

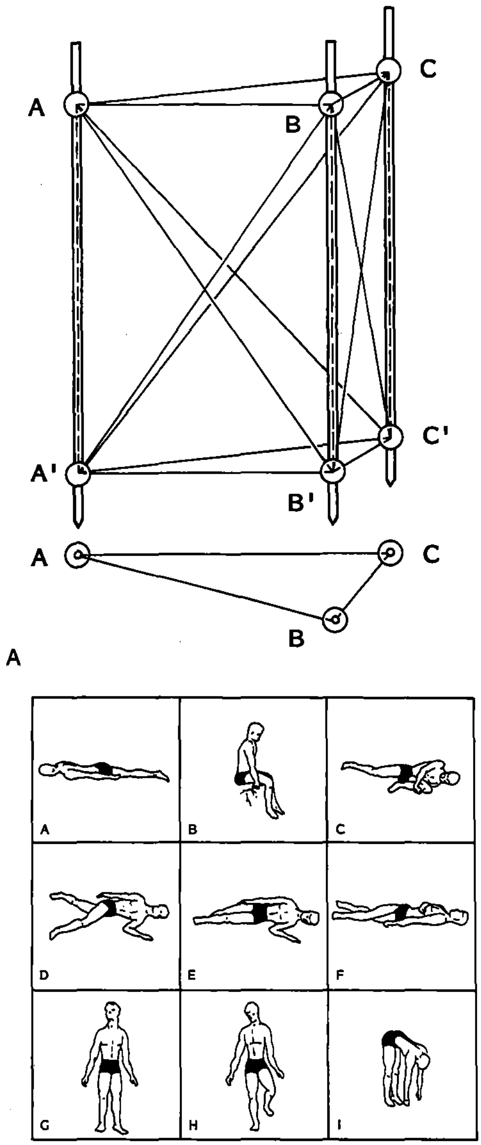


Figure 13. The study of Colachis et al. (1963).
A. Two planes defined by marker points on three rods
B. The positions analysed.

The authors' suggestion that this method is practical does not seem to be justified, due to the invasive character of the technique. A method with real practical value has to be non-invasive.

Data on asymmetrical movement of the right rods were not discussed because they supposedly resulted from movements of the skin or the fascia. Both right rods, however, are placed on the same skin and the same fascia. It is true that the fascia is caudally less thick than cranially but tension could lead to *symmetrical* movements of the rods which, then, would be discussed. An imbalance in presenting the results is certainly possible.

We ourselves did a pilot study on three corpses with rods with a diameter of 0.5 cm. Even with rods of this size, we have observed rod movement due to deformation of the fascia provoked by the exertion of forces on the sacrum and the ilium. Since the rods Colachis et al. used were much thinner, movement resulting from fascia movement can not be excluded.

In conclusion, the study of Colachis et al. appears to indicate that trunk flexion implies a tilting of the sacrum towards ventral and movement of the iliac bones towards dorsomedial. The latter phenomenon is due to increased tension in the dorsal sacro-iliac ligaments.

The study by Lavignolle et al. (1983)

After studying sacro-iliac mobility in preparations, Lavignolle et al. investigated the *in vivo* positions of the generalized movement axes. The most relevant 'movement' in question is a combination of rotation and translation of the ilium with respect to the sacrum. Five volunteers were examined, two women and three men.

In the supine position, active asymmetrical movements were performed, supposed to imitate walking by either flexing the right hip 60° or extending the left hip 15° (in the latter case the left leg was extended alongside the table). The system used to fix pelvis and trunk is not described in detail.

Lavignolle et al. relied on roentgen stereophotogrammetry. The positional transitions were described with reference to a three dimensional framework, skeletal 'landmarks' (which are not specified) and, probably, specific lines being used for orientation.

The calculation of the loci of the various axes was done by averaging the results of experiments using different individuals. The axes were oriented with respect to the ilium (Figure 14). A_1 in Figure 14, for instance, designates the generalized axis for the transition from a relaxed supine position towards a supine position with 60° hip flexion. The average sacro-iliac rotation around this axis (A_1) is 12°, the crest of the right ilium rotating towards dorsal and displacing towards medial (cf. Colachis et al., 1963). Hence, the iliac bones approach each other dorsally. In this process, the right ischial tuberosity tilts (in principle) towards ventral and lateral, which results in a lateral pull on the pubic symphysis. With respect to the sacrum, the ilium translates on the average 0.6 cm.

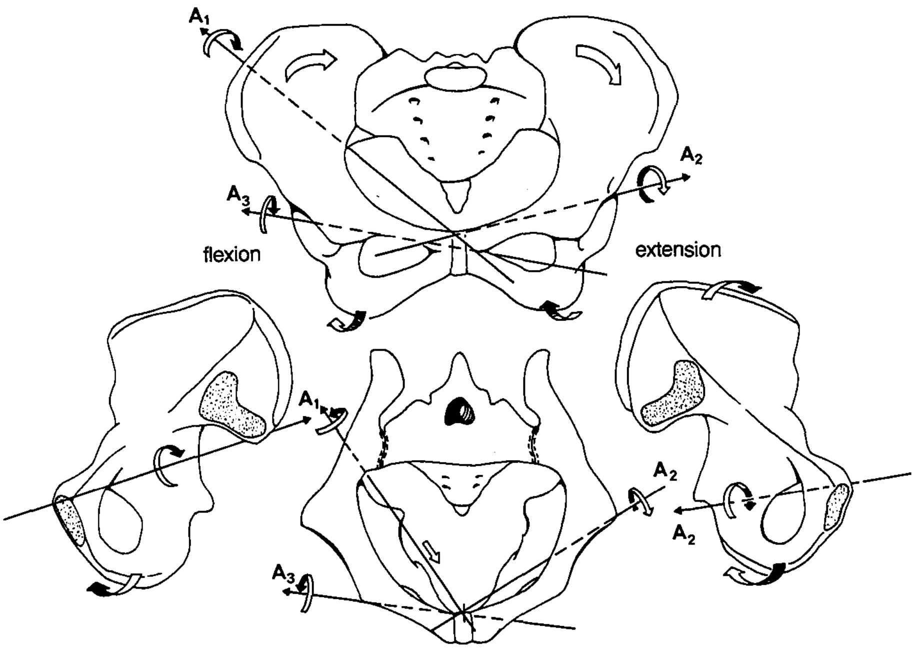


Figure 14. Movement axes according to Lavignolle et al. (1983). All movements take the supine position as the starting point. A_1 is the generalized axis for the right sacro-iliac joint during hip flexion, A_2 is the generalized axis for the left sacro-iliac joint during hip extension, A_3 the generalized axis for interiliac movement.

When the left hip is extended 15°, the left ilium moves with respect to the sacrum. A small rotation—on the average 2°—can be shown to take place around the generalized axis A_2. The crest of the left ilium turns towards ventral, the cranial aspects of the iliac bones move further apart dorsally. The left and right ischial tuberosities, on the other hand, approach each other. Subsequently, Lavignolle et al. calculated the generalized axes for the movements under study with respect to reciprocal displacements of the iliac bones. This calculation was performed for extension on the left side and flexion on the right side. Finally, the 'instantaneous centre of rotation' (ICR) was calculated. This centre appears to be localized in the cranial aspect of the symphysis.

According to Lavignolle et al., the sacrum *translates* towards ventral with respect to the iliac bones in the supine position, both in flexion and in extension of the hip. This movement was presented as anterior 'opening' of the pelvis, allowing rotation of the sacrum with respect to the ilium. This is of relevance since Solonen (1957) remarked that the intrinsic structure of most sacro-iliac joints precludes almost all movement. 'Opening' by translation could be necessary to allow for rotation. Lavignolle et al. concluded that the sacro-iliac joint remains a mystery, notwithstanding all these experiments.

Discussion of this study

In Lavignolle et al.'s sophisticated study, two positional transitions are studied: 60° hip flexion and 15° hip extension, both in the supine position. The resulting sacro-iliac movements (after ventral translation of the sacrum) are taken as nutation and contranutation by the authors. Such movements in a supine position can be characterized as movements in an 'open articular chain'. If one compares the movements in the supine position with walking, one has to realize that during walking a sacro-iliac joint carries part of the body weight even during the swing phase. It is this load that leads to nutation (Weisl, 1955; Egund, 1978; Solonen, 1957), stretching the dorsal ligaments (Solonen, 1957; Weisl, 1955; Wilder, 1980).

Lavignolle et al., on the other hand, investigated a position with abnormal effects of gravity, circumventing thereby the normal functional role of the sacro-iliac joint. Their conclusions should have been restricted to those situations which had been investigated.

The less critical reader of the study by Lavignolle et al. may be tempted to conclude that the sacro-iliac joint 'normally' does not bear the weight of the body. The authors state that hip flexion results in 12° sacro-iliac rotation (i.e., relative nutation of the sacrum) with a relative translation of the ilium towards dorsal. If a person stands upright, however, 12° rotation is impossible since the sacrum has almost reached the end range of motion (Solonen, 1957; Weisl, 1955; Egund, 1978).

There is another way to underpin this critique. During leg extension only 2° rotation, i.e., relative contranutation of the sacrum, is reported. The supine test persons extended their leg beside the table, with the sacrum already in contranutation, a fact which restricted the range of further ventral displacement of the ilium. While standing upright, the opposite is true. Extension of the leg, with the sacrum in nutation, allows the ilium more space to move towards ventral in the sacro-iliac joint.

In the context of various movements, the axes of movement show intra-individual variability (Wilder, 1980). It is misleading to generalize the localization of the axes in the supine position to weight-bearing positions as implied in the study Lavignolle et al. The pinpointing of an ICR, valid for all positions, appears to be highly doubtful.

Lavignolle et al. claim that Weisl also found an ICR in the cranial aspect of the symphysis. This, however, is incorrect since Weisl's research was restricted to sacro-iliac rotations and assumes such rotations to take place around an axis about 5—10 cm caudal to the promontory. Lavignolle et al. proposed to drop the old ideas about the localization of the sacro-iliac axis of rotation.

In our opinion, the most important idea that emerges from the detailed study by Lavignolle et al. is the relatively large amount of sacro-iliac mobility in the supine position (e.g., contranutation of the sacrum). This mobility will reveal itself in the movements of the freely swinging leg or during unilateral activities such as hip flexion. It is to be expected that in people where the upright position does not lead to nutation of the sacrum, sacro-iliac ranges of motion will turn out to be increased.

Egund et al. (1979) demonstrated that the sacrum tilts towards ventral (nutation) whenever a position includes lumbar lordosis. It is of relevance to note that weight lifters, when lifting very large loads, bring the lower back into lordosis if the position of the loads to be lifted allows for such a movement. Apparently, nutation (sacrum tilted towards ventral) can be regarded as the 'secured' position of the joint.

The results of this study, making use of a precise method of calibration, are obviously different from the results of other investigations—a difference which, in our opinion, can be ascribed to the difference in the positioning of the test persons. Egund et al., for instance, gave a maximum of 2° for sacro-iliac mobility, whereas Lavignolle et al. report 12°.

The Lavignolle et al. data have implications for the SLR-test (straight leg raising). A large number of variables plays a role when patients undergo an SLR-test. The study under discussion indicates that the supine position leads to relatively large sacro-iliac mobility during hip flexion. Sacral mobility, in its turn, may influence other parts of the spinal column (Vleeming et al., in preparation).

The study by Walheim et al. (1984)

Ever since the nineteen thirties, a radiological method to diagnose pelvic instability is available, named after Chamberlain (1930). Anterior-posterior radiograms are taken while the patient is asked to stand on one, and then on the other leg, the contralateral leg hanging free. This appears to be the only clinical method to establish pelvic and, hence, sacro-iliac instability.

According to Chamberlain, the criterion for abnormal mobility is vertical pubic movement of more than 0.2 cm. Steiner et al. (1977) mention a minimum of 0.4 cm as being pathological, Hagen (1974) 0.5 cm. Since the symphysis tilts on the average about 45° with respect to the frontal plane, anterior-posterior measurement will tend to underestimate real mobility.

Walheim et al. (1984) endeavoured to develop a better norm for pelvic instability. Pubic mobility around the symphysis was measured electro-mechanically, two rods allowing for continuous registration of pubic movements. These rods, with a diameter of 0.3 cm and a length of 15 cm, were inserted 2 cm into the cranial aspect of each pubic bone (Figure 15A).

Tests were performed on 4 embalmed corpses and, under local anesthesia, on 14 young male volunteers with no known locomotor problems. A second group consisted of 6 male volunteers between 21—27 years of age, 6 nulliparous women, and 3 multiparous women.

The rods were connected to registering devices, allowing for monitoring translations and rotations in two planes. A specific coordinate system was used (Figure 15B) in order to describe the movements. In the starting position, the rods made an angle of 45° with the frontal plane. Walheim et al. reported measurement errors of less than 0.005 cm.

Supine test persons were asked to flex the hip 90° and then perform maximal abduction. Registrations also took place during walking. During these tests, the maximum error was 0.008 cm for translations and 0.08° for rotations.

It could be shown that the pubic bones translate vertically during walking. Average displacement was 0.10 cm in the male and 0.13 cm in the female, with a maximum of 0.31 cm in one of the multiparous women.

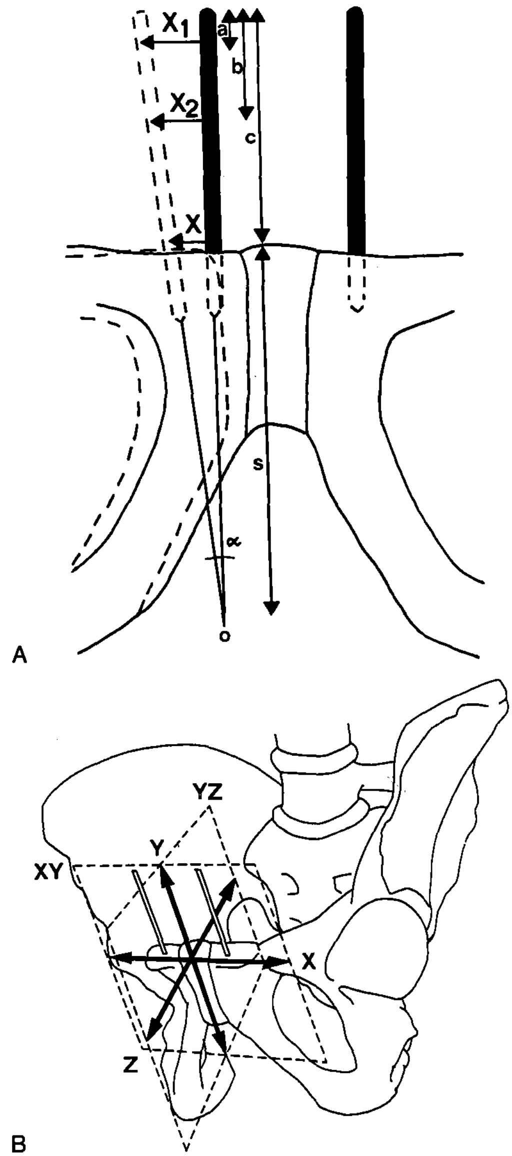


Figure 15. The experimental set-up in the study of Walheim et al. (1984)

A. The rods in the pubic bones with a schematic display of movement in the XY-plane; X_1 and X_2 are the points where the registering device connects with the rods

B. Coordinate system used to describe the data.

Rotations around a transversal axis (i.e., in the YZ-plane) were less than 2°, again with little difference between men and women. The average YZ-rotation was not more than 0.3—0.8°, much less than the values found by Pitkin in 1947 (i.e., 5.5°). Since Pitkin's method of registration lacked precision, Walheim et al.'s data appear to be more reliable.

Rotations around an idealized sagittal axis (i.e., in the XY-plane) were found to be 0.4°, without clear differences between the sexes. During a transition from the supine to the upright position, 0.5° XY-rotation occurred in one multiparous women.

In general, translation in the Z-direction was the same for men and women. In multiparous women, an average value of 0.11 cm was found. These results confirm the idea that multiparous women have relatively mobile pelves (Brooke, 1924; Bowen Cassidy, 1981).

Discussion of this method

Chamberlain (1930) gave the following values for pubic movement in the Y-direction: adult males about 0—0.05 cm; nulliparous women 0—0.1 cm; multiparous women 0—0.2 cm. If in multiparous women the range of motion was larger than 0.2 cm, articular pain was always present.

The study of Walheim et al. revealed little differences between men and women. Walheim et al. suggested, therefore, to increase the threshold values for male instability, indicating that male values of even more than 0.05 cm in the Y-direction did not necessarily lead to pain.

Walheim et al.'s data, however, were derived from a sample with a specific age distribution. Chamberlain's test persons had a much wider age spectrum and included a larger number of people, among whom several patients. Chamberlain explicitly differentiated between presence or absence of pelvic pain. The recommendations of Walheim et al., therefore, have to be considered with great care.

It may be regretted that Walheim et al. failed to use their precise set-up in the analysis of more complex movements such as hip extension from the upright position. Unfortunately, the test position, i.e., 90° hip flexion with abduction, is not very physiological, or at least not very common. The position was chosen in order to allow for conclusions concerning XY-rotations and X-translation. If Y-translation in the upright position were included, comparison would have been possible with the data of Lavignolle et al.

It is impossible to draw conclusions from data concerning movements of the pubic bones with reference to sacro-iliac mobility. In order to be able to use pubic mobility as a measure for sacro-iliac mobility, one would have to exactly know the position of all sacro-iliac axes and the extent of bone deformation. Both these factors are insufficiently known.

The study by Walheim et al. at least shows that the Chamberlain method can be used in practice. Furthermore, one gains the impression that Walheim et al. have succeeded as to their original goal. i.e., developing a norm for pubic symphysis movement. Their values for females are more or less the same as those radiologically found by Chamberlain. As to male values, however, the transition between normal and abnormal appears to be at a somewhat higher value than Chamberlain suspected. Walheim et al. do not distinguish between walking and supine or prone positions.

The study by Weisl (1955)

Weisl (1955) showed that adequate analysis of sacro-iliac movement is possible without advanced technology. In doing so, Weisl proceeds along the lines already indicated in anatomy and gynaecology by researchers such as Walcher (1889) and Schubert (1929). Schubert, for instance, demonstrated radiologically that the conjugata vera lessens by 0.5—0.7 cm if a person moves from the supine to the upright position.

At the time that Weisl started his research, it was already known that a decrease of the pelvic inlet leads to an increase of the pelvic outlet. This was taken to imply nutation of the sacrum in the sacro-iliac joint (Meyer, 1878; Faraboeuf, 1894; Latarjet, 1928).

Weisl tried to establish a generalized axis for various movements, relying on radiological techniques in the living. Volunteers were selected from an age group between 19—28 years. In view of the radiation dose administered, such an investigation would nowadays not be undertaken.

In the supine position, 26 men and 30 women were radiographically examined, after which different positions had to be reached (Figure 16). A similar procedure was used, starting from the prone position (27 men, 28 women), and from the upright position (12 men, 10 women). Comparisons were made between two different positions.

Weisl used lateral radiographs, which show no movement of pelvis, X-ray device and film with respect to each other. A device was constructed (Figure 17), the general form of which was adapted to the form of the pelvis; tight belts connected the iliac bones to the device which, placed laterally, could also be used in the standing position.

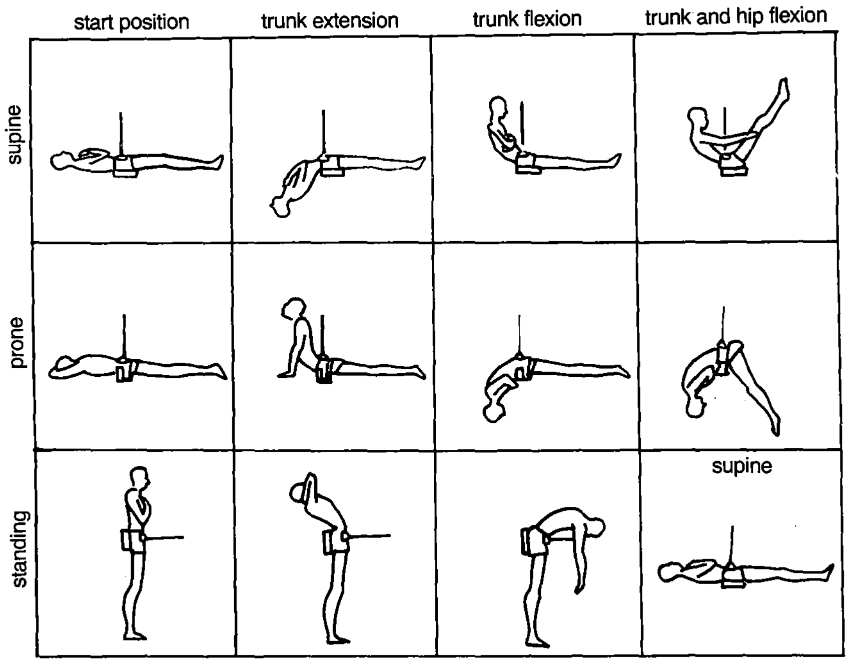


Figure 16. Different positions during radiographic examination in the study of Weisl (1955).
Each individual was radiographed in one of three basic positions (supine, prone or upright), and then additional radiographs were made in the experimental positions.

The radiographs were reconstructed (Figure 18) by means of the following procedure. A sacral line was drawn from the promontory to the ventrocaudal aspect of the last sacral vertebra. The innominate line was indicated as a line from the cranial aspect of the pubic tubercle to a point between both ischial spines. The conjugata vera connects the cranial aspect of the pubic tubercles with the promontory.

The radiographs of two different positions present two triangles that can be compared.

Figure 19 illustrates, as an example, translation when the two innominate lines cover each other. This translation is interpreted as sacro-iliac movement.

The innominate line and the sacral line were measured in every pair of images; if these lengths were different, the material was discarded.

Discussion of this study
Since Weisl observed no clear-cut differences between men and nulliparous women, this distinction will be left out in this discussion.

The most important sacro-iliac change that Weisl found was related to the transition from a supine to the upright position. In 90% of the test persons, there was a pronounced displacement of the promontory towards ventral (an average of 0.56 ± 0.14 cm), whereas in 77% of the test persons, the conjugata vera became smaller. Weisl did not mention why these percentages were different. Weisl found promontory displacement towards dorsal in 5% of the test persons, and in 5% no displacement at all. In other movements less displacement took place.

There was a pronounced difference between male and nulliparous female sacro-iliac mobility on the one hand and multiparous female mobility on the other. Furthermore, Weisl reported a conspicuous difference between sacral movements during the transition from the supine position to trunk extension and those during the transition from the standing position to trunk extension. Only in the upright position trunk extension enlarges the conjugata vera, displacing the promontory somewhat towards dorsal[7].

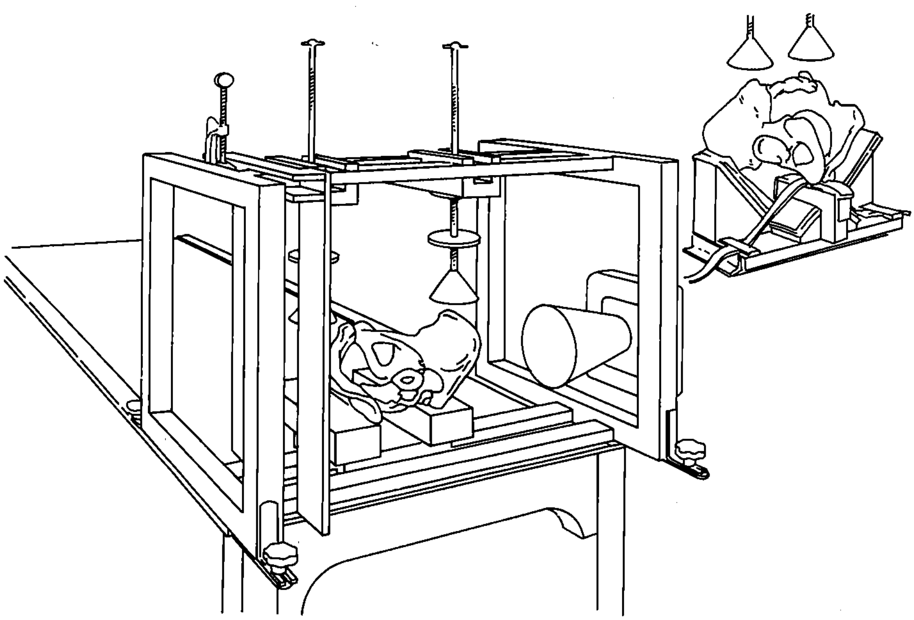


Figure 17. The device used by Weisl (1955).

[7] One has to clearly distinguish trunk extension, as performed here, from assuming maximal lordosis; the consequences of these two manoeuvres for body statics cannot be directly compared. In lordosis, Egund et al. reported a tilting of the promontory towards ventral.

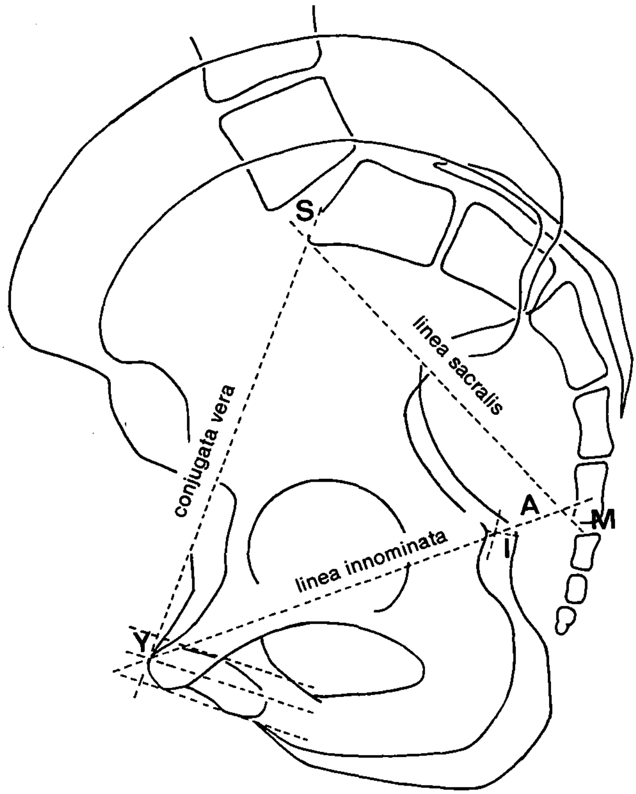


Figure 18. The reference lines used by Weisl (1955).

Weisl gave the following explanation for the remarkable difference between extension in the upright position and extension in a lying position.

In the upright position, the sacrum is displaced towards ventral, that is to say, it is in nutation. In the lying position, however, it is in contranutation. Hence, it is difficult for the sacrum to (further) contranutate in the lying position. For trunk flexion the opposite was observed. Especially in trunk flexion from a lying position—the more so if in combination with hip flexion—the conjugata vera becomes smaller, implying nutation of the sacrum. This pelvic constellation is the same as that during labour, implying enlargement of the pelvic outlet due to the nutation of the sacrum.

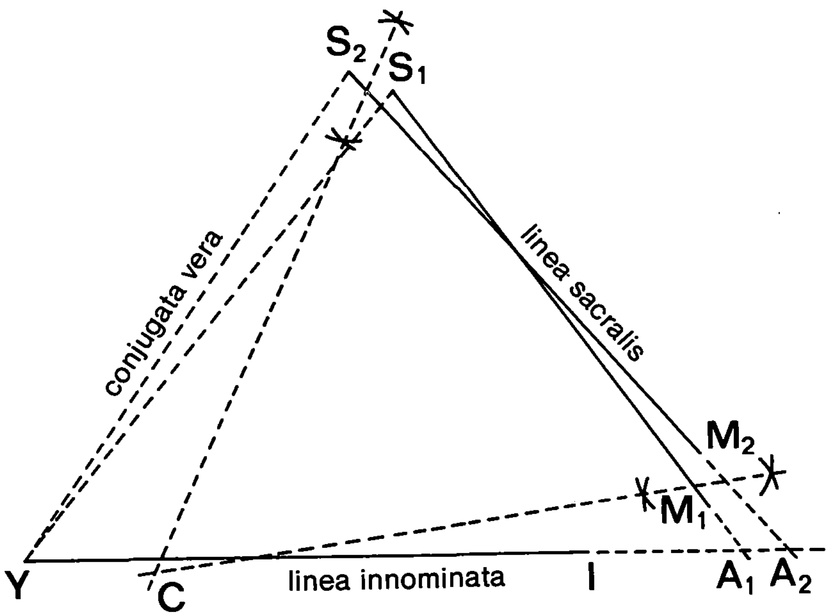


Figure 19. The triangles acquired from two radiograms (after Weisl, 1955).

Apart from parallel movements (i.e., translations), Weisl described how, the sacrum moves angularly (rotations). It is for the latter movements that Weisl calculated the position of the axis of rotation. Weisl found this location to be about 10 cm caudal to the promontory in men and nulliparous women; in multiparous women it was localized a couple of centimetres more cranially. Surprisingly, there was a large intra-individual variation—the position of the axis can change by about 5 cm during different movements. Accordingly, Weisl concluded that this axis is not dependent upon one mechanical factor only, and that sacral movement cannot be purely rotational.

In this way, Weisl demonstrated how a relatively simple methodology can help to understand sacro-iliac mobility. Nevertheless, his methods should be critically evaluated. Weisl himself gave no comment at all concerning his experimental set-up.

Weisl tried to fix the iliac bones in order to avoid moving the photographic plate or other parts of the set-up. In all positions, however, this fixation was rather rigorous. This method of fixation can be seen as an exaggerated form of the pelvic belt as described by Snijders and Snijder (1984). This belt is carried at the S2—level and serves to diminish sacro-iliac hypermobility (alleged or not). Many pregnant women in, among other countries, Indonesia, Turkey and Morocco, carry such a belt. A strong elastic corset is coiled up and used at the same level as the above pelvic belt. If, indeed, these constructions can influence (alleged) hypermobility, the fixation method of Weisl had its own influence on mobility.

We are, therefore, of the opinion that the localization of the sacro-iliac axes, as emerges from Weisl's study, should be regarded with some scepsis. Weisl is the only researcher to find the axes to be localized this far caudally. Without his method of fixation of the pelvis, another localization might have been found. Moreover, Weisl reported no difference between prone and supine positions. This lack of difference, however, is hard to interpret since relaxed lying positions (especially, prone) are hard to realize with this method of fixation.

Walheim et al. (1984) did show that, on the average, differences exist between young men and women with respect to pelvic mobility. Anatomical studies of male and female sacro-iliac joints led Brooke (1924) to conclude that there exists differential mobility in the sexes. Weisl was unable to confirm this. One has to note, however, that Weisl investigated test persons between 17—30 years of age who were, presumably, healthy. Brooke, on the other hand, examined embalmed corpses of a variety of age groups. As mentioned earlier (see the study of Stewart, 1984) there is a pronounced difference in sacro-iliac roughening between men and women from the age of forty onwards.

Finally, Weisl failed to take bony deformation into account and included—without justification—all displacement of the sacral line into his measures of sacro-iliac mobility. As mentioned before, we ourselves did observe deformation of the sacrum.

Final comments with respect to the mobility studies

• The study of Egund et al., and up to a point also the study of Weisl, confirm the idea that the transition from the normal upright position to an upright position, especially with lordosis, implies sacro-iliac movement. The movement in question is a tilting of the sacrum towards ventral (nutation). One has to note, however, that significant differences occurred in only two out of the four patients of Egund et al.

• Standing upright with lordosis could serve as a functional test, where pain resulting from this movement could indicate possible sacro-iliac problems. Obviously, such a test cannot discriminate between sacro-iliac pathology and problems in the lumbar spine. Standing upright appears to lead in most individuals to a close packed position in the sacro-iliac joint.

• The various studies discussed in this Section suggest that sacro-iliac mobility depends on the distribution of load. There are differences as to the degree and the direction of the possible rotational and translational movements. It appears to be justified to conclude that in the upright position the sacrum nutates during trunk flexion, contranutates during trunk extension, and maximally nutates in maximal lordosis. In prone or supine positions, the position of the sacrum is relatively contranutated (Weisl, 1955; Lavignolle et al., 1983).

• One may want to use mobility data in clinically testing sacro-iliac movement. It appears, however, that there exists a large interindividual variability. Weisl observed that in the transition from a lying to an upright position, no nutation took place in 5 %, whereas in 5% even contranutation was seen. It would be interesting to establish in patients with low back pain how the sacrum moves during this transition.

• Lavignolle observed that hip flexion in a supine position leads to relatively large sacro-iliac movements. In our opinion, this requires great care in the interpretation of 'straight leg raising'. Lavignolle et al. speculated that in lying positions, the sacro-iliac joints have to be 'opened' via translation before other movement can occur. It is conceivable that this process, if it exists, is different at different ages.

• All studies discussed in this Section have the common problem that sacro-iliac displacements are ascribed to sacro-iliac joint mobility only, and not to bony deformation. The study by Frigerio et al. may be an exception, but very little material was used and, probably, errors have been made in the experiments.

• Limited information appears to be available as to sacro-iliac mobility in the elderly. Measurement of sacro-iliac mobility is done exclusively in a static context. Dynamical measurement, with force and time as independent variables, is completely missing.

ISSUES IN SACRO-ILIAC RESEARCH

General conclusions from the literature

The morphology of sacro-iliac mobility

From Hippocrates (460—377 B.C.) until Vaesalius (1514—1564), it has been suggested that the sacro-iliac joint is mobile during pregnancy only. Paré (1634) confirmed this by examination of corpses. Diemerbroch (1689), however, claimed that the sacro-iliac joint is usually mobile, both in women and men. Albinus (1697—1770) and Hunter (1718—1793) observed that the sacro-iliac joint has a synovial membrane and concluded that it must be mobile. In 1864, Von Luschka describes the joint as a real diarthrosis, i.e., a mobile joint with a joint cavity between two bony surfaces. Zaglas (1851) investigated sacro-iliac mobility in corpses. He concluded that most sacral movement takes place around a transversal axis, situated at the level of the second sacral vertebra.

Upon careful analysis of topographical anatomy, as well as investigation of corpses, Duncan (1854) concluded that the generalized pivot of the sacro-iliac joint must be localized at the level of the iliac tuberosity. This tuberosity is a bony structure located behind the auricular part of the sacro-iliac joint (in 1984, it will be described by Bakland and Hansen as the iliac aspect of the axial joint). Meyer (1878) and Klein (1891) supported this opinion. Duncan suggested to coin sacro-iliac rotations around a transversal axis as 'nutation' (ventral tilting) and 'contranutation' (dorsal tilting).

In 1949 Testut and Laterjet concluded that the sacro-iliac joint contains a freely mobile ventral aspect and an ossified dorsal aspect. One could speak of an 'diarthro-amphiarthrosis', i.e., a joint that has the characteristics both of a freely mobile joint (diarthrosis) and an ossified joint (synarthrosis). Bakland and Hansen (1984) described the latter dorsal aspect of the sacro-iliac joint as the 'axial joint'. Since they observed the presence of cartilage, they concluded that movement may occur in the axial joint as well.

Ehara et al. (1988), using CT-scanning, observed the axial joint in not more than 13 out of hundred test persons. They reported that the axial joint may be present at birth, just as a true diarthrosis, but that it also can appear postnatally, in which case the joint is supposed to be fibrocartilaginous. According to some anatomists (Faraboeuf, 1894; Strasser, 1908; Fick, 1911; Palfrey, 1984), the iliac articular surface has a central ridge, corresponding to a groove on the articular surface of the sacrum.

In 1954, Weisl described the joint as consisting of two condyles, forming what may schematically be regarded as a sellar joint. However, several investigators (Brooke, 1924; Schuncke, 1938; Solonen, 1957) have shown that congruence is rare in the sacro-iliac joint. Strong reliance on simple models of a joint, therefore, can be misleading for the sacro-iliac joint. Moreover, Fischer et al. (1976) demonstrated great intra- and inter-individual sacro-iliac variability. This was confirmed by Bakland and Hansen (1984).

Solonen (1957) described the articular surface as 'nodular and pitted' and regarded this as pathological. He tried to come to an understanding of sacro-iliac function by conceiving the sacrum as a wedge between the iliac bones. This form, according to Solonen, guarantees a strong connection.

Functional dynamics of sacro-iliac mobility

Several investigators have tried to model sacro-iliac function. The common assumptions appear to be the following: an increase of the load on the sacrum leads to tilting the proximal aspect of the sacrum towards ventral (nutation), a process by which dorsal ligaments are stretched and the dorsal aspects of the two iliac bones are drawn together (Meyer, 1953; Albee, 1909; Magnusson, 1937; Rauber-Kopsch, 1940; Ship & Haggart, 1950).

Weisl (1955) succeeded in demonstrating sacro-iliac mobility by using radiological techniques. He used the terminology proposed by Duncan (1826—1898): nutation and contranutation, terms referring to a combined rotation-translation. Nutation implies a deepening of the lumbar lordosis, whereas contranutation lessens the lordosis.

In 1978, Egund, using stereophotogrammetry, showed that in the sacro-iliac joints different positions are assumed in transitions from one body position to another. In the prone patient, manual pressure on the apex of the sacrum leads to contranutation. The upright position leads to nutation, an upright position with maximal lordosis to increasing the nutational tilt.

Lavignolle (1983), also relying on stereophotogrammetry, observed large sacro-iliac mobility in the supine position with hip flexion. This implies that 'straight leg raising' (SLR) can mobilize the sacro-iliac joint. Since the joint sends nerve impulses to a variety of segments (L3—S2), pain during SLR is not very specific.

This non-specificity is further strengthened by the presence of connections between the sacrotuberous ligament and the biceps femoris as well as the gluteus maximus (Vleeming et al., 1989-a & b).

Sexual differences and the roughening of sacro-iliac surfaces

Female sacro-iliac mobility may be functional in allowing passage for the child during labour. Sacro-iliac curvature is usually less pronounced in women than in men, a fact which is supposed to allow for a higher mobility (Weisl, 1955; Solonen, 1957).

During pregnancy, the sacro-iliac fibrous apparatus loosens under the influence of relaxine (a hormone produced by the ovary), and relative symphysiolysis occurs, both factors resulting in an increase in sacro-iliac mobility. Hypermobility of the joint may lead to complaints (Bonaire & Bué, 1899; Brooke, 1924; Hisaw, 1925; Schubert, 1929; Chamberlain, 1930; Heyman & Lundquist, 1932; Abramson et al., 1934; Thorp & Fray, 1938; Borell & Fernstrom, 1957; Walheim et al., 1984).

Research by Walheim et al. (1984) and Snijders and Snijder (1984) indicates a positive effect of a pelvic belt ('Trochantergurt') on sacro-iliac hypermobility in pregnant women. Both studies report pain reduction. This observation could serve to explain why in several cultures (e.g., Indonesia, Turkey, Morocco), an elastic corset is worn at the S2—level from the 6th month of pregnancy onwards. In the male pelvis, contrary to the female, there appears to be no functional role for pronounced sacro-iliac mobility. Especially in men, 'blocking' of this joint has often been described (Lynch, 1920; Jackson, 1930; Haggart, 1938; Caviezel, 1973).

Moreover, particularly in males above the age of 35, macroscopic sacro-iliac changes have been described (Stewart, 1984). Without justification, terms such as 'arthrotic processes' (British literature, e.g., Brooke, 1924) or 'arthritis' (American literature, e.g., McCarty, 1979), are often used in the sacro-iliac literature in referring to these changes.

In 1892, Braune and Fischer related the position of the centre of gravity to sacro-iliac function. They assumed that a change in the localization of the centre of gravity is related to a change in sacro-iliac function. The larger the distance between the sacro-iliac joint and the vertical line through the centre of gravity, the less stable the joint, since rotational torque increases as a function of the length of the lever arm (see Figure 20).

It is our opinion that the large distance between the assumed rotational pivot of the sacro-iliac joint and the vertical line through the centre of gravity is a major cause of the development of the specific form of the sacro-iliac joint, which secures its necessary stability.

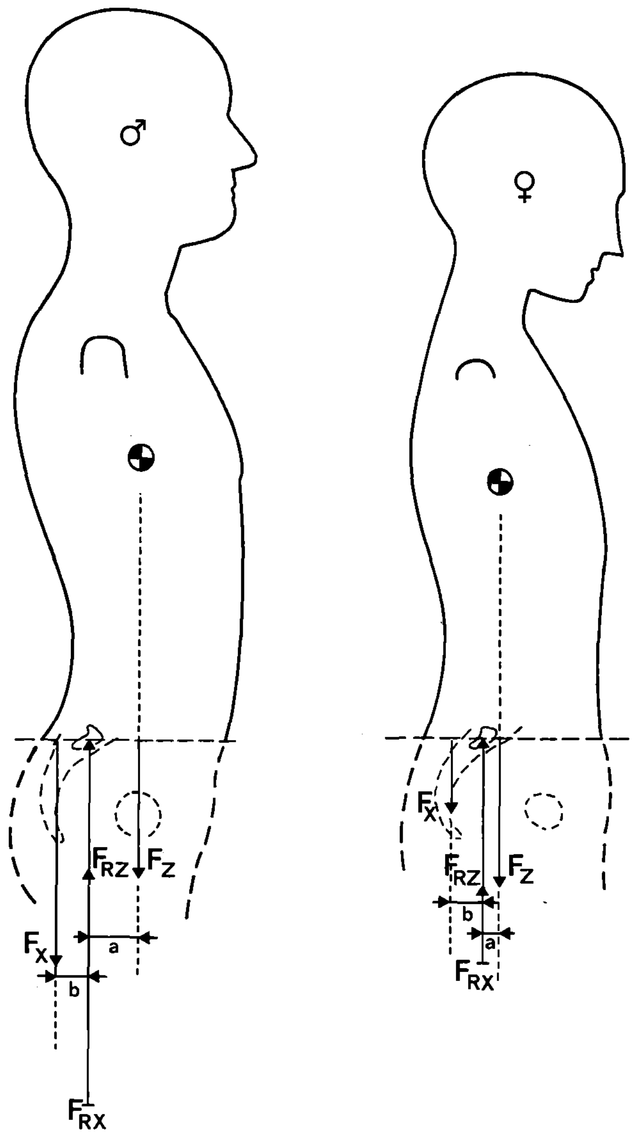


Figure 20. Relationships between the sacro-iliac joint and the vertical line through the centre of gravity in men and women.
Note that the lever arm in females is supposed to be smaller.

Several authors indicated a different position of the centre of gravity in men and women. In women, for instance, the vertical line through the centre of gravity is supposed to pass directly in front of, or through the sacro-iliac joint whereas in men its position is further ventral (Braune & Fischer, 1892; Tischauer et al., 1973; Bellamy et al., 1983). This would imply a greater lever arm in men than in women, resulting, of course, in higher loads on the joints (Figure 20).

As a result, the male sacro-iliac joint will become stronger, with restricted mobility, if, indeed, the surmised difference in the localization of the centre of gravity exists. More research will be needed before this can be decided. At the moment, the whole discussion is based on rough empirical estimates.

Apart from these differences between men and women, the load carrying surface of the female sacro-iliac joint is usually smaller, and the position of the sacrum is usually more horizontal (Derry, 1912; Brooke, 1924; Sashin, 1930; Schuncke, 1938; Solonen, 1957).

Brooke (1924) reported roughening of the articular surfaces in 70% of male preparations above the age of 76; this roughening was ascribed to arthrotic processes. In female preparations, Brooke, however, found no evidence of roughening. Stewart (1984) concluded on the basis of an extensive investigation using material from different races that female sacro-iliac ankylosis is extremely rare, even in the high age groups. In the male sacro-iliac joints, on the other hand, there is an increasing tendency to roughening of the articular surfaces above the age of 35, a phenomenon which Stewart attributed largely to arthrotic processes.

Sacral and iliac auricular roughening are different. In 1938, Schuncke concluded that differences between the auricular surfaces exist as early as the intra-uterine period. Sacral cartilage was regarded as hyaline cartilage by Schuncke, iliac cartilage, on the other hand, has the macroscopic appearance of fibrocartilage. After birth, Schuncke stated, also sacral cartilage becomes fibrocartilage.

As a rule, auricular roughening starts at the ilium. Although the sacral auricular surface will start to roughen also, it will continue to stay behind the development of the ilium in this respect (Brooke, 1924; Sashin, 1930; Schuncke, 1938; Weisl, 1955; Bowen & Cassidy, 1981; Paquin, 1983; Stewart, 1984; Dijkstra et al., 1984). Bowen and Cassidy (1981) observed, as did Schuncke, that iliac cartilage is rougher than sacral cartilage already before birth. Paquin et al. (1983) also observed macroscopic and microscopic differences between iliac and sacral cartilage, iliac cartilage being more fibrous and, hence, rougher; biochemically, however, iliac cartilage resembles hyaline cartilage more than fibrous cartilage.

Sacro-iliac complaints

Low back pain occurs frequently; psychosocial factors play an important role (Oosterhuis, 1982; Verkes & Megchelen, 1985). The underlying physical mechanism usually is thought to concern the lower lumbar spine (L3—L5). The sacro-iliac joint received much less attention in this respect. Lesions of the lumbar intervertebral discs occur much more frequently than sacro-iliac lesions (Mixter & Barr, 1934), and lumbosacral pathology is relatively easy to diagnose. Nevertheless, pathogenesis of low back pain does not always start in the lumbar region. After all, lumbar and sacro-iliac problems may be interrelated (Goldthwait & Osgood, 1905; Brooke, 1924; Aberle et al., 1955).

The diagnosis of deviations of the sacro-iliac joint is difficult, on the one hand because the sacro-iliac joint does not easily allow for specific functional testing, on the other hand because mobility is very limited even under optimal circumstances. Moreover, sacro-iliac innervation is rather unspecific—the same segments being responsible for the innervation of the sacro-iliac joint with its ligaments, and the lumbar spine (Solonen, 1957).

Goldthwait and Osgood (1905) postulated that ischialgia may result from irritation of the nerves, caused by ventral sacro-iliac changes. In 1934, this idea was replaced by the observation of Mixter and Barr that changes in the intervertebral disc are an important, if not the most important cause of ischialgia. From that time onwards, the sacro-iliac joint started to receive less attention.

In the last decades, some authors have even denied the possibility of pain caused by sacro-iliac afflictions other than acute infections (Platt, 1948; Ghormley, 1951). In 1928, 36% of ischialgia was thought to be caused by sacro-iliitis (Yeomen, 1928). Solonen (1957) concludes in a study of low back pain (6895 patients) that only 2.4% can be ascribed to direct sacro-iliac afflictions (apart from infections and *osteitis condensans ilii*). Solonen emphasized, however, that this percentage is a rather global estimate.

Towards a sacro-iliac research programme

Form-function relationships of the sacro-iliac joints

In view of the literature and our own data, the following theory is formulated concerning the form-function relationship in the sacro-iliac joint. The form of the healthy sacro-iliac joint is specifically related to functional demands, the most important demand in the non-pregnant subject being the stable connection between the spinal column and the pelvic girdle. In preparations of young persons, sacral and iliac articular surfaces are usually flat. Small ridges and grooves, however, can already be observed in frontal sections. This process has been described in the literature but usually attributed to incipient arthrosis (Brooke, 1924; Sashin, 1930; Schuncke, 1938; Weisl, 1955; Solonen, 1957).

In general, signs of iliac roughening become more pronounced after puberty. This roughening can be divided into two types (Vleeming et al., in press-a & b). The first type is restricted to the cartilage, and mostly to the iliac side of the joint. This roughening, which can hardly be seen macroscopically, is coined 'coarse texture'. The second type involves also the underlying bone; it is classified as 'ridges and grooves'. It occurs on both sides of the joint, ridges being complementary to grooves. Especially this last form of roughening is important since cartilage appears to have the same thickness over ridges and grooves as in the more flat regions. In frontal sections, the ridges resemble osteophytes (if one does not take the cartilaginous covering into account).

We hypothesize that sacro-iliac roughening—coarse texture as well as ridges and grooves—is a physiological process starting at the iliac side of the articular cartilage. We do not think that roughening is a sign of incipient arthrosis, eventually leading to complete ankylosis.

In order to test this hypothesis, the anatomy of the joint is investigated with particular attention to frictional forces. It will be attempted to show whether coarse texture as well as ridges and grooves can be of functional importance.

The basic assumption is a functional one. If mobility between two bones in a joint would impede normal function, it is to be expected that a bony connection (i.e., a synostosis) will develop between them. If some mobility is functional, flexible fusion occurs in the form of a syndesmosis, synchondrosis or symphysis. If considerable mobility would be functional, a synovial diathrosis would emerge.

Since the sacro-iliac joint is not a synostosis, without, however, allowing for considerable mobility, we surmise that its major function is to ensure 'flexible stability'.

The following propositions have not or as yet not sufficiently been underpinned by experimental data:

- ridges and grooves on the articular surfaces of the sacro-iliac joint, are complementary;
- intra-articular presence of ridges and grooves in the sacro-iliac joint, implies a higher friction;
- sacro-iliac stability depends more on the presence of ridges and grooves than on coarse texture.

These propositions call for determining frictional coefficients of a variety of sacro-iliac joints, with different architecture and texture. A biomechanical model is required to serve as a framework for closure in terms of form and forces. This model will include frictional values.

A biomechanical model of the sacro-iliac joint

A biomechanical model is developed, based upon the general architecture of the sacro-iliac joint and taking the physiological nature of roughening as its starting point. The model, developed by Snijders and Vleeming, assumes form closure as well as force closure.

Three elements are presented, elements which are functional from a biomechanical point of view (Figure 21): 1. resistance between the articular surfaces of the individual sacro-iliac joints; 2. wedge-shaped geometry of the sacrum; 3. a self-bracing effect of the sacro-iliac joint.

In the following, the model concerns forces and torques in the frontal plane in the upright position with equal loading of both legs.

The weight of the supra-sacral part of the body, about 60% of body weight, is carried mainly by the sacrum.

The vertical force vector F_B coincides with the longitudinal axis. Fibrous structures such as ligaments (or a pelvic belt) exert a lateral force F_L in the same direction as the transversal axis (Figure 23).

Theoretical distinction of form closure and force closure can be illustrated with the help of the different configurations in Figures 22 and 23.

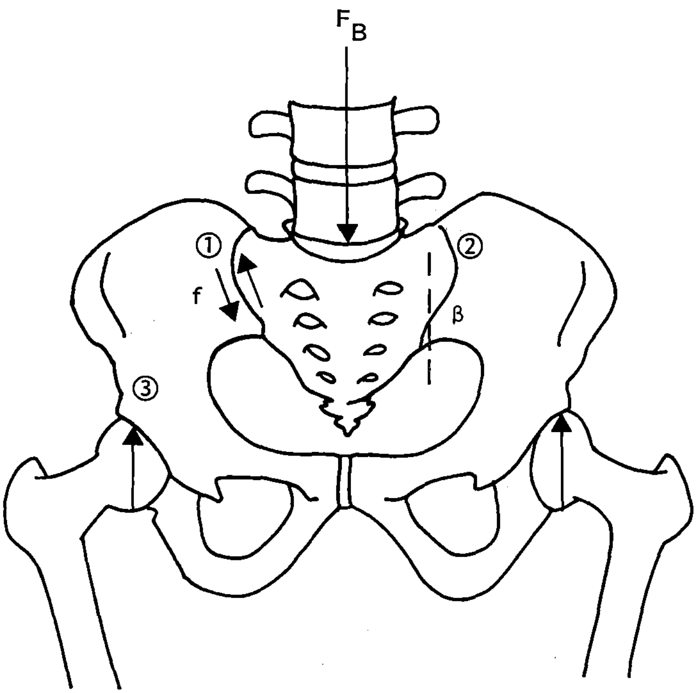


Figure 21. Model parameters (see text).

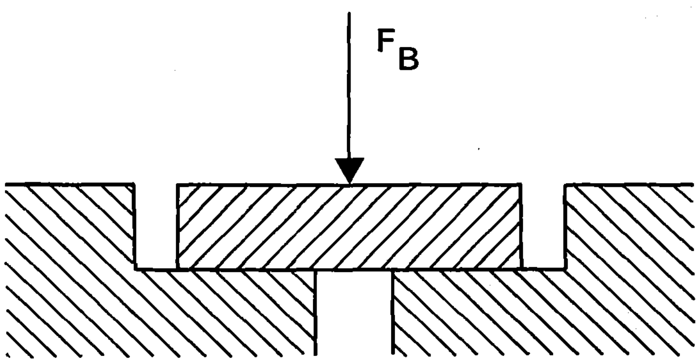


Figure 22. Form closure.

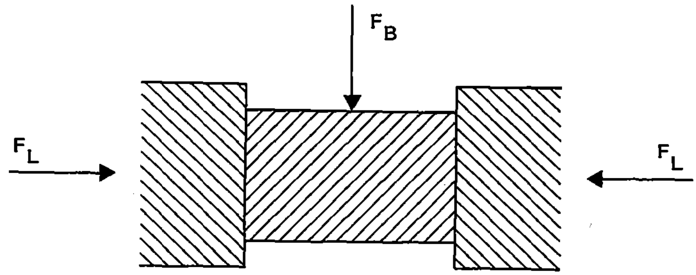


Figure 23. Force closure.

Form closure refers to a stable situation where no extra forces are needed to maintain the state of the system, given the actual load distribution (Figure 22). If the sacrum would fit into the pelvis with form closure, no lateral forces would be needed to counterbalance the effects of the vertical force.

Force closure refers to an indifferent situation. A lateral force is needed to maintain a situation of vertical load (Figure 23). The presence of friction is assumed.

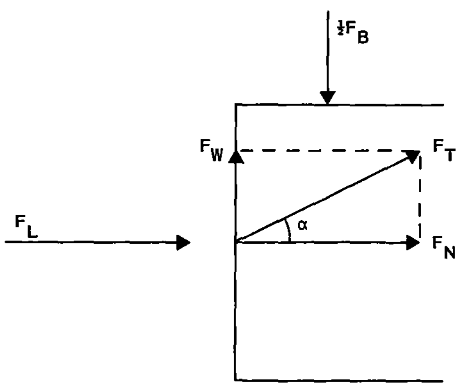


Figure 24. The stabilizing effect of friction (see text).

Friction

Figure 24 illustrates the stabilizing effect of friction, being an example of 'force closure'.

The lateral forces in this scheme (F_L) are perpendicular to the articular surface, a fact which allows them to exert normal force F_N. In this case:

$$F_N = F_L \ .$$

Both sacro-iliac joints carry the body weight. Hence, for one sacro-iliac joint we have to take half the body weight into account: 0.5 F_B. The sacrum remains in position if there is a vertical balance of forces:

$$F_W = 0.5\, F_B \ .$$

The component representing articular friction, is F_W. This force has as its maximum the product of the frictional coefficient f and the normal force F_N:

$$F_W\ (\text{max}) = f.\ F_N \ .$$

The coefficient of friction, f, can be seen as the ratio F_W (max) / F_N, which equals tan(α):

$$F_W \leq F_L \times \tan(\alpha) \ .$$

It will be clear that α increases if f increases. In such cases, a smaller force in the ligaments would be sufficient to carry the body weight.

Wedge-shape (without friction)

In Figure 25 the hypothetical situation is depicted where a wedge-shaped sacrum is frictionless. Again, F_L is the lateral force of the ilium against the sacrum. Since there is no friction, the only force that will be conveyed is the one perpendicular to the articular surface, i.e., F_N.

Vector analysis of F_N results in a horizontal force F_R and a vertical F_V :

$$F_V = F_R \times \tan(\beta) \ ,$$

β indicating the angle of the wedge.

Since there must be a vertical as well as a transversal balance:

$$F_V = 0.5\, F_B$$
and
$$F_R = F_L \ ,$$

it follows that:

$$0.5\, F_B = F_L \times \tan(\beta)\ .$$

This leads to the conclusion that for a larger wedge angle β, less force in the ligaments is needed to carry the body weight. This is an example of combined form and force closure.

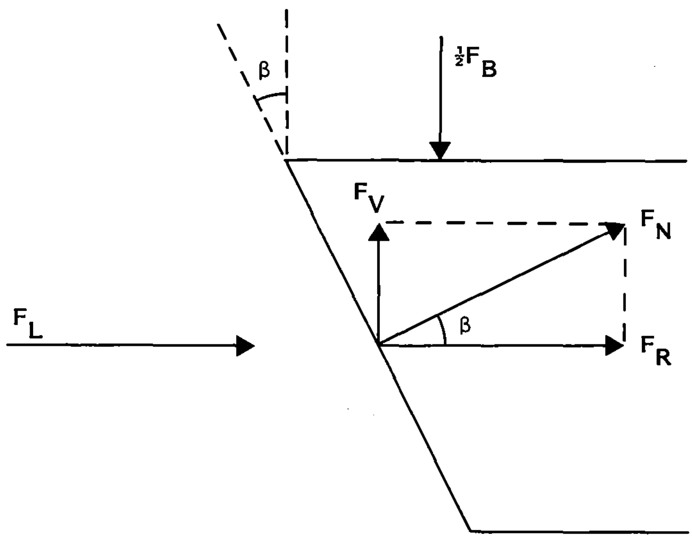


Figure 25. Wedge-shape (no friction).

Wedge-shaped geometry with friction

Figure 26 depicts the total contact force F_T , acting on the sacrum in the sacro-iliac joint. Force F_T can be analysed as the composition of two mutually perpendicular forces: force F_N perpendicular to the surface, and frictional force F_W in the plane of the articular surface.

It must be true that:

$$F_W\,(\text{max}) = f \times F_N = \tan(\alpha) \times F_N\,.$$

This same force F_T is actually the resulting force of transverse force F_R (= F_L) and vertical force F_V (= 0.5 F_B).

Here, in comparison to the situation without friction, even less force in the ligaments is needed to carry the body weight since it holds:

$$0.5\,F_B \leq F_L \times \tan(\alpha + \beta)\,.$$

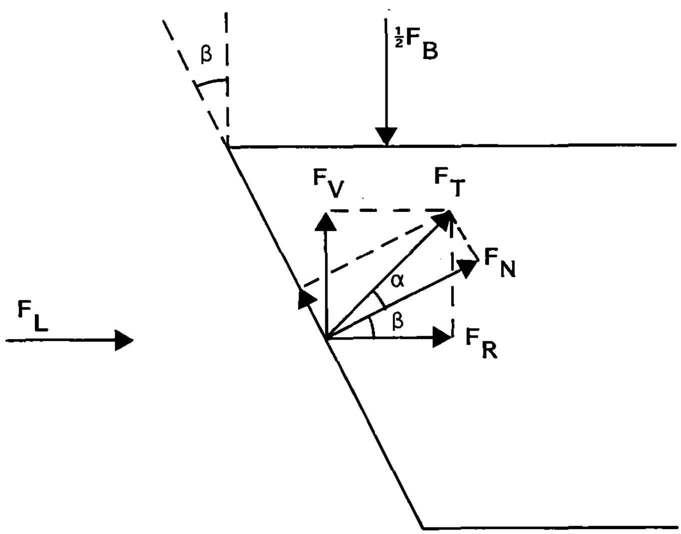


Figure 26. Wedge-shape with friction.

Self-bracing effect

So far, we have only modelled forces that act on the sacrum. In Figure 27, also the iliac aspect of the sacro-iliac joint is taken into consideration.

Again, the ligaments exert force F_L on the pelvis. F_N stabilizes the joint in the transversal direction. Both forces compose a couple with lever arm b and moment M_1:

$$M_1 = F_N \times b\,.$$

The body weight is conveyed to the head of the femur in such a way that each head exerts a force of 0.5 F_B on the ipsilateral pelvic half.

There must be equilibrium of forces:

$$F_V \leq F_W\,(max) = F_N \times \tan(\alpha)\ .$$

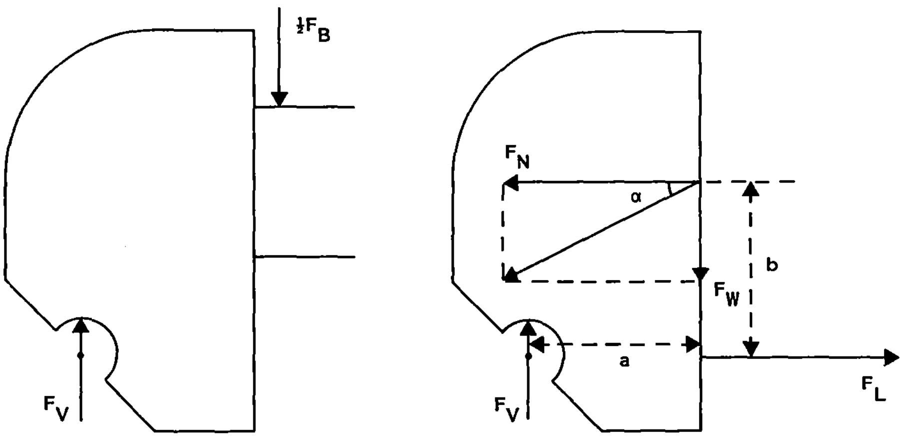


Figure 27. Self-bracing effect with friction.

Also F_V and F_W form a couple with lever arm a and clockwise moment M_2:

$$M_2 = F_V \times a\ .$$

Equilibrium of moments leads to:

$$F_N \times b = F_V \times a\ .$$

Since:

$$F_N \times b \leq F_N \times a \times \tan(a)\ ,$$

it follows that:

$$b \leq a \times \tan(\alpha) .$$

As long as the latter condition is fulfilled, the sacrum stays in place.

Note that no forces play a role in the last equation. This implies that only the place where these forces are exerted is important, and not their magnitude. This is what is essentially meant by the notion 'self-bracing effect'.

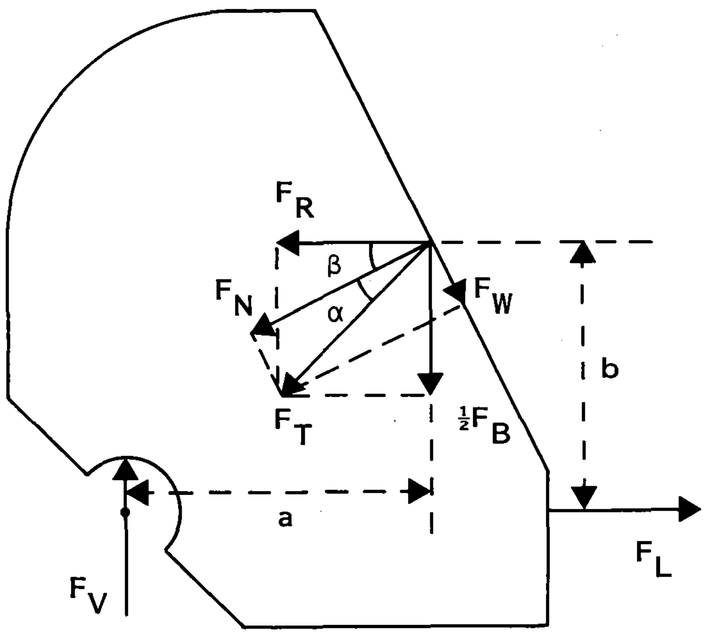


Figure 28. Self-bracing effect with friction and wedge-shaped geometry.

Self-bracing effect with friction and wedge-shaped geometry

In Figure 28 one recognizes the situation linked with Figure 26. The combination of friction and the wedge-shaped geometry, now leads to the following condition for the self-bracing effect:

$$b \leq a \times \tan(\alpha + \beta) .$$

Realistic values of β and a can be obtained from radiographs. Values of, respectively, 16° and 4 cm result in:

$$b \leq 4 \times \tan(\alpha + 16°) \text{ cm.}$$

Variables in mobility of the sacro-iliac joint

Mobility studies in the literature—as we have extensively discussed—appear to circumvent the issue of relevant variables, such as bony deformation, asymmetrical loading, tension in ligaments, etc.

Therefore, we chose a set-up which allows analysis as well as experimental control of bony deformation. This set-up has the potential to allow investigation of other variables.

The following propositions are formulated:

- sacro-iliac joints in the elderly are, in principle, mobile;
- there is a possibility to stretch the sacrotuberous ligament by muscle action which influences movements in the sacro-iliac joint.

Visualization of the sacro-iliac joints

On the basis of the anatomy of the sacro-iliac joints, a contribution is presented to the optimization of the diagnostic possibilities for sacro-iliac afflictions.

An alternative radiological method is recommended.

The following proposition is formulated:

- if radiographs are taken non perpendicularly to the joint cavity, the presence of corresponding grooves and ridges may be mistaken for osteophytes on the auricular surfaces.

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CHAPTER

Relation between form and function in the sacro-iliac joint, Part 1: Clinical anatomical aspects

Vleeming, A.[1], *Stoeckart, R.*[1], *Volkers A.C.W.*[2], *Snijders, C.J.*[2]

[1] Department of Anatomy, anatomists

[2] Department of Biomedical Physics and Technology, bioengineers

Research group of clinical anatomy and medical technology,
Erasmus University, Rotterdam, The Netherlands .
For correspondence: A.Vleeming/R.Stoeckart, Department of Anatomy,
Faculty of Medicine, Erasmus University, P.O. Box 1738,
3000 DR Rotterdam, Netherlands.

Abstract

Observations on sectioned and opened preparations of human sacroiliac joints (SI-joints) show the presence of cartilage covered ridges and depressions, which are complementary on the auricular surfaces. These macroscopically visible features of the joints, which become visible relatively early in life, are more pronounced in men than in women. This type of roughening, as well as that by increased coarseness of the auricular surface, is viewed upon as a non-pathological adaptation to the forces exerted at the SI-joints, leading to increased stability. Differences between men and women may be attributed to childbearing and to a difference in the centre of gravity. It is emphasized that intra-articular ridges and depressions can roentgenologically be misinterpreted as osteophytes.

Key words

sacro-iliac joint, sacrum, joint diseases, joint instability, articular cartilage, pelvic bones, anatomy.

Introduction

For understanding low back pain it is important to know whether the SI-joints are involved. However, as we demonstrated in a previous study (Dijkstra et al, 1989[6]), certain anatomical features of the SI-joints are not easily classified as normal or pathological. It appeared that certain SI-joints which could not be diagnosed as normal by plain radiography were normal with a tailored version of oblique tomography.

During life certain macroscopic features of the SI-joints become more outspoken. These features are described as a duller and rougher iliac surface (Bowen and Cassidy, 1981[2]), roughening of the articular surfaces by intra-articular tubercles (Brooke, 1924[4]), a ridge on the iliac side corresponding with a groove at the sacral side (Bowen and Cassidy, 1981[2]) and irregularities in the articular surfaces (Sashin, 1930[9]). In general it is stated that the SI-joints show degenerative changes (Bowen and Cassidy, 1981[2]). Sashin (1930[9]), e.g., stated that pathological changes of the articular cartilages and osteoarthritic changes were found in over 90% of the male SI-joints.

In this article the question is put forward whether certain macroscopic changes of the auricular cartilages have to be viewed upon as pathological or as functional adaptations. It might well be that a textbook statement such as: "The sacro-iliac synovial joint rather regularly shows pathological changes in adults, and in many males more than 30 years of age, and in most males after the age of 50 , the joint becomes ankylosed ...." (Hollinshead, 1962[7]) is based on incorrect interpretation of anatomical data. Therefore, the articular surfaces of the SI-joints were studied in embalmed and fresh specimens of different gender.

Materials and methods

For inspection of the SI-joints 47 specimen were used, which were derived from our dissection room. Most of them (41), concerned people older than 60 years of age (17 males, 24 females). Five preparations, of which four females, were between 35 and 59 years of age. In addition a preparation of a 12 year old boy was available. Apart from three unfixed *post mortem* specimens, the specimens were embalmed. Twelve (embalmed) specimens were frozen and sectioned frontally with a slice thickness of about 7 mm. In the other 35 specimens the SI-joints were opened for direct inspection of the auricular surfaces.

Two different aspects of "roughening" of the auricular surfaces were considered: a. texture and b. ridges and depressions. Texture refers to the (lack of) smoothness whereas ridges and

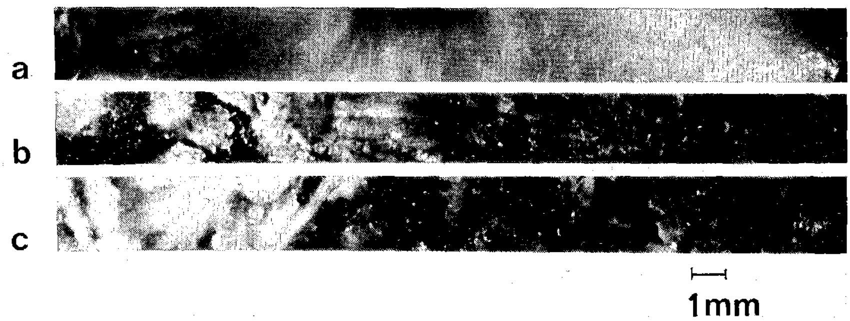

Figure 1. Photomicrographs of cartilage of the iliac side of the SI-joint.
A shows smooth cartilage derived from a 12 year old male specimen,
B coarse cartilage,
C pronounced coarseness.

depressions refer to the (lack of) flatness. The features of texture are: 1. elevations macroscopically not visible or just visible, 2. confined to the cartilage and 3. non-complementarily distributed on the cartilage surfaces. Cartilage characterized by absence of such elevations was called "smooth" (see fig. 1A). Cartilage characterized by the presence of just visible elevations was called "coarse" (fig. 1B). In case a multitude of relatively large elevations was present the coarseness was called pronounced (fig. 1C).

The features of ridges and depressions are: 1. macroscopically clearly visible, 2. involving both cartilage and underlying bone (the cartilage follows the contour of the bone) and 3. complementary on both sides of the joint. Thus, the joining surfaces fit very well.

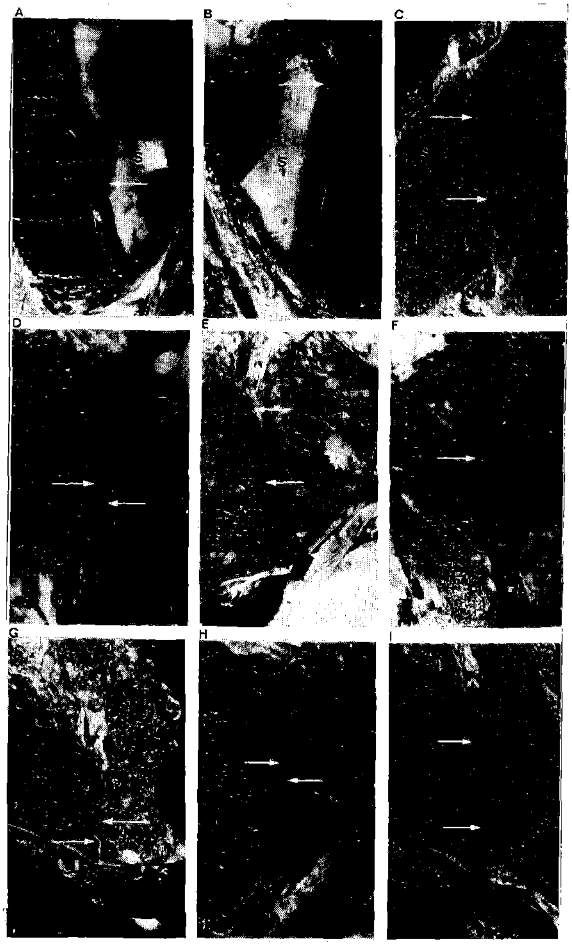

Figure 2. Frontal sections of the SI-joints of embalmed male specimen.
S indicates the sacral side of the SI-joint.
A and B concern a twelve year old boy.
C to I concern male specimen older than 60 years.
Arrows are directed at ridges and depressions.
The ridges and depressions shown are covered by intact cartilage, which was checked by opening the joints afterwards.

Results

<u>*1. macroscopy of the SI-joints in sections*</u>

In slices of the SI-joints it can be seen that sacral auricular cartilage is much thicker than iliac auricular cartilage (fig. 2). In all preparations ridges can be seen (on the iliac and/or the sacral side), which concern both bone and cartilage (fig. 2c to 2i). At the site of a ridge a complementary depression exists in the other part of the joint; both are covered by cartilage. As a consequence of the size and the irregular shape of these ridges and depressions, large differences in the shape of the SI-joints exist between the front and the back of a slice, even at a thickness of 7 mm. It is noteworthy that ridges and depressions are already visible at young age, as is apparent from the examples, albeit very small, in a 12 year old boy (fig. 2A, 2B). SI-joints of females showed, in general, less pronounced ridges and depressions than SI-joints of males, as was especially apparent in the frontal sections derived from relatively old people. Otherwise stated, the auricular surfaces in females are more flat than in males.

2. Macroscopy of the SI-joints in preparations

In the opened SI-joints single or multiple ridges and depressions can be found in most specimens. The ridges and depressions fit well into each other. In most preparations differences were found between the sacral and iliac auricular cartilage of the SI-joints. The sacral cartilage not only is thicker, but also whiter and smoother than the cartilage of the iliac side. The texture is less coarse than that of the iliac part. The iliac cartilage has, at least in preparations of relatively young persons, a somewhat bluish and striped appearance (as described by Bowen and Cassidy, 1981[2]). In preparations of persons of old age differences between sacral and iliac cartilage are less conspicuous or not visible at all. Whenever differences are visible, the coarseness at the iliac side is more pronounced than at the sacral side. In the preparations of the twelve oldest men, coarseness was visible on both sides of the joint. In two of these preparations the articular cartilage was not fully intact; coarseness was pronounced and in addition para-articular ankylosis was present.

Discussion

Macroscopically visible alterations of the auricular surfaces of the SI-joints have been described by several authors. Generally, such changes are considered as pathological (Sashin, 1930[9]; Bowen and Cassidy, 1981[2]). In that case, it might be expected that such changes of the SI-joints, which become gradually apparent or more prominent from puberty onwards and which are more prominent in men than in women, cause pain or problems especially in (older) men. In the view presented here, however, macroscopically visible changes like coarse texture and ridges and depressions represent adaptations to stability, which will be promoted by the increase in weight during the adolescent growth spurt. One reason for this view is the presence of ridges and depressions and of coarseness in practically all male preparations. Another reason is the observation, that ridges and depressions are complementary and as a rule covered by intact cartilage, even in specimens of old age. However, whether the pronounced coarseness observed in the SI-joints of certain old males belongs to, or finally results in a pathological process can not be excluded.

Features like a coarse texture of the articular cartilage and ridges and depressions can enhance friction and consequently stability in the SI-joints, as we describe in a separate biomechanical study (Vleeming et al. 1989[11]). For two reasons it is, in our view, not surprising that these features are more prominent in men than in women:

1. according to several authors (Braune and Fisher, 1892[3]; Tischauer et al., 1973[10]; Bellamy et al., 1983[1]) the centre of gravity of the part of the body above the SI-joint in women is localized in approximately the same frontal plane as the SI-joints whereas in men the centre of gravity is localized more ventrally. If this is indeed the case, then the load in the SI-joints of men is larger because of greater torque. Thus, stabilization of the SI-joints by complementary ridges and depressions may be a special adaptation for men. 2. for women, movement in the SI-joints is important because of childbearing, which process is favoured by widening of the pelvic inlet and outlet.

With standard radiological techniques, the (cartilage covered) ridges and depressions can be easily misinterpreted as pathological, because of the well-known overprojection in SI-joints. We want to emphasize that part of the radiologically visible "osteophytes" in fact represent cartilage covered ridges in the SI-joint which, in our opinion, are not pathological.

This can be in line with the statement of Bluestone (1979) in the book *Arthritis and Allied Conditions* of McCarthy[8]: "Conceivably other conditions than ankylosing spondylitis may cause chronic changes in the sacroiliac joints which are radiographically indistinguishable from those due to ankylosing spondylitis." It might well be that those "other conditions" concern the load normally present in the SI-joints of men and certain women.
Possibly, the presence of intra-articular ridges is related to the incorrect diagnoses of (presumed) diseases of SI-joints which we reported earlier (Dijkstra et al., 1989[6]), and to the radiologically demonstrated abnormalities of the SI-joints in patients without known joint disease and without complaints (Cohen et al, 1967[5]).

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Relation between form and function in the sacro-iliac joint, Part 2: Biomechanical aspects

Vleeming, A.[1], *Volkers, A.C.W.*[2], *Snijders, C.J.*[2], *Stoeckart, R.*[1]
[1] Department of Anatomy, anatomists.
[2] Department of Biomedical Physics and Technology, bioengineers

Research group of clinical anatomy and medical technology,
Erasmus University, Rotterdam, The Netherlands .
For correspondence: A. Vleeming/R. Stoeckart, Department of Anatomy,
Faculty of Medicine, Erasmus University, P.O. Box 1738,
3000 DR Rotterdam, Netherlands.

Abstract

The amount of friction between the articular surfaces of sacro-iliac joints (SI-joints) was determined and related to the degree of macroscopical roughening. Results show that articular surfaces with both coarse texture and ridges and depressions have high friction coefficients. The influence of ridges and depressions appears to be of greater influence than coarse texture. The data are compatible with the view that roughening of the SI-joint concerns a physiological process.

Key words
low back pain, sacro-iliac joint, biomechanics, friction, articular cartilage, pelvic bones.

Introduction

The physical cause of low back pain is generally sought in the lumbar vertebral column. However, before the "invention" of the intervertebral discs (Mixter and Barr 1934[7]) the SI-joints were often held directly responsible for low back pain (Brooke, 1924[2]; Sashin, 1930[8]).

For centuries there was disagreement on the possibility of mobility in the SI-joints. Nowadays it can be safely stated that small movements, especially nutation and contranutation, are indeed possible (Weisl, 1955[15]; Egund et al, 1978[4]; Bakland and Hansen 1984[1]; Lavignolle et al, 1983[5]; Stewart, 1984[11]; Walheim and Selvik, 1984[13]; Miller et al, 1987[6]).

However, movement in the SI-joints introduces a problem in case of asymmetric SI-joints (Bakland and Hansen 1984[1]; Dijkstra et al. 1989[3]): abnormal movement of the sacrum in the SI-joints could be the result, leading to abnormal stress of intervertebral discs and joints.

Anatomical studies of the SI-joint surfaces revealed differences between men and women. Brooke (1924[2])

showed that the form of the SI-joints changes drastically after puberty. He described, for preparations of men over 35 years of age, an increasing roughness of the joint surfaces; in female preparations, even of high age, such features were not apparent (Brooke, 1924[2]; Stewart, 1984[11]). The female SI-joints are not only smaller (Solonen, 1957[10]) but also flatter (Brooke, 1924[2]; Stewart, 1984[11]; Vleeming et al., 1989[12]). The relatively small and flat SI-joints of females, combined with hormonal weakening of ligaments and symphysis, may during pregnancy lead to unstable SI-joints and pain. A device developed to enhance SI-stability (the pelvic belt-Snijders et al, 1984[9]) proved to be effective in reducing pain. This pelvic belt is tightened just cranial of the symphysis. The study of Walheim (1984[14]) is supportive for this theory.
In a former anatomical study (Vleeming et al, 1989[12]) two aspects of roughening of the articular surfaces were described: coarse texture and ridges and depressions. Both aspects are considered to be a physiological adaptation and not a pathological process. The anatomical differences between male and female SI-joints were related to childbearing and presumably to a difference of the load acting on these joints (Vleeming et al. 1989[12]).
The present study concerns the relation between roughening of the articular surfaces and friction in the SI-joint. For this purpose friction experiments were carried out on iliac and sacral auricular cartilage.

Materials and methods

The specimen used were obtained from the dissection room (see Vleeming et al, 1989[12]). Most of the material was fixed; for comparison also unfixed SI-joints were used (see table 1). The material concerned different ages and sexes. In order to have joints with varying degrees of textural coarseness and ridges and depressions, a selection of the SI-joints was made. Category 1 in table 1 encloses samples with minimal ridges and depressions ("no ridges and depress"). Category 2 encloses samples with clearly visible ridges and depressions. Both categories contained cartilage of different texture (smooth or coarse).
From each specimen a sample of the SI-joint was taken. For comparison also intact knee joints were used. Corresponding pieces of sacral and iliac SI-joint surfaces were chosen (see fig. 1). The same holds for the knee joints.

Each pelvis was cut into frontal slices of about 4 mm. thick. Out of the slices straight pieces of the SI-joint were selected and cut according to fig.1. Hence the samples are pieces of bone and cartilage from both sides of the joint cleft. The samples are about 10 mm long, 4 mm wide, and 4 mm thick. Thus, the joint facets are only about 4 x 4 mm. The fixed samples were stored in phenoxy-ethanol. Measurements on fresh material was ended within four hours after autopsy.

Table 1: Used human material.

number	fresh or fixed	age (y)	gender	texture sacrum	texture ilium	ridges depress.
knee 1	fixed	12	m	(knee: smooth)		no
knee 2	fixed	60	m	(knee: smooth)		no
SI 1	fixed	12	m	smooth	smooth	no
2	fixed	40	f	smooth	coarse	no
1 3	fixed	75	f	coarse	coarse	no
4	fresh	36	f	smooth	smooth	no
5	fresh	45	m	smooth	coarse	no
6	fresh	60	f	smooth	coarse	no
7	fresh	52	f	coarse	coarse	no
8	fixed	≥ 60	m	coarse	coarse	no
9	fixed	≥ 60	m	coarse	coarse	yes
2 10	fixed	≥ 60	m	smooth	smooth	yes
11	fixed	≥ 60	m	coarse	coarse	yes

The friction coefficient was determined according to a statistical method. The dynamic coefficient of friction (i.e., during movement) was not determined. The determination of the coefficient of friction is based on the minimal force needed to slide one sample over another, while the two samples were pushed together with a known force.

The samples of the SI-joints were mounted in separate blocks. The lower block is attached to an adjustable cross-table. The upper block is attached to a bearing with a long stick in order to make it freely revolving. In order to enlarge the normal force F_N, a tray (for accessory weights)

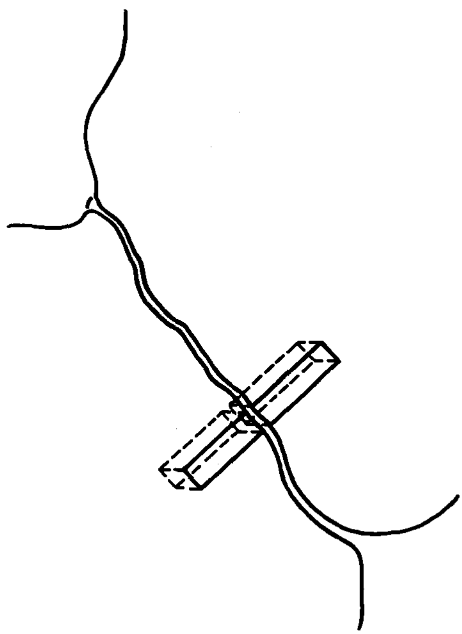

Figure 1. Samples taken from the SI-joint.

is mounted to the end of the stick.
A horizontal force F_T (with a mass of 100 gm) is applied to the upper block by means of a string over a pulley. This load is also attached to a steelyard which can be raised or lowered by an electro-motor.
In the starting position the weight fully pulls at the steelyard. While it is raised by the motor the weight is increasingly pulling on the upper block. The increase of the load is about 2.5 gm/s.
Before each determination, the samples were wetted by a drop of fixation fluid (fixed material) or synovia (fresh material). As to be expected, and demonstrated in a pilot study, wet samples revealed lower friction coefficients.
When the upper sample starts to slide over the lower one, a reading is made of the steelyard. The pulling force F_T is calculated by subtracting this value from the mass of the weight. The friction coefficient is calculated from:

$$f = F_T / F_N .$$

Each measurement on one set of a sacral and iliac sample consisted of 15 determinations. The average of the 15 measurements was calculated.

Results

The friction coefficients (f; see also the appendix) are represented in table 2.

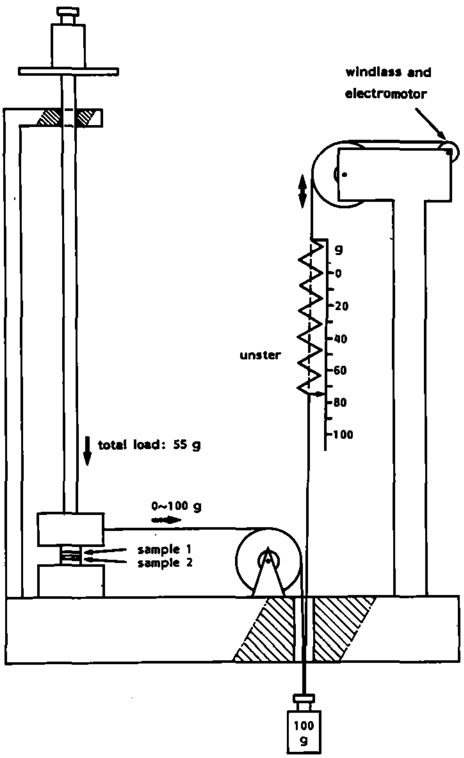

Figure 2. Schematic drawing of the apparatus for determination of friction.

Based on the calculated friction coefficients the following conclusions can be drawn:

1. the lowest friction coefficients of the SI-preparations are comparable to the values for the knee joint samples,
2. the friction coefficients for the younger samples (younger than about 60 years) vary between about 0.25 and 0.40,
3. the highest friction coefficients (1.20 and 1.33) are found in preparations

Table 2: Resulting friction coefficients.
f_{mean} (standard deviation).

number		f	texture sacrum	texture ilium	ridges depress.
knee 1		0.24(0.02)	(knee: smooth)		no
knee 2		0.32(0.03)	(knee: smooth)		no
		sacrum/ilium			
SI	1	0.33(0.06)	smooth	smooth	no
	2	0.34(0.04)	smooth	coarse	no
1	3	0.41(0.05)	coarse	coarse	no
	4	0.24(0.02)	smooth	smooth	no
	5	0.39(0.03)	smooth	coarse	no
	6	0.28(0.06)	smooth	coarse	no
	7	0.28(0.04)	coarse	coarse	no
	8	0.89(0.04)	coarse	coarse	no
	9	1.20(0.05)	coarse	coarse	yes
2	10	1.16(0.02)	smooth	smooth	yes
	11	1.33(0.04)	coarse	coarse	yes

showing both coarse texture and ridges and depressions,
4. the sample characterized by the presence of ridges and depressions and smooth texture shows a higher friction coefficient (1.16) than samples without ridges and depressions (0.89 or less),
5. no obvious difference exists between fixed and fresh samples,
6. the friction coefficients in adult men (0.34 to 1.33) are higher than in women (0.28 to 0.41).

Discussion

Ridges and depressions combined with coarse texture show, as to be expected, the highest friction coefficients. The influence of ridges and depressions appears to be of greater influence than coarse texture. For clarity it has to be added that categorizing SI-joints as having either smooth texture or coarse texture is artificial, since certain auricular surfaces show both aspects.

It can be assumed that joints without ridges and depressions allow movement. Joints with extensive ridges and depressions in combination with coarse texture can be expected to have a very limited amount of mobility.

Under abnormal loading conditions of SI-joints having ridges and depressions, it is theoretically possible that a SI-joint is forced into a new position where ridges and depressions are no longer complementary. Such an abnormal joint position could be regarded as a blocked joint. In literature however there is (as yet) no solid proof of this phenomenon.

Summarizing we can conclude from the friction experiments that in SI-joints (with intact cartilage) the friction coefficients are especially high in preparations with complementary ridges and depressions. This is in agreement with the biomechanical model (see appendix): ridges and depressions can be considered as a wedge-angle β, which can be added to the angle α (which is an indication of the friction coefficient). On trigonometric basis, a 6° increase of angle β corresponds, within limits, with an increase of the friction coefficient of about 0.1.

The biomechanical model shows, that a higher friction coefficient as well as a greater wedge-angle influence the stability of the SI-joint: less force in the ligaments is needed for bearing the upper part of the body (and accessory loads).

As we proposed in a former article (Vleeming et al., 1989[12]), formation of complementary ridges and depressions as well as of coarse texture have to be considered as normal, reflecting a dynamic development of the SI-joints.

Appendix

Biomechanical model concerning load bearing by the sacro-iliac joint

A model is proposed with three elements which are functional from a biomechanical point of view:

a) friction between the two surfaces of each joint;

b) a wedge-shaped geometry of the sacrum,

c) self bracing effect.

The curved shape of articular surfaces of the SI-joint and the spatial configuration of adjacent bones are reduced to the model of fig. 3A. Here the restriction is made to upright standing with equal load on both legs. The principle of the model, however, is also applicable to other loads, e.g. standing on one leg.

In the free body diagram of the symmetrical sacrum (Fig. 3B) the resultant of the bone to bone contact forces in the SI-joint is given by F_T. The vertical component (F_V) of this force equals half of the weight of the part of the body above the sacrum ($1/2\ F_B$).

The resultant force F_T can also be resolved into a force perpendicular to the joint surface (F_N) and a tangential force (F_F), the latter resulting from friction. The relation between both forces is given by

$$F_F \leq F_N.\tan(\alpha)$$

which becomes, just before the start of sliding:

$$F^F = F^N.\ \tan(\alpha)$$

where $\tan(\alpha) = f$ is the friction coefficient.

The wedge shape of the sacrum is represented by the wedge angle β (if the model is applied to a local ridge, β will be the inclination angle of that ridge). This leads to the following relation between the horizontal and the vertical component of the joint reaction force F_T:

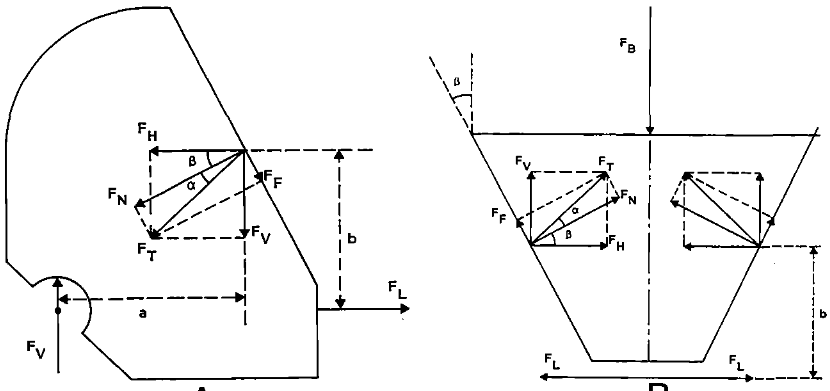

Figure 3. Free body diagram of the os ilium (A) and the os sacrum (B). This model comprises a self-bracing effect, depending on the friction coefficient (tanα) of the sacro-iliac joint surfaces, the wedge angle (β) of the sacrum and the lever arms (a and b) of respectively the supporting force in the hip joint (F_V) and the resultant of ligament forces (F_L) with respect to the SI-joint reaction force.

$$F_H = F_V/\tan(\alpha + \beta).$$

In the free body diagram of the ilium (Fig.3A) half of the weight of the upper body is carried by a vertical force in the hip joint. In order to obtain equilibrium of forces in horizontal direction a resultant ligament force (F_L) is introduced which equals F_H.

Furthermore the location of F_L, indicated by the lever arm b, is essential with respect to the warranty of equilibrium of moments:

$$F_V.a = F_L.b = F_H.b = F_V.b/\tan(\alpha + \beta)$$

which leads to:

$$b = a.\tan(\alpha + \beta).$$

In this equation F_V does not occur. So independent of the load, equilibrium will exist (self-bracing effect) whenever holds:

$$b \leq a.\tan(\alpha + \beta).$$

Typical values for β and a are 16° and 4 cm, respectively, so equilibrium is ensured whenever:

$$b \leq 4.\tan(\alpha + 16^\circ)\ \text{cm}.$$

With tan α = 0.3 (see Table 2), α = 17°. Introducing this value, as an example, in the foregoing equation shows, that self bracing exists with

$$b \leq 4.\tan(17^\circ + 16^\circ) = 4.\ 0.65 = 2.6\ \text{cm}.$$

When tan $\alpha = 1.2$, the corresponding angle $\alpha = 50°$. This leads, as an example, to: $b \leq 4.\tan(50°+16°) = 4 . 2.25 = 9$ cm.

Acknowledgment

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Complex motion tomography of the sacroiliac joint

An anatomical and roentgenological study

By P. F. Dijkstra, A. Vleeming, and R. Stoeckart

Radiologist, Jan van Breemen Instituut, Amsterdam, Clinical Anatomist, Department of Anatomy, Research group on Clinical Anatomy and Medical Technology, Erasmus University Rotterdam

Summary

To find a better method for diagnosing sacroiliac (SI) joint disease, an anatomical approach was combined with conventional roentgenology, complex motion tomography and computed tomography. Complex motion tomography is suggested as the method of choice in the investigation of the SI-joint. Because of its complex (sinusoidal) form, the dorsal portion of the joint has to be tomographed in frontal projection and the middle and ventral portions in oblique projection. In 56 patients, referred for probable ankylosing spondylitis, 72 SI joints were investigated. Based on plain radiography six and on frontal tomography five SI joints were diagnosed as normal. However, based on oblique tomography 31 joints were diagnosed as normal.

„Complex motion" – Tomographie des Sakroiliakalgelenks – Eine anatomische und röntgenologische Studie

Zur Auffindung und Festlegung einer besseren Methode zur Diagnostik des erkrankten Sakroiliakalgelenks wurde die anatomische Untersuchung ergänzt durch ein kombiniertes diagnostisches Vorgehen mit konventioneller Röntgenologie, „Complex motion"-Tomographie und Computertomographie. Die „Complex motion"-Tomographie wird als Methode der Wahl bei der Untersuchung des Sakroiliakalgelenks empfohlen. Infolge seiner komplexen (sinusoidalen) Gestalt muß der Dorsalteil des Gelenks in Frontalprojektion tomographiert werden, die mittleren und ventralen Teile dagegen in obliker Projektion. 72 Sakroiliakalgelenke wurden an 56 Patienten untersucht, die wegen Verdachts auf Spondylitis ankylosans eingewiesen worden waren. Native Röntgenaufnahmen zeigten sechs Sakroiliakalgelenke als normal an, Frontaltomographie dagegen fünf. Die oblike Tomographie ergab jedoch bei 31 Gelenken keinen pathologischen Befund.

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Introduction

The approach in diagnosis and therapy varies largely in case of sacroiliitic (SI) joint disease. This is not surprising since structure and biomechanics of the SI joints are poorly understood. In diagnosing presumed structural defects of the SI joint, radiology fulfills an important role. However, detailed knowledge of the complex configuration of the joint, including knowledge of the so-called axial joint (1) located dorsal to the auricular part combined with an approach based on this knowledge, is a prerequisite to arrive at solid conclusions. Because of the complex configuration of the SI joints, early sacroiliitis is difficult to diagnose on plain film or frontal tomography. The physical nature of tomography makes it impossible to delineate parts of the body without distinct borders and an object oblique to the tomographic movement of the X-ray tube will be show up as having indistinct borders. Thus, it will be difficult to differentiate such a structure from the surrounding tissues, if at all possible (2). Although conventional radiography can be just as good as computerised tomography (CT) (3), CT usually renders superior results (4). However, CT is expensive and good results in diagnosing early sacroiliitis are to be expected with complex motion tomography tailored to the orientation of the SI joints (2). Therefore, embalmed cadavers were used to compare radiological and anatomical data and to investigate the anatomical basis of tomographic pictures.

Plain radiography, frontal and oblique complex motion (spiral) tomography and CT were compared with anatomical sections of cadaver SI joints, the hypothesis being that fine detail diagnosis is possible if tomography is tailored to the shape of the SI joints. As a result of this project, a tailored version of oblique tomography is implemented in our rheumatology department for the detection of SI joint disease; the results of the first 56 patients are shown.

Material and methods

A1. Radiographs of a pelvis derived from a 66 years old embalmed woman were made in anterio-posterior (AP) and postero-anterior (PA) direction. To simulate the various views, serial radiographs were made with 5° interval from 25° cranial to 25° caudal and with 5° interval from 25° left side to 25° right side (Fig. 3). CT (Fig. 5) was performed with the gantry in the 0° position to allow for better comparison of the different techniques, although 20° is the method of choice. After inserting a steel pin in the left ilium near the SI joint, both SI joints were tomographed in the frontal plane with spiral movement and 5 mm intervals (standard procedure: Fig. 2 a). The left SI joint was subsequently tomographed in a 25° oblique position by lifting the left side of the pelvis (Fig. 2 b).

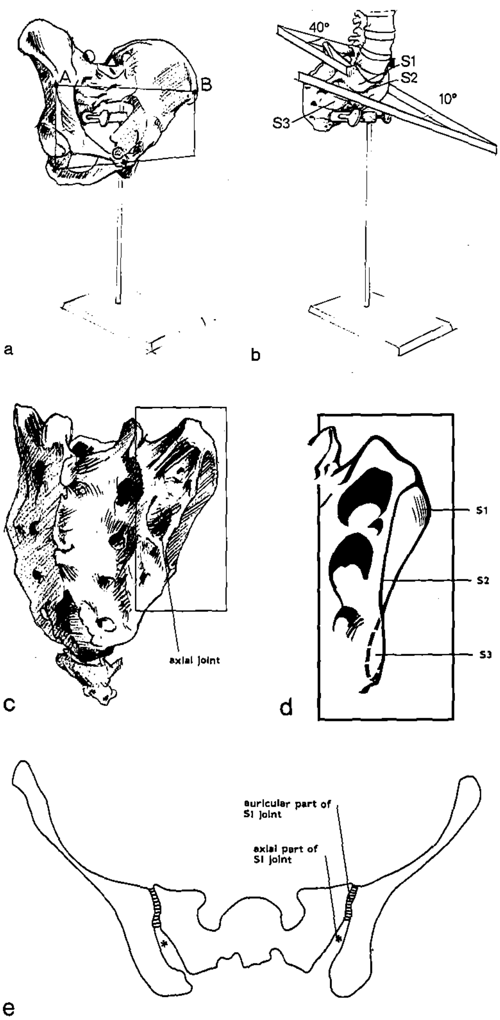


Fig. 1 a Ventrolateral view of pelvis in erect posture.

Fig. 1 b Ventrolateral view of sacrum, showing the angle between the sacral auricular surfaces of the SI joint at the level of S1 and S3.

Fig. 1 c Dorsolateral view of the sacrum.

Fig. 1 d Schematic drawing of the sacral auricular surface of the right SI joint, showing the generalised orientation.

Fig. 1 e Drawing of a horizontal section of ilium and sacrum just above the anterior superior iliac spines, through the first pelvic sacral foramina (adapted from Mc Grath/Mills). The hatched parts refer to the cartilage covered auricular parts of the SI joint. The site of the axial joint, which is located dorsal to the auricular part, is indicated by an asterisk. Note the sinusoidal configuration of the SI joints.

Fig. 1 Artist drawing of the pelvis and SI joint to show the relation between the orientation of the joint and the surrounding bones.

A2. Subsequently, the right SI joint was anatomically sectioned in the frontal plane and the left SI joint in the oblique plane, 25° in respect of the frontal plane (section thickness of 5 mm). Care was taken to fit the tomographic 5 mm sections with the anatomical sections. The anatomical sections were colour photographed on both sides.

B. To verify the interindividual variety, the orientation of the auricular surfaces of the SI joints was established in 10 cadavers by measuring the angles between the sacral auricular surfaces (Fig. 1 b).

C. The macroscopic appearance of the cartilage covered auricular surfaces was studied in a sample of 50 embalmed cadavers, mainly to get a better understanding of a possible relation between peripheral osteophytes and arthrotic processes in the SI joints.

D. A clay model was designed to investigate whether a hand-made erosion of 2 mm depth could be detected by tomography (Fig. 4). This model was treated in the same way as the cadaver pelvis (plain radiography and tomography at different angles).

E. In 56 patients (45 males, 11 females), sent to the institute for verification of the diagnosis of ankylosing spondylitis, radiography of the spine and SI joints was done, including frontal and oblique tomography of the SI joints.

Results

Anatomy

1. Orientation of the SI joints

The surface of an SI joint can be divided into three parts, roughly corresponding to the three sacral elements (S1, S2 and S3) that participate in the (sacral) auricular surface. The three parts, of which the S1-part ist the largest and the S3-part the smallest, are generally designated as the cranial, middle and caudal part, although in the erect posture (Fig. 1 a, b) terms like ventral, middle and dorsal would be more appropriate since, in this position, the sacrum is tilted forwards.

The orientation of the auricular surfaces of the S1- and S2-parts (Fig. 1 b, c, d) is roughly from mediodorsal to lateroventral, that of the S3-part predominantly in the sagittal plane.

The general orientation of the SI joint was measured at three nearby horizontal levels by measuring the angle between the auricular surfaces of the sacrum at the level of S1, S2 and S3. For this purpose the sacrum and the innominate bones were mounted in erect posture with the anterior iliac spines in a horizontal plane and these spines and the pubic tubercles in one frontal plane (Fig. 1 a). Before measurement the innominate bones were removed (Fig. 1 b, compare (5)).

The angles between right and left sacral auricular surfaces were measured with a specificity of 5°. More detailed measurements, as done by *Solonen* (5), are only possible if one focusses on the bony edges of the joint, whereas we focussed on the (irregular) cartilage covered part of the joint surface.

As shown in Table 1 the mean angle of the right and left sacral auricular surface together was 40° at the level of S1, 25° at the level of S2 and −10° at the level of S3. The negative value indicates that the general orientation of the joint

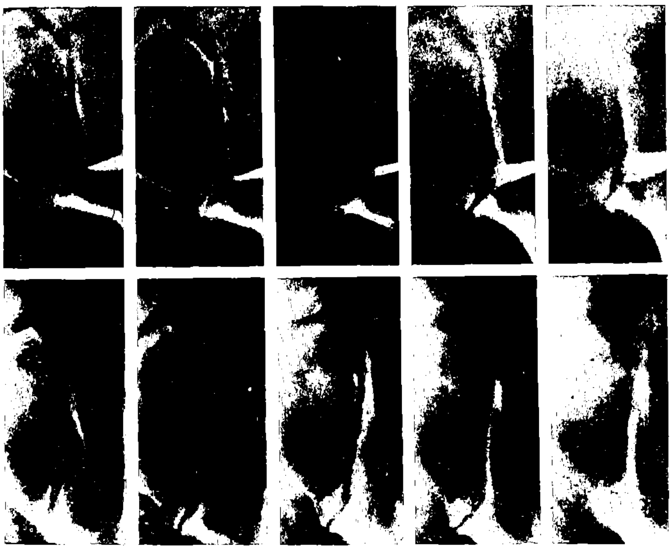


Fig. 2 a Frontal tomography. The white stripe represents a metal pin, inserted into the ilium for directional reference.

Fig. 2 b Oblique tomography. The black spot represents the hole caused by the (removed) pin. The borders of the SI joint are much sharper than with frontal tomography.

Fig. 2 Left SI joint of a cadaver.

at the level of S3 is from dorsolateral to ventromedial and not from dorsomedial to ventrolateral (Fig. 1 b). These data are in good agreement with the measurements of *Solonen* (5). From his data we calculated for the angles at S1, S2 and S3 as means (± SEM): 43.0° (3.56), 24.5° (3.32) and −10.7° (3.60). His data were based on 26 preparations. These data indicate that the generalised orientation of a single joint with respect to the sagittal plane (from dorsomedial to ventrolateral) is about 20° at the level of S1, 12.5° at the level of S2 and −5° at the level of S3.

Table 1 shows an additional, practically important feature of the SI joints. Even in this small sample a large variation exists in the orientation of the auricular surfaces with respect to each other: from 20 till 50° at S1, from 10 till 60° at S2 and from −30 till 15° at S3. As to be expected, *Solonen* (5) found in his larger sample even more variation, respectively from 0 till 64°, from −6 till 62° and from −45 till 37°.

Tab. 1 Orientation of the SI joints (compare Fig. 1 b). Angle between left and right auricular (sacral) surface at the level of S1, S2 and S3 (n = 10). The mean values (± SD) are 40.0° (11.55) at the level of S1, 25.0° (17.79) at the level of S2 and −9.5° (14.0) at the level of S3.

sacrum	S1	S2	S3
1	20	10	5
2	50	15	0
3	45	20	15
4	20	10	−5
5	40	35	−15
6	50	25	−5
7	50	10	−30
8	45	60	−20
9	45	50	−25
10	35	15	−15

In order to understand radiographs of the SI joints it has to be emphasised that these data reflect a generalised orientation: a sinusoidal configuration is superimposed on the general orientation (Fig. 1 d; Fig. 5). In this sinusoidal configuration the dorsal (in erect posture in fact rather caudal) portion of the joint is predominantly oriented in the sagittal plane. The sinusoidal configuration is even more conclusive if in addition the axial joint is taken into consideration (Fig. 1 e).

2. Macroscopic anatomy of the auricular surfaces

In a sample of 37 embalmed cadavers (24 female, 13 male), mostly of advanced age, obvious differences were apparent between the cartilage covered auricular surfaces of ilium and sacrum.

The cartilage of the iliac part is more or less rough and striated and fibrocartilagenous in appearance. These features were also apparent, but less outspoken, in an 8-month foetus and a 12-year old boy, where the cartilage was rather bluish in colour. *Paquin* et al. (6), however, showed by collagen typing that in the iliac part no collagen typical for fibrocartilage could be detected. According to them the iliac cartilage is more of a hyaline than of a fibrocartilage nature. The orientation of the collagen fibrils is, however, abnormal in being organized throughout its depth parallel to the auricular surface.

The cartilage of the sacral part is, especially in cadavers of young age, smooth, white, glistening and hyaline in nature. The cartilage is thick if compared with that of the iliac part (Fig. 6). At an advanced age the cartilage of the sacral part becomes more rough and somewhat gray in colour. These observations are in accordance with those mentioned in a thorough study by *Bowen* and *Cassidy* (7).

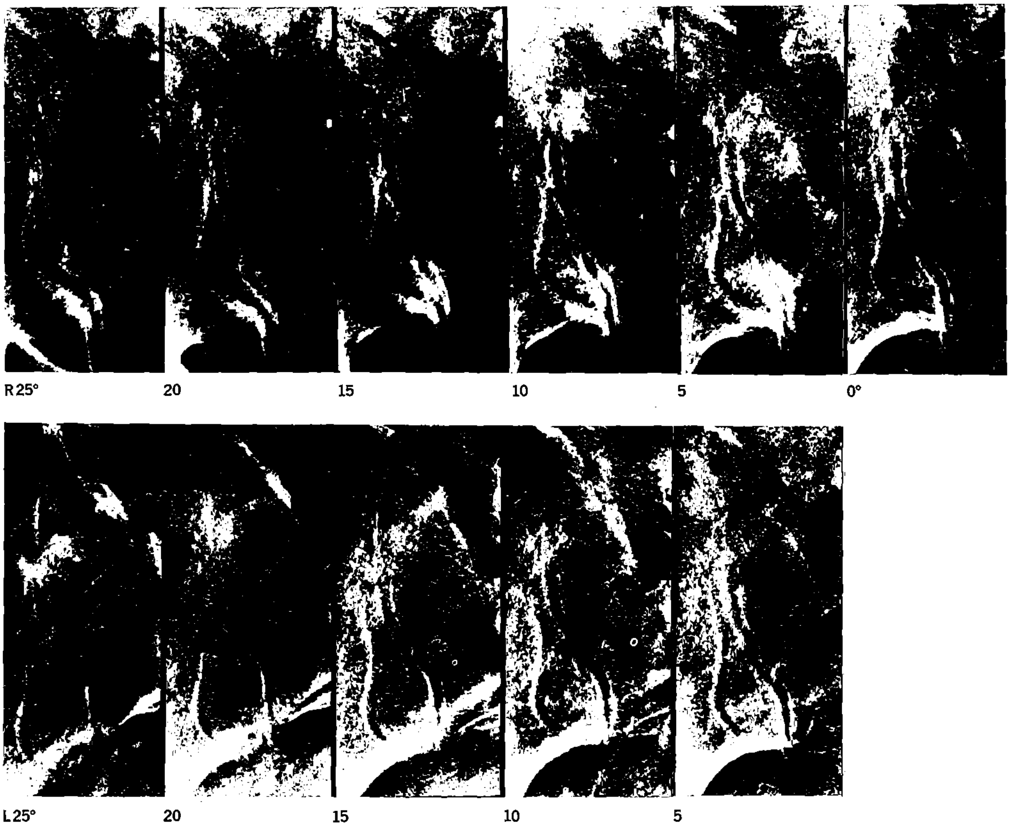


Fig. 3 Right SI joint; plain radiography. X-rays at 5° interval from 25° right to 25° left direction to show the effect of oblique projection. With every step other portions of the joint come into view. The first radiograph at 25° shows the superimposed projection of the ventral and dorsal portion; the middle portion is seen continuous with the dorsal portion at 0°.

The macroscopic appearance of the cartilage covered auricular surfaces in 21 of the 24 female cadavers, was, notwithstanding the advanced age, compatible with movement of the SI joints. In these preparations small, non-bridging anterior peripheral osteophytes were regularly present. The SI joints of most male cadavers, in contrast, showed aging cartilage in varying degrees; mobility did not seem possible (see also *Stewart* (8)). In an additional study, 13 cadavers (males and females) were selected on the basis of absence or minor development of anterior peripheral osteophytes. Most male joints showed aging cartilage on both sides of the joint, although more severe at the iliac part. This observations may indicate that, especially in males, the mobility of the SI joints may be impeded by aging cartilage despite the absence of major osteophytes.

Roentgenology

1. Clay model

An aim of this study was to prove the possibility of detecting small erosions in oblique tomography, small erosions which could not be detected in frontal tomography. The clay model shows the features that have to be proved.

Plain radiography of the clay model (Fig. 4 a) does not show the erosion, whereas the frontal tomogram shows a vague light spot which could be the erosion (Fig. 4 b). Oblique tomography clearly delineates the small 2 mm deep erosion (Fig. 4 c). Since, in reproduction, it appeared to be somewhat difficult to show the erosion, the erosion was painted with a drop of contrast medium. After all, this makes the erosion somewhat more realistic since most erosions of the SI joint have a slight sclerotic border. Plain radiography of the clay model illustrates in addition (Fig. 4 a) that only a part is seen of a seemingly "open" joint; the part with the erosion is not visible.

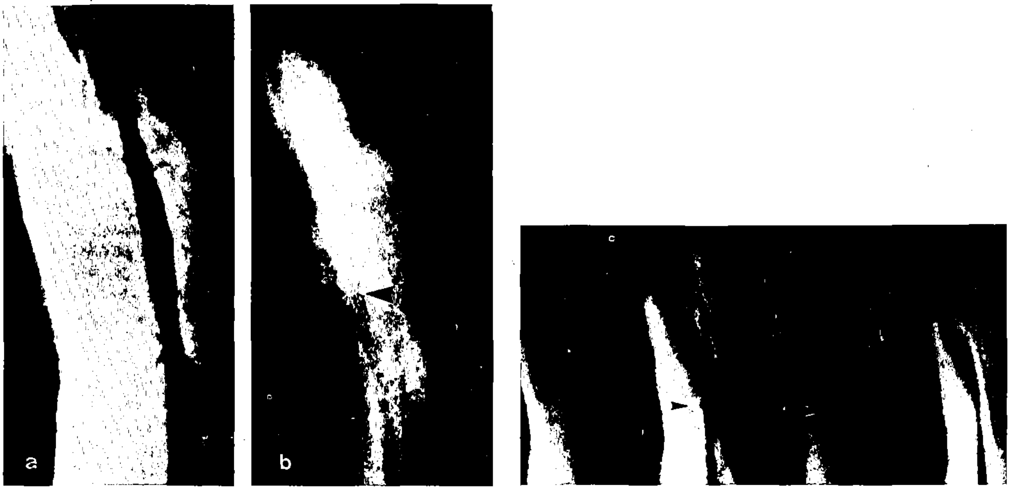


Fig. 4 a Plain radiography; no signs of erosion.

Fig. 4 b Frontal tomography with dubious projection of the erosion.

Fig. 4 c Oblique tomography at subsequent tomographic slices (5 mm interval) with clear delineation of joint, erosion (large arrow) and shadow of erosion (small arrow).

Fig. 4 Radiographs of a clay model with a 2 mm deep erosion, painted with contrast medium.

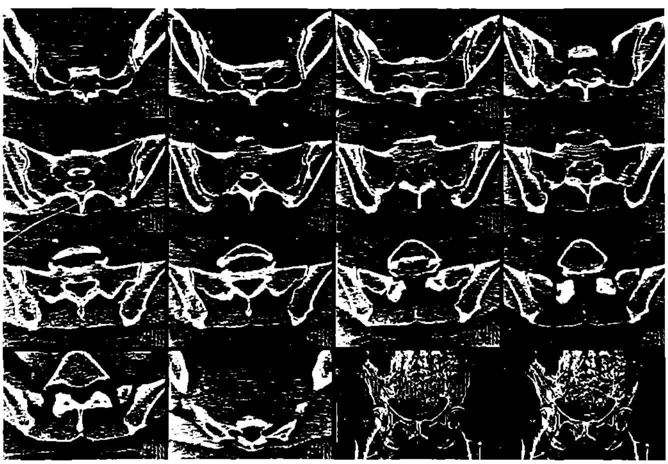


Fig. 5 CT of cadaver SI joints and pelvis. Gantry in 0° position (for better comparison with tomography). Note the sinusoidal form of the SI joints.

This brings us to the position of the SI joint in normal radiography. In every projection only part of the joint is visible. Oblique projections may look useful but mask a large part of the joint. Exclusively that part of the joint is visible that happens to be open in the direction of the x-rays, which, in frontal projection (0° in Fig. 3), is the dorsal portion, and in oblique projection mostly the middle and ventral portion of the joint.

A further point of discussion in tomography is the detectability of a lesion within a slice. Therefore, tomograms were made of the clay model at 2 mm intervals. The shadow of the erosion could be detected over an area of about 6 mm, which implies that small erosions are detectable with normal equipment and 5 mm interval slices.

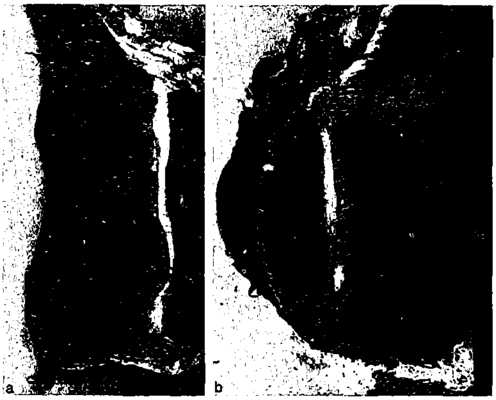


Fig. 6 Front (a) and back (b) of one anatomical slice of the left SI joint. Note the difference in configuration of the joint, notwithstanding a section thickness of only 5 mm.

2. Cadaver

In the CT scans of the cadaver pelvis, the complexity of the SI joints is clearly seen. A sinusoidal form can be reconstructed from ventral to dorsal (Fig. 5).

The frontal tomograms of the right SI joint coincided well with the anatomical sections of the cadaver joint. The dorsal portion of the joint is oriented in a sagittal plane. The middle and ventral portions of the joint are oblique, so the edges have unsharp borders, both in tomograms and in anatomical sections. The oblique tomograms of the left SI joint (Fig. 2 b) matched the oblique anatomical sections of the cadaver joint (Fig. 2 b). In the oblique tomograms, the dorsal portion is not sharp (it is directed in a sagittal plane, Fig. 2 a) if compared with the frontal tomograms. The middle and ventral portions are oriented perpendicular to the tomographic movement and thus the projection has sharp borders.

In comparing the frontal and oblique tomograms of the SI joint with the anatomical sections it is obvious that, for the middle- and ventral portion of the joint, oblique tomography is superior to frontal tomography. For these specific cadaver SI joints it is of course only possible to compare left oblique anatomical sections with right frontal anatomical sections.

Also between the front and the back of an anatomical slice differences exist, even with a slice thickness of 5 mm (Fig. 6). This explains why in the frontal tomographic movement the edges of the joint surfaces are more or less blurred: the joint surface is not perpendicular to the movement of tomography (Fig. 2 a, b).

3. Clinical results

A practical result of this study is the implementation of the technique in our large rheumatology department, where ankylosing spondylitis is given special attention. For this purpose, in 56 successive patients referred to our clinic with suspected ankylosing spondylitis, 59 SI joints were investigated in males and 13 in females.

As shown in Table 2, six normal SI joints were found with plain radiography, whereas with oblique tomography 31 joints were diagnosed as normal.

In accordance with *Dihlmann* (9, 10), SI joints were diagnosed as having sacroiliitis on the basis of the combination sclerosis, erosions and/or ankylosis. Joints with confusing signs which could not lead to a firm diagnosis of normal joint or sacroiliitis were scored as non-diagnostic which means that we were not able to judge these joints reliably. Those joints which showed exclusively either a. a more or less generalised joint space narrowing or b. slight sclerosis of the iliac borders were scored as non-related (to sacroiliitis).

As shown in Table 2, 43 joints were scored as non-diagnostic in frontal tomography and 15 joints as non-related in oblique tomography. This discrepancy is largely due to the finding that with oblique tomography 24 of the 43 joints (Table 2 a) were scored as normal because of a well delineated middle portion of the joint in oblique tomography.

With the three different techniques used about the same numbers of sacroiliitis were scored (Table 2), but this is rather misleading. As shown in Table 2 a 5 cases out of the 24 cases of sacroiliitis in frontal tomography were diagnosed as normal or as non-related in oblique tomography, whereas 7 out of the 26 cases of sacroiliitis in oblique tomography were categorised as non-diagnostic in frontal tomography.

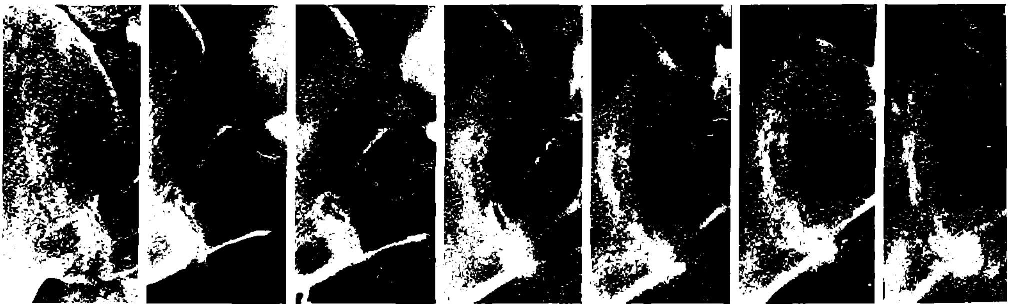
Between plain radiography and frontal tomography there is little difference in the detection of disease activity (Table 2). This may partly be due to the fact that in experienced hands plain radiography can be assessed accurately to the point of detection of disease activity (3).

Tab. 2 Diagnosis on basis of plain radiography, frontal tomography and oblique tomography. The SI joints were investigated with three x-ray modalities (n = 72). Non-diagnostic are confusing signs which cannot lead to the firm diagnosis of normal joints or to sacroiliitis. Non-related are changes within the SI joint which cannot be attributed to sacroiliitis, as some sclerosis or some narrowing of the joint without further evidence of erosions or ankylosis.

	plain radiography	frontal tomography	oblique tomography
normal	6	5	31
sacroiliitis	19	24	26
non-diagnostic	47	43	–
non-related	–	–	15

Tab. 2 a Diagnosis on basis of frontal and oblique tomography (n = 72). This table is compiled to elucidate the discrepancies in Table 2.

frontal tomography	oblique tomography	total
non-diagnostic	to normal	24
non-diagnostic	to sacroiliitis	7
non-diagnostic	to non-related	12
sacroiliitis	to normal	2
sacroiliitis	to non-related	3
sacroiliitis	to sacroiliitis	19
normal	to normal	5



AP 9.5 10 10.5 11 11.5 12

Fig. 7 a AP plain radiography and frontal tomography of right SI joint. "Typical" erosions, sclerosis, jointspace narrowing and ankylosis.

14.5 15 15.5 16 16.5 17 17.5

Fig. 7 b Oblique tomography. Slight joint space narrowing, slight sclerosis of iliac side of the joint, no ankylosis and no erosions. The numbers refer to the distance between table top and centre of tomographic slice. The photographs show – in case of a narrow angulated joint – the problems typical of plain radiography and frontal tomography.

Fig. 7 Patient of 56 years of age with low-back pain. No clinical signs of ankylosing spondylitis but referred to our clinic as having this disease because of plain radiography.

Especially in patients with instability of the spine or legs, and SI joints with a more lateral course, we have seen many errors in diagnosing ankylosing spondylitis. To demonstrate a rather typical case, see Fig. 7 as an example of the power of oblique tomography.

Discussion

Obviously, oblique tomography of the SI joints renders superior results if compared with frontal tomography. It is suggested that a practical implementation of this project for tomography of the SI joints is the combination of frontal tomography for the dorsal portion of the joint and oblique tomography at an angle of 25° for the middle and ventral portion. As shown in Table 1, there is large variation in the configuration of the SI joints. In patients with only a slight inclination of the middle portion of the joint or with a more angulated dorsal portion, tomography has to be tailored to the special configuration, which means an angle different from 25°. A better understanding of the anatomy of the SI joints affords a greater insight into these joints.

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Mobility in the SI-joints at high age: A kinematic and roentgenologic study

Vleeming, A.[1], Van Wingerden, J.P.[1,2], Dijkstra, P.F.[3], Stoeckart, R.[1], Snijders, C.J.[2], Stijnen, T.[4]

[1] Department of Anatomy, anatomists

[2] Department of Biomedical Physics and Technology, bioengineers

[3] Jan van Breemen Instituut, radiologist

[4] Department of Biostatistics, biostatistician

Research group of clinical anatomy and medical technology,
Erasmus University, Rotterdam, The Netherlands .
For correspondence: A.Vleeming/R.Stoeckart, Department of Anatomy,
Faculty of Medicine, Erasmus University, P.O. Box 1738,
3000 DR Rotterdam, Netherlands.

Abstract

Movement in the sacroiliac joints was measured in preparations of embalmed elder human cadavers and correlated with a radiographic survey. The pelvis was fixed at the fifth lumbar vertebra. The connections between sacrum and fifth lumbar vertebra were spared as were the surrounding ligaments. To induce movement, forces were directed at the acetabula.

In the sagittal plane both ventral rotation (as part of nutation) and dorsal rotation (as part of contranutation) could be demonstrated. Most sacroiliac joints were mobile, allowing—for the combination of nutation and contranutation—total rotation of up to 4°. In younger persons larger rotation can be expected. The sacroiliac joint with the lowest mobility showed radiographically marked arthrosis.

The sacro-iliac joint showed a limited amount of "creep". Attention is paid to intra-individual differences in the mobility of the sacroiliac joints. The impact of the findings on kinematic chain and clinical diagnosis is discussed.

Key words

sacro-iliac joint, sacrum, joint instability, pelvic bones, anatomy, radiology, spinal injuries, intervertebral disc.

Introduction

Two large leverage arms, the trunk and the lower extremity, act directly on the sacro-iliac (SI-)joints. As shown by several authors, these joints permit more or less free movement (Brooke 1924[2]; Weisl 1955[17]; Solonen 1957[7]; Egund et al. 1978[4]; Lavignolle et al. 1983[5]; Walheim and Selvik 1984[15]; Miller et al. 1987[6]).
In a former study (Vleeming et al. 1989[12]) we suggested that during growth these leverage arms generate an increasing force until full body weight is reached. As a consequence, the SI-joint will be dynamically modified by changes in the direction and strength of the forces acting on it.
It is assumed that the alteration of forces during pubertal growth results in roughening of the sacro-iliac articular surfaces. This roughening is characterized by curvatures of the articular surfaces, by increased texture of the cartilage and by symmetric ridges and depressions, which involve both bone and cartilage. These features of roughening are considered as normal for the adult SI-joint (Vleeming et al. 1989[11]). As a result of roughening, friction is increased (Vleeming et al. 1989[12]) and movement restricted. However, even at high age SI-joints with increased intra-articular roughening are, judged by the morphology, in a condition to allow mobility (Stewart 1984[8]; Vleeming et al. 1989[11]; Dijkstra et al.1989[3]).
Mobility studies of the SI-joints have been performed on a mobile sacrum and completely or partly fixed iliac bones (Strachan 1938[9]; Miller et al. 1987[6]). This choice seems logic since the large iliac bones are relatively easy to fix. However, a problem with *partial* immobilization, used by Miller et al., could be that physiological bone deformation of the ilium is excluded. In that case the applied forces caused movement in the SI-joint larger than normal. Another drawback of fixed iliac bones could be that the sacro-iliac ligaments are partly fixed too.
For the present study a construction was developed which allows mobility of the SI-joint with freely moving iliac bones and sacrum. Since both SI-joints were left intact an intra-individual comparison of mobility was possible. Furthermore, an artificial gravity force was applied. In testing these load bearing joints, we consider this force essential.
Because of the surmised influence of the condition of the SI-joints on their mobility, all data were related to a radiographical survey.

Materials and methods

Four bodies were embalmed by vascular perfusion with 15-25 litre of a medium containing 2.2% formaldehyde. Embalment was started between 12-48 hours post mortem. The bodies ranged from 65 - 82 years of age.
The bodies were sectioned transversally at the upper level of L4 and 20 centimetres caudal of the ischial tuberosity.

Femurs and hip joint capsules were removed. As far as possible, the pelvis and the lumbar vertebrae were dissected bluntly, freeing the superficial ligaments. The iliolumbal, (dorsal) sacroiliacal, sacrotuberous and sacrospinous ligaments were spared. To diminish dehydration, the muscles attached to the pelvis were spared where possible.

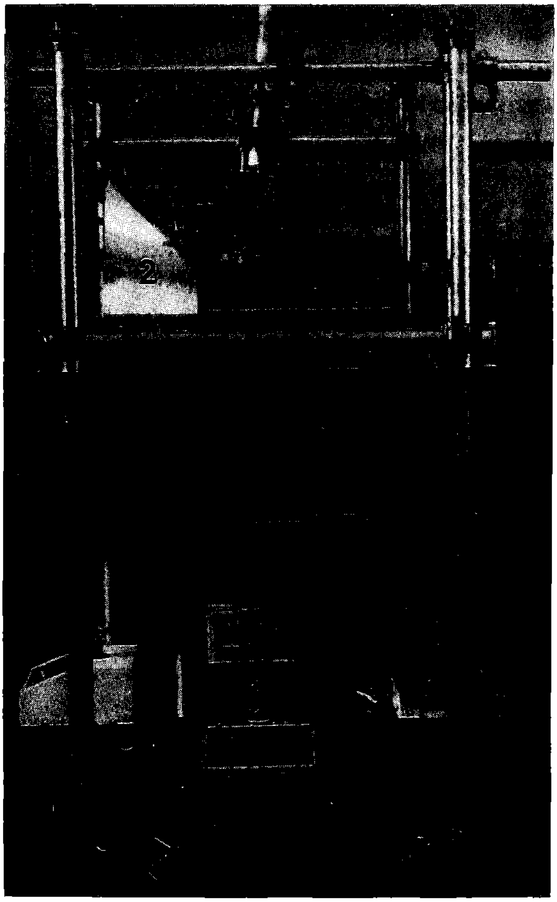
The vertebral foramina of L4 and L5 were slightly widened and a tapering 270 mm long stainless steel rod (mm 12) with thread and notches was fitted in the foramina. The acetabula were chosen as force transfer points. Holes were drilled into the acetabula and stainless steel rods 190 mm (mm 10) were fitted from lateral to medial through the acetabula. From small holes in these rods, steel wires passed through internal and external acetabular holes. The vertebral and acetabular rods were centred in respectively foramina and acetabula, and stabilized with Technovit 7100 (a two component hardening resin).

The pelvis was connected to a special inner and outer frame with the following specifications.

The steel rod, fitted in the lumbar vertebral foramina, was mounted to a hole in the top plate of a steel and perspex inner frame (fig. 1-2, 3-1), adjustable on a tripod (fig. 3-2). The anterior superior iliac spines and the pubic tubercles were adjusted in a frontal plane. Two Perspex triangles were mounted to the top plate (fig. 2-4). The triangles were fixed with bone screws and Technovit to the ventrolateral part of the vertebral bodies of L4 and L5.

A steel outer frame (fig. 1-1) was constructed with pipes mm 50. The outer frame served to connect the inner frame and was equipped with 4 power units, type Eltrac Enraf Nonius 471-1471.905 (fig.1-3). The units generate gradual adjustable pull forces with a maximum capacity of 900 N. The forces were transferred by steel wires to 8 pulleys connected to the outer frame pipes. The inner frame was rigidly fixed to the outer frame. Polyethylene wedges were used to exclude movements in the tripod. The top plate of the inner frame is rigidly connected with a steel pipe of the outer frame construction (fig. 2-2). The vertebral rod, fixed to the inner frame top plate (fig. 2-1), was also connected to a polyethylene block making part of the outer frame (fig. 2-3). Connected to the inner frame were digital Mitutoyo displacement meters type IDU 25 575-113 and IDU 25E 575-103-5 (fig. 3-3). The meters were coupled via a Mitutoyo UB5 Multiplexer 011028 to a registration unit Mitutoyo Digimatic miniprocessor DP-1 DX 264-501-1. This assembly enabled us to obtain data in graphic form.

The construction described was used to measure movement in the SI-joint in the sagittal plane after load application to the iliac bones. Since rigid meters can not record the complex movements



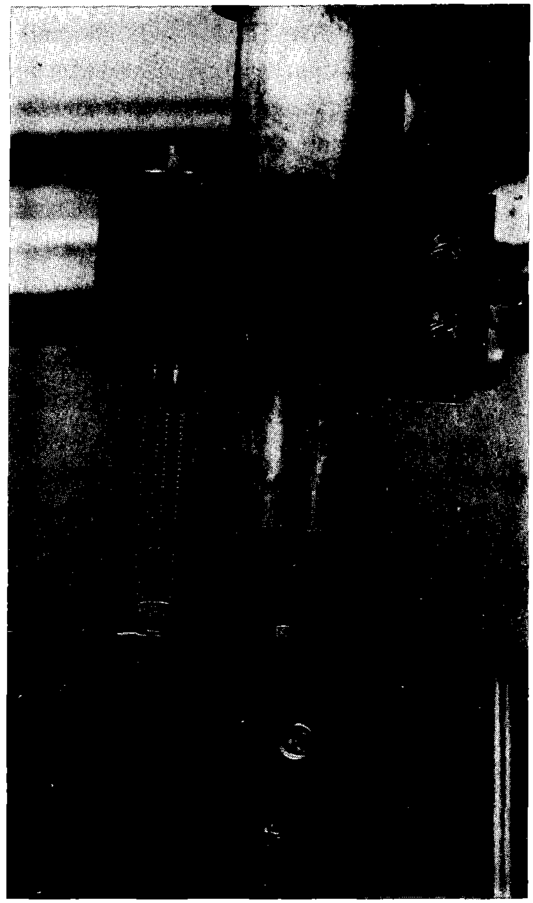


Figure 1 (left). Pictures of the test construction (see text for explanation).
1. Outer frame. 2. Inner frame and 3. Traction units.

Figure 2 (right). Detail of upper side of inner frame connected with outer frame.
1. Steel vertebral rod. 2. Steel pipe connection between inner and outer frame.
3. Polyethylene block serving to connect the vertebral rod to the outer frame.
4. Perspex triangles securing the lumbar vertebra to the inner frame top plate.
See text for explanation.

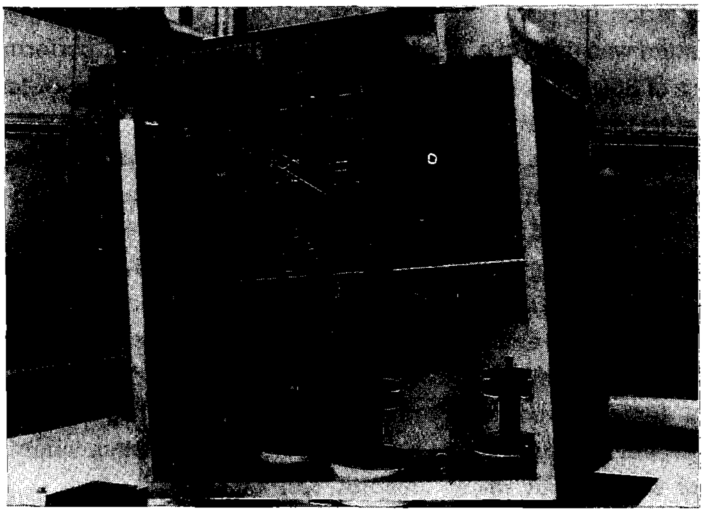


Figure 3. Detail of the back of the inner frame.
1. Inner frame. 2.Tripod. 3. Displacement meters.
See text for explanation.

(see Weisl 1955[16]; Lavignolle et al. 1983[5]) in the SI-joints, we exclusively measured rotation of the sacrum. For this purpose, two Perspex plates (5 ×90×40 mm each) were fitted with bone screws to respectively the sacrum and the posterior superior iliac spine. The plate was located at the centre of the sacrum, since fixation at the lateral side of the sacrum would destroy part of the sacroiliac ligament. The two plates were adjusted in the same plane and fixed by Technovit.

Two sets of two meters (fig. 3-3), connected to the inner frame, were (at a distance of 40 mm) adjusted in the sagittal plane perpendicular to the ilium and sacrum plates. The meters were calibrated to the 0 position. Since the plates connected to sacrum and ilium were making an angle with the frontal plane, the meters were adjusted to this new plane. The new values of the meters were used in a correction calculation and the meters were again calibrated to zero. A trigonometric calculation was applied to obtain the final dorsal (contranutation) and ventral (nutation) rotation (Vleeming et al. 1989[13]).

To obtain displacement, all forces were acting at the acetabular rods. Before actual measurements the construction was tested for deformation. Deformation could not be demonstrated even with forces far exceeding those used in this study.

The specimens were stored in preservation liquid up to the experiment. During testing, specimens and inner frame were located in a humidity chamber designed for this purpose.

To induce ventral rotation (as part of nutation) a combination was used of a cranial directed force of 300 N bilaterally (150 N at each side) and a ventral directed force of 200 N bilaterally. The cranial force in combination with the rigid top plate served to establish compression in the specimen, replacing gravity. To induce dorsal rotation (as part of contranutation) the same forces were used directed caudal and dorsal. The caudal force served to decompress the specimens. Use of larger forces did not significantly increase displacement. Displacement was measured during a period of 15 min.

To avoid early destruction of the material (and deceptive data), reproducebility of the data was not tested with the mentioned loads but at 2/3 of this load. Furthermore, measurements were only repeated for total rotation (nutation and contranutation) as part of a specific experiment described elsewhere (Vleeming et al.[14]). Two sets of 8 measurements were performed in two different sessions. Thus, for each joint the total rotation was measured 16 times, each two minutes after the start of loading. In the results the coefficients of variation (CV) of the 16 measurements are given. Since meters and registration unit had a negligible S.E.M. (0.005 mm) and no deformation of the construction was found with even larger forces, we regard the data obtained by this replication study relevant for the whole study.

The experiments were followed by a specific radiological study, performed by a radiologist specialized in SI-joint diseases.
Frontal tomography and a tailored version of oblique tomography was used as described in a previous study (Dijkstra et al. 1989[3]). To mimic normal gray scale values, the material was radiographed submerged in a liquid testing box, with the diameter of a normal human being. The radiologist was not informed of the biomechanical results.

Results

The graphics of fig. 4, 6, 8 and 10 (A and B) represent the rotation (in the sagittal plane) of sacrum and ilium relative to each other. Top lines (positive) represent rotation during contranutation and bottom lines (negative) during nutation.

Rotation in the first minute is characterized by a steep line, resulting from the linear load increase of the traction apparatus. At the end of this steep line, the full load is acting at the specimen. It was not possible to generate sudden synchronous bilateral loading. Besides, we expected that immediate loading of a specimen, without the counter force of muscles, could cause deceptive joint motion.

Of each SI-joint one oblique tomogram is shown (fig. 5, 7, 9 and 11).

Pelvis nr. 1, female 73 years

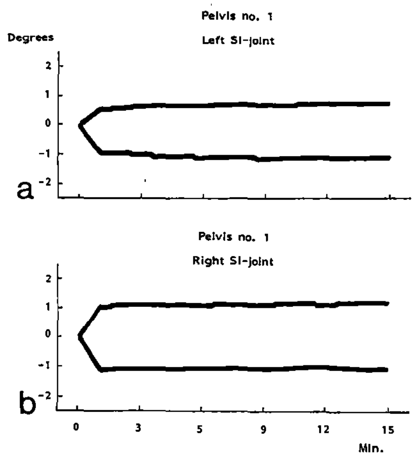


Figure 4A and B. Rotation in left and right side of pelvis nr.1. Top lines (positive) represent rotation during contranutation and bottom lines (negative) during nutation. Rotation is displayed in degrees and related to a loading period of 15 minutes. See text for explanation.

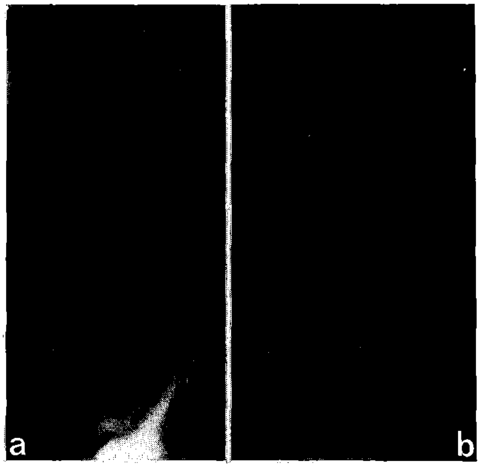


Figure 5A and B. Oblique tomographs of left (12.5) and right (10) SI-joints of pelvis nr. 1. The numbers indicate the depth of the tomograph (in cm) taken from the dorsal side (the roentgen table) to ventral, including a mattress located between table and preparation. This practically means that higher numbers relate to a more ventral part of the SI-joint. See text for explanation.

Left side (fig. 4A)

A total rotation of approximately 2° is present. Ventral displacement (bottom line) is slightly larger than dorsal displacement. As in most other figures, rotation is represented by a dented line, which might well be caused by the presence of roughness in the articular cartilage of ilium and/or sacrum (see discussion). With 2/3 of loading a total rotation was found of 1.36° (± 0.06). CV = 0.03.

According to the radiological description (see also fig. 5A), the intervertebral joints of L5-S1 are practically normal. On the frontal tomographs (not shown) a normal SI-joint space is visible which strongly deviates from the sagittal plane. In the dorsal part of the SI-joint, at level S3, sclerosis and subchondral cyst formation is visible. On the oblique tomographs (see fig. 5A) light sclerosis of the iliac part is visible with a small osteophyte at the caudal side of the joint. The axial joint is wide. Bony grooves and ridges are hardly developed.

Right side (fig. 4B)

The total rotation is also approximately 2°, but somewhat larger than left. Dorsal displacement is slightly larger than ventral rotation. The ventral displacement is characterized by a non-dented line. With 2/3 of loading a total rotation was found of 1.29° (± 0.04). CV = 0,03.

According to the radiological description (see also fig. 5B) normal intervertebral joints are present at L5-S1. On the frontal tomographs a smooth SI-joint is visible. On the oblique tomographs only local sclerosis with subchondral cyst formation is visible. A relatively narrow axial joint is present, if compared with the left side. Possibly the smooth graphical line during ventral rotation is related to the smooth SI-joint as observed on radiography.

Pelvis nr. 2, male 75 years

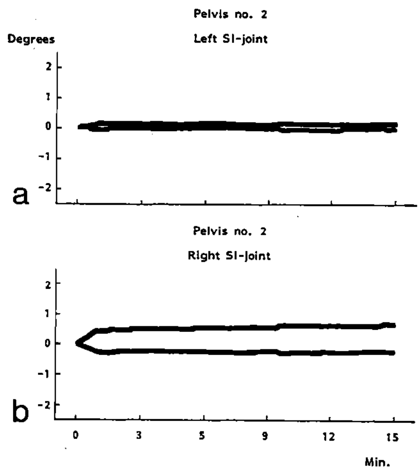


Figure 6A and B. Left and right side of pelvis nr. 2.
See fig.4A and B. and text for explanation.

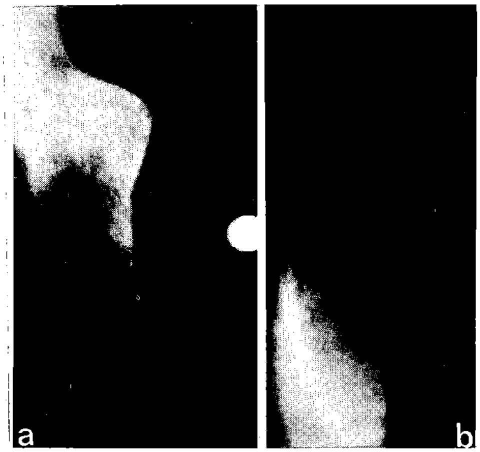


Figure 7A and B. Oblique tomographs of left (10) and right (9) SI-joints of pelvis nr. 2.
See fig. 5A and B. and text for explanation.

Left side (fig. 6A)

No rotation is seen. The small deviation of the zero line is regarded as distortion of the cartilage. Therefore, no replication was performed on this joint.

On frontal tomographs a bilateral sclerotic joint space, osteophytes and cyst formation at the intervertebral joints at L5-S1 are visible. Striped sclerosis and multiple local subchondral cyst formation of the SI-joint is clearly visible on the oblique tomographs (see also 7A). Osteophytosis is present on the caudal side of the SI-joint. The axial joint is narrow. Grooves and ridges are present. Arthrosis of the SI-joint is outspoken if compared with the right side.

Right side (fig. 6B)

Approximately 1° of rotation is present. Dorsal rotation (top line) is larger than ventral rotation. The rotation shows "creep", which means that a longer period of loading creates larger rotation. With 2/3 of loading a total rotation was found of 0.55 ° (± 0.03). CV = 0,05. On the frontal tomographs the intervertebral joint is sclerotic (see text of left side). The SI-joint shows striped sclerosis of the iliac side and subchondral cyst formation is outspoken.

On the oblique tomographs (see also 7B), which give a better view of the joint space, mild sclerosis is visible with a frayed joint line on the iliac side. Bony grooves and ridges are present.

<u>*Pelvis nr. 3, female 83 years*</u>

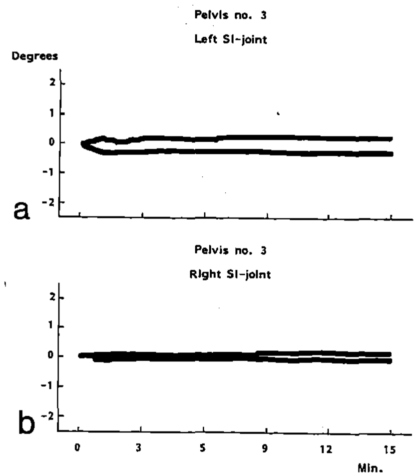


Figure 8A and B. Left and right side of pelvis nr. 3.
See fig.4A and B and text for explanation.

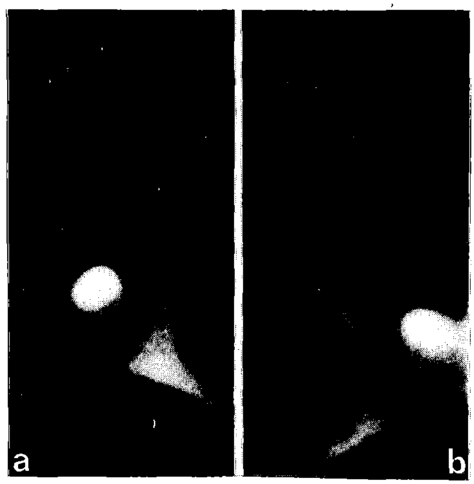


Figure 9A and B. Oblique tomographs of left (9.5) and right (9) SI-joints of pelvis nr. 3. See fig. 5A and B and text for explanation.

Left side (fig. 8A)

Total rotation does not exceed 0.8°, indicating that rotation is very limited. With 2/3 of the loading a total rotation was found of 0.55° (± 0.09). CV = 0.16. The rotation of 0.55° is not significant, which can be explained by the fact that this joint became more mobile during the third measurement.

On the frontal tomographs the intervertebral joints of L4-L5 and L5-S1 are irregular, with sclerosis and joint space narrowing. Arthrosis is outspoken. The SI-joint space is normal. Sclerosis is present on the iliac side and characteristic condense iliitis is present (see also fig. 9A)

The transition of the auricular part of the SI-joint to the axial part shows a small angle - this in contrast to the right side.

Right side (fig. 8B)

Slight rotation is seen after 10 minutes of loading. According to the radiological description (see also fig. 9B) the intervertebral joints at this side are also arthrotic. On frontal tomographs a strongly curved SI-joint is visible with normal joint space. No clear evidence of sclerosis is visible in the SI-joint. On the oblique tomographs an outspoken curved transition is present between the dorsocaudal (S3) and middle (S2) part of the SI-joint.

Pelvis nr. 4, female 77 years

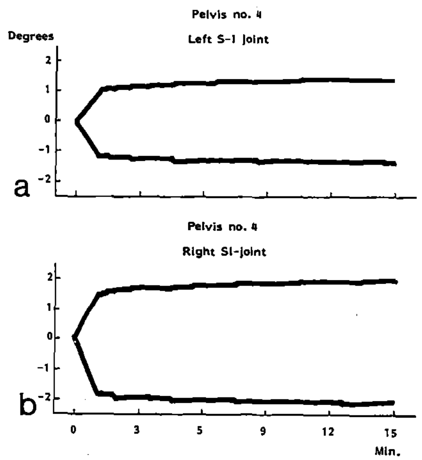


Figure 10A and B. Left and right side of pelvis nr. 4. See fig. 4A and B and text for explanation.

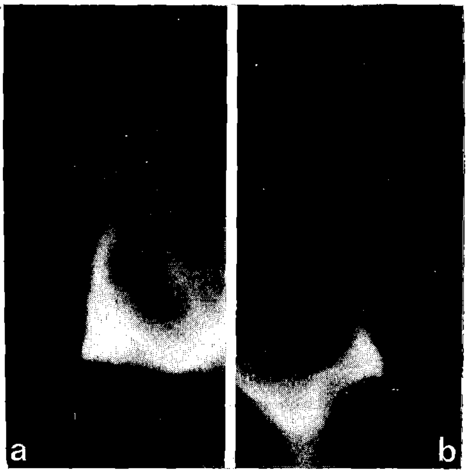


Figure 11A and B. Oblique tomographs of left (9) and right (10) SI-joints of pelvis nr. 4. See fig. 5A and B and text for explanation.

Left side (fig. 10A)

A total rotation is seen of 3°. Rotation is characterized by a dented line. There is only a small difference between ventral and dorsal rotation. Especially dorsal rotation shows "creep." With 2/3 of the loading a total rotation was found of 1.9 ° (± 0.04). CV= 0,02.

Radiological evaluation of the frontal tomographs shows a narrowed intervertebral joint with sclerosis at L5-S1. L5 and S1 are connected by a syndesmophyte. The SI-joint space is narrow in comparison with the right side. Characteristic condense iliitis is present on the iliac side in the mid-ventral portion of the joint (see also 11A). The general condition of the joint is described as starting arthrosis.

Right side (fig. 10B)
Up to 4 ° of rotation is possible at this side of the pelvis with a total hip replacement. Dorsal rotation is most outspoken. With 2/3 of the loading a total rotation was found of 2.6 ° (± 0.07). CV = 0.03. The radiographic film shows a horizontal orientated intervertebral joint at L5-S1. The right side of L5 has a bony connection with the sacrum. On the frontal tomographs subchondral cyst formation of the SI-joint is present.
The general condition of the joint is good (see also fig. 11B).

Discussion

Kinematic comments
The following important features were considered:

A. Realistic data of pelvis mobility and specifically the SI-joints can only be obtained if the joint ligaments are spared. In addition to the joint ligaments, the ligaments surrounding the SI-joint are essential. It can be expected that ligaments at a certain distance from the joint have a relatively large momentum. Therefore these ligaments are of importance for mobility and stability of the SI-joints. The relevant ligaments are the sacrotuberous, sacrospinous, dorsal sacroiliacal and iliolumbal ligaments.
In two other studies (Vleeming et al, 1989[13],[14]) we emphasized that the sacrotuberous ligaments are of special importance to the SI-joints. These ligaments can be stretched by the gluteus maximus muscle and in some individuals by the biceps femoris and the piriform muscle (Vleeming et al. 1989[13]). When testing pelvic and SI-joint mobility, intact connections between sacrum and intervertebral joints and discs are essential. After all, torsion of the sacrum relative to the iliac bones is diminished by the sagittal orientation of the lumbar intervertebral joints and by the intervertebral discs as well.

B. Fixing of sacrum or (parts of the) ilium should be avoided. It can be expected that bone under physiological conditions deforms in every part, and therefore influences mobility in the SI-joint.

C. Several studies indicate that, in the standing position, gravity induces nutation of the sacrum whereas a recumbent position (lying supine) is associated with contranutation (Weisl, 1955[17]; Egund et al., 1978[4]; Lavignolle et al., 1983[5]; Sturesson et al. 1989[10]). For this reason ventral rotation, as component of nutation, was measured simultaneously with an artificial gravity force and dorsal rotation was measured with the gravity force excluded.

D. Movements of the sacrum and ilium relative to each other should be measured in three planes.

As a consequence of the above mentioned considerations the SI-joint ligaments and surrounding ligaments, the intervertebral joints and the discs of L4-L5-S1 were spared. Movement in the intervertebral joints of L5-S1 remained possible. No part of sacrum or ilium was fixed, whereas the vertebral bodies of L4 and L5 were rigidly fixed.

In the studies of Weisl (1955[17]), Egund et al. (1978[4]), Lavignolle et al. (1983[5]) and Sturesson et al. (1989[10]) changes in the posture of living persons were related to SI-joint mobility. Rotation in the sagittal plane was most outspoken. These studies also revealed that nutation and contranutation are complex movements including rotation (angular displacement) and translations.
However the translation is small (Sturesson et al. 1989[10]). In patients studied with radiostereophotogrammetry they found a mean translation of 0.5 mm. which never exceeded 1.6 mm.

The requirements stated before were incompatible in our test construction with three dimensional mobility control of sacrum and ilium. In the present study exclusively rotation of the sacrum relative to the ilium is studied (in a sagittal plane). Thus, translation is not included.

<u>Bilateral loading</u>
In the present study unilateral measurements were performed with bilateral loading. Miller et al. (1987[6]) used unilateral loading of the ilium and found larger rotation in the SI-joints than in the present study. In the absence of muscle force, bilateral loading is thought to be more realistic.

<u>Testing of specimens versus living persons</u>
This study on preparations shows that, even at high age, rotation in the SI-joints is possible if all ligaments are intact. More specific results can be expected when rotations of pelvis and sacrum are studied in living persons with stereophotogrammetrical methods as developed by Selvik (Egund et al.1978[4]; Lavignolle et al. 1983[5]; Sturesson et al.1989[10]). However, this study was designed to study the effect of loading on rotation in the SI-joints of specimens of elder persons and compare these data radiographically. This kind of study is impossible to perform on living subjects. Measurements on fresh specimen were not possible because of the long duration of the experiment.

<u>Creep</u>
By measuring rotation in the SI-joint in relation with time "creep" could be demonstrated in certain SI-joints, although in minor degree. This indicates that a long-continued posture results in deformation of (among others) the SI-joints and suggests that recovery

takes its time. We did indeed demonstrate that recovery is time consuming. Such a slow recovery may result in an abnormal position of the sacrum, generating abnormal stress of intervertebral discs and joints. Especially in specimens showing "creep" it is to be expected that increase of load results in greater rotation.

Asymmetry

In the material tested intra-individual differences occur in the mobility of the SI-joints. This observation supports the conception that asymmetry in form and function of the SI-joints is normal (Bakland and Hansen, 1984[1], Vleeming et al, 1989[13]). Therefore, differences in the mobility of left and right SI-joint, as shown by clinical manual tests, cannot be followed by the conclusion that one of the SI-joints is pathological.

In most graphics, rotation is presented by a dented line. We suggest that this might well be caused by the presence of ridges (or roughness in general) in the articular cartilage of ilium and/or sacrum. In that case each dent in the lines represents a passage of a certain part of one side of the joint over an irregularity in the other.

The function of the SI-joint in the kinematical chain

In the literature on SI-joints and lower vertebral column not much attention is paid to specific kinematical aspects. Therefore the following. In standing, the sacrum moves generally to a nutation position (Weisl 1955[17]; Egund et al. 1978[4]). However, it is not questioned whether nutation is the result of sacrum movement relative to the ilium or vice versa or a combination (see axis of rotation).

It can be assumed that ventral rotation of the (promontory of the) sacrum relative to the iliac bones causes stretch of the anterior longitudinal ligament. Since this ligament connects the anterior sides of sacrum and lumbar vertebral bodies, ventral rotation of the sacrum could increase in this model stabilization of the lower vertebral column.

Axis of rotation

According to Egund et al. (1978[4]) the sites of the axis of rotation in different persons are scattered dorsal of the auricular part of the SI-joints. In the study of Weisl (1955[17]) the sites of the axis of rotation are, in different individuals and in different situations, scattered over the pelvis. We suppose that the differences with the axis as described by Egund et al. are caused by the extreme fixing described by Weisl of the photographic plate to the pelvis. In a new study with the present laboratory construction, we observed an effect of a pelvic belt on rotation in the SI-joints. In our opinion, Weisl's fixing method can be regarded as the use of several strongly fixed pelvic belts. For this reason we regard the axis of rotation found by Egund et al. (1978[4]) more realistic.

Mobility at high age

The data of the present study are in support of several other SI-joints studies. Even at high age small movements are possible in the SI-joints. Ankylosis of SI-joints in this age group is not the normal situation. This is in agreement with the morphological study of Stewart (1984[8]) and the biomechanical study of Miller et al. (1987[6]). However, Miller et al. conclude for elder persons that mean rotations in clockwise axial torsion, viewed from above, with unilaterally fixed ilium result in 6.21° rotation of the sacrum. In a former study we reported the biomechanical influence of cartilage roughness and complementary ridges and depressions in the SI-joints. It was shown that roughening in the SI-joints, which is marked in elder persons, results in higher friction-coefficients (Vleeming et al. 1989[12]). In the study of Miller et al. not only the intervertebral disc and joints were removed, but also the sacrotuberous, sacrospinous, iliolumbar and (probably) dorsal sacro-iliac ligaments. For this reason normal compression of the joint parts and friction will be diminished. Especially the removal of the intervertebral joints and discs, will enlarge the normal axial rotation.

In our opinion the study of Miller et al. needs the comment that SI-joint motion is conditioned, not only by the SI-joint, but that in addition (and among others) the nearby intervertebral joints play an essential role.

Sturesson et al. (1989[10]) found no decrease of mobility with age, in a group of patients up to 45 years. In that study Sturesson et al. used hyperextension in the hip in prone position and sitting with straight legs to mimic, respectively, extension and flexion during walking. However, on the basis of the studies of Lavignolle et al. (1983[5]) and Egund et al. (1978[4]), it can be expected that other values for SI-joint rotation are to be found in recumbent positions than in standing positions. Therefore, it would be interesting to see new studies on selected patients with the advanced technology, used by Sturesson et al. on the effects of hyperextension and flexion in standing positions.

We conclude from the material presented here that even at high age mobility in the SI-joints, although small, is normal.

Radiological comments

The radiography of the SI-joints as performed in this study suggests a relation between mobility and certain radiographical features. Arthrosis of the SI-joint or of the nearby intervertebral joints, combined with outspoken curvatures or grooves and ridges of the auricular part of the SI-joint, appears to be associated with limited SI-joint mobility (pelvis nr. 2 left and nr. 3 right). It may be significant that the SI-joint showing marked arthrosis (nr. 2 left) had the least mobility. At the right side of pelvis nr. 3 an arthrotic intervertebral joint is present. The SI-joint shows no clear arthrosis but is strongly curved.

Sclerosis of the SI-joint (especially the iliac part) was seen both in mobile and in hardly mobile joints, whereas sclerosis was absent in a joint showing negligible mobility (nr. 3 right).
Bony ridges and depressions were bilaterally present in a male pelvis; this pelvis showed limited mobility on one side and no mobility on the other. No ridges and depressions were seen in a female preparation showing the largest mobility. These grooves and ridges are, in our view, directly related to the friction coefficient of the joints (Vleeming et al. 1989[12]).
Condense iliitis was seen in two SI-joints, one with outspoken mobility, the other hardly mobile. However, the number of joints involved is obviously far too small for any far reaching conclusion in this respect. It has to be emphasized that evaluation of the SI-joints, and especially of the curvatures, demands detailed radiographic and anatomic knowledge of the SI-joint. Furthermore the performing radiologist works in a specialized rheumatic centre where evaluating SI-joints is a standard routine.
It is important to emphasize that parts of the SI-joint can not be surveyed radiographically. This concerns the nature and condition of the axial part of the SI-joints (Bakland and Hansen, 1984[1]). Especially the condition of the interosseous ligaments surrounding the axial part of the SI-joint and the sacrotuberous ligament can be of importance for mobility. Also the condition (texture, grooves, ridges; see Vleeming et al., 1989[11]) of the *cartilage* of the auricular surfaces of the SI-joint cannot be studied.
Pelvis nr. 4 is of special interest. The left side shows a syndesmophyte between sacrum and L5. The intervertebral joint of L5-S1 is orientated (as normal) in the sagittal plane. The right intervertebral joint of L5-S1 is oriented in the horizontal plane. In the SI-joints outspoken bilateral rotation is possible. This mobility will mainly reflect rotation of the ilium relative to the sacrum, since the left side of the sacrum is by a syndesmophyte connected with L5 - and L5 is rigidly fixed to the frame. The greatest mobility was found at the right side. It is noteworthy that on this side a total hip replacement was present. Further study has to reveal whether indeed arthrotically and preoperatively decreased mobility of the hip joints are compensated for by increased mobility of the SI-joint.

Concluding, the data show rotation in the sagittal plane in SI-joints of elder persons. At the side of a total hip replacement the largest rotation between sacrum and ilium was found (4°). Since roughening of the articular surfaces of the SI-joint is more outspoken in relatively old people, especially men (see Vleeming et al, 1989[11]), we expect that rotations in younger people in general will be larger. This expectation is supported by the studies of Egund et al. (1978[4]) and Sturesson et al. (1989[10]).

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The sacrotuberous ligament: a conceptual approach to its dynamic role in stabilizing the sacroiliac joint

A Vleeming[1]
R Stoeckart PhD[1]
C J Snijders PhD[2]

Research Group of Clinical Anatomy and Medical Technology, Departments of Anatomy[1] and Medical Technology[2], Erasmus University Rotterdam, The Netherlands

Summary

Based on studies of embalmed specimens, the sacrotuberous ligaments are considered to be important structures in the kinematic chain between the pelvis and vertebral column. Muscles attached to these ligaments, such as the gluteus maximus, and in some individuals the piriformis and long head of the biceps femoris, may influence movement in the sacroiliac joints.

Relevance

When examining and treating patients with low back pain the kinematic relationships of various structures have to be taken into consideration. The sacrotuberous ligament is a neglected part of the kinematic chain.

Key words: Sacroiliac joint, sacrotuberous ligament, low back pain, straight leg raising test

Introduction

Thorough knowledge of the anatomy and biomechanics of the low back region is necessary to understand the multiple causes of low back pain. The low back pain region includes the sacroiliac (SI) joints and their related ligaments. The SI joints, which are apparently mobile[1–5] may be of importance in low back pain[6]. However, the anatomical and functional relationship between these joints and the surrounding muscles and fascia is obscure. It was hypothesized that the sacrotuberous ligaments could be of particular importance, because of the relatively large distance to the SI joints, and consequently the large mechanical moments. Therefore, we studied the structures surrounding the SI joint with especial interest in the muscle connections to the sacrotuberous ligament.

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Correspondence and reprint requests to: Dr R Stoeckart, Department of Anatomy, Erasmus University Rotterdam, PO Box 1738, 3000 DR Rotterdam, The Netherlands

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Methods

The study was performed on 12 cadavers of both sexes, embalmed by vascular perfusion with a solution containing 2·2% formaldehyde. After immersion in the embalming medium for a period of 3 months the cadavers were transferred to a solution containing phenoxyethanol[7]. The lower vertebral column, SI joints and surrounding structures were dissected from the dorsal side. After removing skin and subcutaneous tissue by blunt dissection as far as possible, fascia and muscle fibres were removed layer by layer. The proximal muscle stumps of the gluteus maximus, as well as the piriformis muscle, the long head of the biceps femoris, and the dorsal sacroiliac ligaments were spared. In a preliminary study, forces not exceeding 50 N were applied to muscles or muscle stumps, pulling in the direction of the insertion.

In an additional series of 11 cadavers attention was focused on the relationship between the long head of the biceps and the sacrotuberous ligament.

Results

In all preparations ($n = 12$) the thin fascia covering the dorsal aspect of the piriformis muscle was continuous with the sacrotuberous ligament. In two cases, the fascia was bilaterally aponeurotic (Figure 1). In addition, muscle fibres of the piriformis were attached directly to the ventral part of the sacrotuberous ligament in most preparations.

In all cases, the gluteus maximus muscle was connected to the sacrotuberous ligament. In six preparations a third connection with the sacrotuberous ligament existed. Here, part of the tendon of origin of the long head of the biceps femoris muscle was fused with the ligament (Figure 1). In four preparations this occurred unilaterally, whereas in two (female) specimens the biceps was completely fused bilaterally with the sacrotuberous ligament. No connection occurred in these two specimens between muscle and ischial tuberosity.

In the additional series of bodies (six male, five female) four showed bilateral fusion of the long head of the biceps with the sacrotuberous ligament and one showed unilateral fusion. Among the four bodies showing fusion bilaterally, three were female.

In all preparations, forces applied to the muscle stumps in the direction of the insertion caused tension of the sacrotuberous ligament, as was obvious from visual inspection. The stretch at the ligament was strongest with forces applied to gluteus maximus and long head of the biceps femoris (if fused with the ligament).

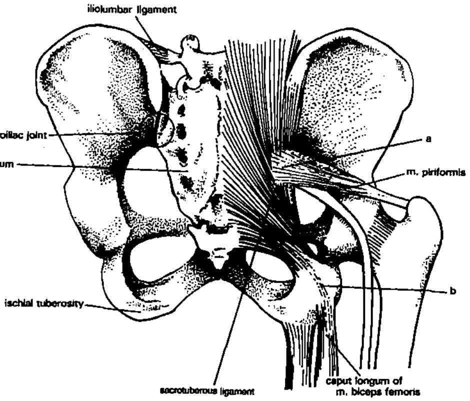

Figure 1. Schematic dorsal view of the low back. The right side shows the relation between the sacrotuberous ligament and the dorsal fascia of the piriformis muscle (a). Also shown is the continuation of the long head of the biceps into the sacrotuberous ligament (b). The left side shows the sacroiliac joint and the iliolumbar ligament.

Discussion

This study shows that several muscles are attached to the sacrotuberous ligaments and are able to stretch them. Since these ligaments bridge the SI joints (Figure 1), it can be expected that the gluteus maximus, and also in some individuals the piriformis and long head of the biceps femoris, influence the mobility and/or stability of the SI joints.

The connections of the piriformis muscle and the long head of the biceps femoris to the sacrotuberous ligament are omitted in several textbooks and atlases[8–11]; see also[12], but even if mentioned[13,14], a functional context is lacking.

The described connections to the sacrotuberous ligament are of more than academic interest, since they have a bearing on the kinematic chain to which the vertebral column belongs. For clinical purposes we give the following examples.

1. Connections occur between the sacrotuberous ligament and the gluteus maximus muscle and in some individuals (especially female and bilaterally) the biceps femoris muscle. Therefore it can be expected that the sacrotuberous ligament can be tensed by the straight leg raising test, and more so in the presence of muscle shortening. Since the sacrotuberous ligament bridges the SI joint, the position of the sacrum may be changed. In the case of one-sided muscle shortening, the sacrum can be affected asymmetrically. Hence the joint between L_5 and S_1 (and possibly more cranial ones), including the intervertebral disc, can be affected. Indeed, Lavignolle et al.[3] demonstrated the influence of straight leg raising on the SI joint: in patients lying supine, hip flexion of 60° caused distinct movement in the SI joint. Therefore, pain elicited by the straight leg raising test may have a multitude of causes, including SI joint strain. Kinematically the relationship is even more complicated. Rotation in the SI joints has been demonstrated by several authors[3–5,13]. Therefore, an asymmetric pull on the pelvis can rotate the innominate bones with respect to the sacrum. As a result, the iliolumbar ligaments (Figure 1) can be stretched and act at the lumbar vertebrae.

2. By active and maximal extension of the hip the ipsilateral gluteus maximus muscle is maximally active[15]. In this position the gluteus maximus muscle can exert an additional effect – stabilization of the SI joint. This can occur not only by direct attachment to the sacrum but also by tensing the sacrotuberous ligament. If this is so, then training of the gluteus maximus muscles might have an effect on the stabilization of the SI joints.

In conclusion, the connections to the sacrotuberous ligaments have to be taken into consideration when examining patients with low back pain or when biomechanically studying the kinematic relations in the low back. The presented material prompted us to a biomechanical study to substantiate the anatomical data, and test the hypothesis that small changes in the tension of the sacrotuberous ligament influence (the range of) motion in the sacroiliac joint.

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Load application to the sacrotuberous ligament; influences on sacroiliac joint mechanics

A Vleeming[1]
J P Van Wingerden[1,2]
C J Snijders PhD[2]
R Stoeckart PhD[1]
T Stijnen PhD[3]

Research Group of Clinical Anatomy and Medical Technology, Departments of Anatomy[1], Medical Technology[2] and Biostatistics[3], Erasmus University Rotterdam, The Netherlands

Summary

In the embalmed human pelvis, the connections between sacrum and fifth lumbar vertebra were spared together with most of the ligaments. The effect of load application to the sacrotuberous ligament was studied on rotation in the sacroiliac joint. It was shown that load application along the direction of hamstring and gluteus maximus muscles significantly diminished ventral rotation of the sacrum. The results imply that loading the sacrotuberous ligament restricts nutation of the sacrum. Consequently, muscles which attach to the sacrotuberous ligaments, such as the gluteus maximus, and in certain individuals the long head of the biceps, can dynamically influence movement and stability of the sacroiliac joints. The importance of sacrotuberous ligaments and sacroiliac joints as parts of the kinematic chain is emphasized.

Relevance

Demonstration that certain muscles can influence the sacrotuberous ligaments and, consequently, the sacroiliac joints is of importance for understanding and treating low back pain.

Key words: Sacroiliac joint, sacrum, joint instability, pelvic bones, anatomy, spinal injuries, intervertebral disc

Introduction

Up to 1934 the sacroiliac (SI) joints were thought to be the chief cause of low back pain. With the study on the invertebral discs of Mixter and Barr[1] a better understanding of ischialgia and low back pain became possible.

However, the SI joints are often neglected as part of the low back[2], and as late as 1983 Lavignolle et al.[3] described the joints as an enigma. Literature on coupled motions of the SI joint is particularly scarce. This may be due, at least in part, to the regional approach by which the lower vertebral column (like many other systems) is taught in most medical courses. Particularly for the musculoskeletal system, we regard this approach as a handicap in understanding such a complex system.

For clinical reasons we are interested in whether abnormal displacement between sacrum and ilium can be responsible for abnormal displacement or stress of the lumbar vertebrae. Being part of the complex kinematic chain between legs and spine, even a small displacement of the sacrum or ilia may have important effects. Displacement of sacrum relative to ilia simultaneously affects the SI joints, the intervertebral joints at L_5–S_1 and the intervertebral disc of L_5 and S_1. Ilium displacement relative to the sacrum affects the SI joints and symphysis[4,5]. Since the iliolumbar ligaments connect the ilium and lumbar spine, ilium displacement can generate stress on the lumbar vertebrae. When muscle action is taken into consideration, the situation is more complex.

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Correspondence and reprint requests to: A Vleeming, Department of Anatomy, Erasmus University Rotterdam, PO Box 1738, 3000 DR Rotterdam, The Netherlands

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In an anatomical study of the sacrotuberous ligament (ST ligament) it was shown that the ST ligament can be tightened dynamically[6]. It was suggested that the muscles attached to the ST ligament have a function in stabilizing the SI joint.

In a biomechanical study[7] we developed a method for testing the mobility of intact SI joints in preparations from elderly people. By loading the joints, mobility could be confirmed in most specimens.

The present study concerns the effect of load application to the ST ligament on SI joint displacement. Support for such an effect would highlight the potential importance of muscles attached to the ST ligament in stabilizing the SI joints. Possibly, it could also clarify why certain aspecific surgical approaches to the SI joint were shown to have favourable effects. One of these (obsolete) approaches concerned operating on the SI joint and performing arthrodesis for curing ischialgia. Direct relief of pain was described[8] before any consolidation of the two joint parts occurred.

Materials and methods

Part of the materials and methods concerning the instrumentation will be briefly dealt with. See Vleeming et al.[7] for details and discussion.

Four cadavers were embalmed by vascular perfusion with a medium containing 2·2% formaldehyde. Their age and sex were (A) 73 , female; (B) 75, male; (C) 83, female; (D) 77, female. The pelvis was removed leaving vertebrae L_4 and L_5 intact. The femora with joint capsules were removed. Blunt dissection followed, leaving the iliolumbar, sacroiliac, sacrotuberous and sacrospinous ligaments intact. The vertebral foraminae of L_4–L_5 were slightly widened and a tapering steel rod was fitted in the foraminae as far as the caudal part of L_5. Each pelvis was mounted on an inner frame, which was connected to an outer frame (Figures 1 and 2). The acetabula were chosen as points of force transfer. Stainless steel rods were fitted from lateral to medial through the acetabula (Figure 2–*3*). Through small holes in the rods, steel wires (Figure 3–*1*) were passed through the external acetabulum holes. Acetabulum and vertebral rods were centred and stabilized with a two-component industrial hardening resin. Steel wires were connected to four power units (Eltrac 471-1471.905, Enraf Nonius) generating gradual adjustable tensile forces on the acetabula.

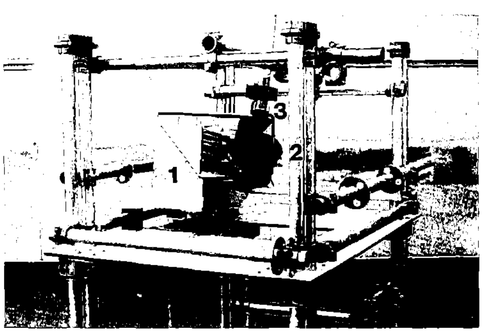

Figure 1. Laboratory instrumentation showing inner (*1*) and outer frame (*2*). One of the connections between inner and outer frames is also shown (*3*).

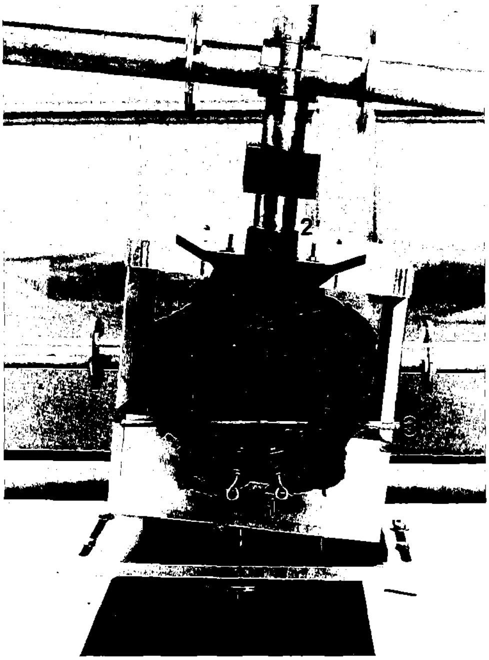

Figure 2. Details of the inner frame (*1*) and top plate making contact with the outer frame (*2*). The acetabular rods are also shown (*3*).

Digital Mitutoyo displacement meters (type IDU 25 575-113 and IDU 25E 575-103-5) were connected to the inner frame (Figure 3). The meters were coupled with a Mitutoyo UB5 Multiplexer 011028 to the registration unit (Mitutoyo Digimatic miniprocessor DP-1 DX264-501-1).

To record displacement, a Perspex plate (5×90×40 mm) was fitted to the centre of the sacrum with bone screws. The plate could not be fitted to the lateral side of the sacrum without destroying part of the sacroiliac ligaments. Another Perspex plate with the same dimensions was connected to the posterior superior iliac spine (Figure 3–*3*). The two plates were adjusted to lie in the same plane and were fixed with hardening resin.

Two sets of two displacement meters, all lying parallel to each other and connected to the inner frame (Figure 3–*2*), were adjusted in the sagittal plane, perpendicular to plates on the ilium and sacrum. The meters of one set were located at a distance of 40 mm. The meters were calibrated to the zero position. Since the plates on the sacrum and ilium were inclined to the frontal plane, the meters were adjusted to this new plane. The new values of the meters were used in a correction calculation and the meters were again calibrated to zero.

For measuring sagittal plane rotation of the sacrum relative to the ilium, the following calculation was used. In Figure 4, one set of meters ($M1$ and $M2$) is shown located on an ilium (compare with Figure 3). Line N shows the neutral position of the meters. Line P shows the position of the meters adjusted to the Perspex plate on the sacrum or ilium. Line Q represents a possible position of the meters after displacement of sacrum and/or ilium. The values first registered ($c1$ and $c2$) are used as a correction factor and, consequently, line P is considered as the zero position. The difference between P and Q is registered ($m1$ and $m2$). For calculating rotation between lines P and Q, the following procedure was used. By subtracting $c1$ from both $c1$ and $c2$, the original line P now, as line P', intersects line N at point 0. The value of meter $M1$ for line P (at the position of line P') becomes zero and the value of meter $M2$ for line P becomes $c2-c1$. For the position at line Q, the same procedure is followed. Thus, $c1+m1$ are subtracted from the values at Q. As a result of this calculation, line Q (as line Q') intersects line N also at point 0. The value of $M1$ for line Q' now becomes zero and the value of $M2$ for line Q' becomes $(m2+c2)-(m1+c1)$.

The angle between line Q and line P (representing the angle displacement from line P to Q) can be calculated from angle $Q'0P'$ = angle $Q'0N$−angle $P'0N$.

Angle $P'0N$ is calculated from:

$$P'0N = \arctan\left[\frac{(c2-c1)}{a}\right]$$

Angle $Q'0N$ is calculated from:

$$Q'0N = \arctan\left[\frac{(m2+c2)-(m1+c1)}{a}\right]$$

Subtraction gives the angle between line Q and P. This calculation is repeated for the other set of meters located on the sacrum and registering sacrum displacement. These displacement angles are subtracted from each other.

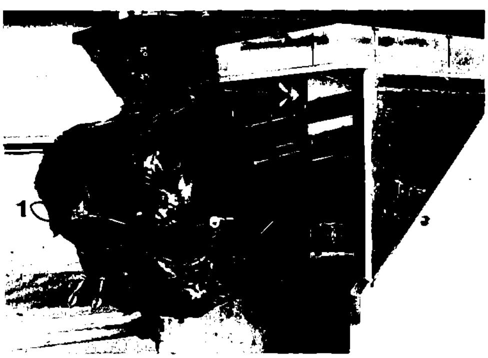

Figure 3. Details of inner frame showing steel wire to load transfer point (*1*), meters (*2*), perspex ilium plate (*3*), inner frame top plate (*4*) and triangles used to secure the vertebral column (*5*).

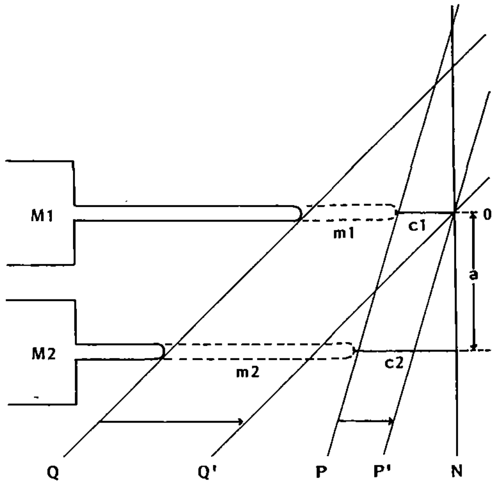

Figure 4. Graphical presentation of the goniometric method to calculate the amount of rotation.

As stated before, the acetabula were chosen as force transfer points. To induce ventral rotation (as part of nutation) the following loads were used: F cranial bilateral 200 N; F ventral bilateral 100 N.

To induce dorsal rotation (as part of contranutation) the following loads were used: F dorsal bilateral 200 N; F caudal bilateral 100 N.

To avoid destruction of material by the large number of measurements, the loads were smaller than those used in a former study[7].

The cranial force was chosen to reproduce gravity. The rigid top plate transforms this force into a compressive force on the specimens. The caudal force was necessary since the rigid top plate transforms part of the dorsal force into a compressive force, resembling gravity. To exclude this compression, the caudal force was introduced. Excluding gravity appears to be a prerequisite for contranutation (Weisl[9]; Egund et al.[10]; Lavignolle et al.[3]).

The rotation of sacrum and ilium relative to each other was tested as a function of loading the ST ligament. For this reason the ST ligament was fixed to a specially developed string (Figure 5). The string was connected to a steel wire running over a pulley to a traction unit. The ST ligaments were loaded bilaterally, each side with 50 N. Since the gluteus maximus muscle and in some individuals, the long head of the biceps femoris muscle, are connected to this ligament[6], a laterocaudal direction of loading was chosen (Figure 5). Then, the applied loading of the ligament is approximately perpendicular to the ventral and middle part of the SI joint (Dijkstra et al.[11]).

In the results section, the effect of loading the ST ligament on dorsal and ventral rotation is shown separately for each SI joint. Specimens 1 and 2 and specimens 5 and 6 are the left and right side, respectively,

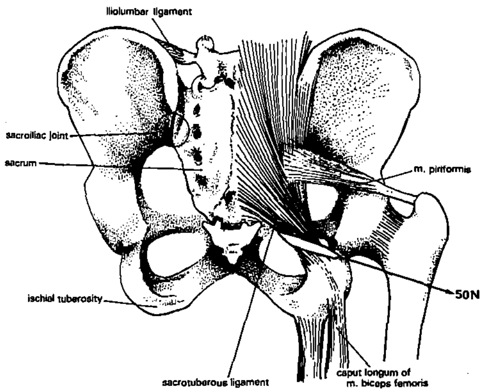

Figure 5. Diagram showing the direction of the force acting at the sacrotuberous ligament. Loading occurred bilaterally (in the frontal plane).

of pelvis A and D. Specimens 3 and 4 are, respectively, the right side of pelvis B and the left side of pelvis C. The other sides of pelvis B and C are not shown, since mobility was hardly possible (see Vleeming et al.[7]). Translation, which represents a relatively small part of the total nutation and contranutation[9,10,12] was not measured in this study.

In preliminary studies, we observed that successive measurements influenced each other. Therefore, the measurements were replicated in pairs consisting of one measurement with and one without loading of the ST ligament; a random order was used within each pair. Sixteen pairs of measurements were made in two sessions of eight. In order to investigate the effect of loading of the ST ligament for each specimen, a three-way analysis of variance was performed for each specimen separately. In these analyses of variance, the factors were ST ligament (loaded or unloaded), order of measurement within the pair (1 or 2) and session (1 or 2).

To investigate the effect of loading for all specimens averaged together, an analysis of variance was performed in which, in addition to the above mentioned factors, the specimen was taken up as a random factor. P values $\leq 0{\cdot}01$ were considered to be significant.

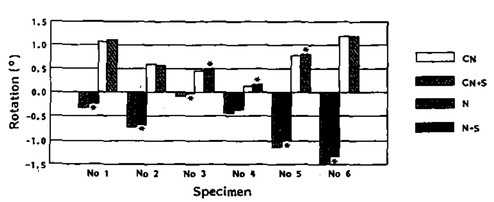

Figure 6. Graphical presentation of the effect of loading of the sacrotuberous ligament (*S*) on the rotation of the sacrum during nutation (*N*) and contranutation (*CN*). Positive rotation (displayed in degrees) relates to dorsal rotation as part of contranutation. Negative rotation relates to ventral rotation as part of nutation. ($^*P \leq 0{\cdot}01$.)

Results

During nutation the amount of rotation was decreased by loading of the ST ligament. This decrease was small but significant in all specimens except no. 4 (see Figure 6). For all specimens averaged, the effect of loading was significant ($P < 0{\cdot}01$).

The effect of loading during contranutation is not consistent. In specimens 3, 4 and 5, loading of the ST ligament during contranutation gives a slight but significant increase in rotation (see Figure 6). In specimen 2 rotation is slightly (but not significantly) decreased. For all specimens averaged together, the effect of loading was not significant.

By loading of the ST ligament the amount of total rotation (nutation plus contranutation) was significantly decreased in specimens 1, 2, 5 and 6. For all specimens averaged, the effect of loading was significant.

Specimens 5 and 6, which belong to one pelvis, are of special interest, since the long head of the biceps femoris muscle was bilaterally completely connected with the ST ligament and not with the ischial tuberosity. In specimens 5 and 6, loading of the ST ligament decreased the ventral rotation by 14% and 10%, respectively. In specimen 5, dorsal rotation was increased by 5%.

Discussion

In this study, sagittal plane movement was measured in the SI joints. In the experimental setup not only was movement in the SI joints possible, but also movement in the intervertebral joints of L_5 and S_1, as well as in the disc of this level. In our opinion this is a requisite for realistically testing movement in the SI joints[7].

As we showed in a former study[6], extensive connections can exist (in addition to those of the gluteus maximus muscle) between the long head of the biceps femoris muscle and the ST ligament, These connections suggest considerable loading of the ligament in certain individuals, but we chose to simulate minimal loading. Since no counterforces of muscles were present in this experimental setup, larger forces were thought to be unrealistic.

It was expected that loading of the ST ligament would decrease the amount of ventral rotation (part of the nutation). As shown in the results, ventral rotation was indeed significantly decreased in all specimens. In specimen 1 this amounted to 27% and in specimen 3 to 78%, but the actual rotations were very small.

The effect of loading during contranutation was less consistent. In three specimens dorsal rotation (part of contranutation) showed a small but significant increase.

In former studies[13,14] it was demonstrated that the amount of friction between the articular surfaces of SI joints was related to the degree of macroscopic roughening of the articular surfaces. It was hypothesized that, in general, this roughening is a normal process. Articular surfaces with both coarse texture and ridges and grooves (depressions) showed high friction coefficients[14].

The influence of ridges and depressions appeared to be greater than that of a coarse texture. Biomechanically we introduced a free body diagram of the symmetrical sacrum where the resultant of the bone-to-bone contact forces in the SI joint is given by F_T. The force F_T can be resolved into a force perpendicular to the joint surface (F_N) and a tangential force (F_F), the latter resulting from friction. The relationship between both forces is given by

$$F_F \leqslant F_N \tan(\alpha)$$

which becomes, just before the start of sliding of two SI joint parts over each other:

$$F_F = F_N \tan(\alpha)$$

where $\tan(\alpha) = f$, the friction coefficient.

The force direction of the loading of the ST ligament in real life situations creates a force that is approximately perpendicular to the oblique ventral and middle part of the SI joint[11]. As shown in the present study, loading the ST ligament diminishes the total range of ventral rotation. From the experiments presented here we propose that in real life situations the muscles connected to the ST ligament can dynamically influence F_N.

In specimens 5 and 6, loading of the ST ligament could not directly change the position of the sacrum in these specimens since it was radiologically demonstrated that L_5 was (bilaterally) fused with the sacrum (see pelvis no. 4 in Vleeming et al.[7]). Since the vertebrae L_4 and L_5 are rigidly fixed to the inner frame, it can be assumed that the sacrum is immobilized in this pelvis. However, nutation was also diminished in these specimens after loading the ST ligament (see Figure 4). In our opinion this effect can be explained by the cranial connections of the ST ligament with the ilium, and the loading of the ST ligament in combination with the cranial and ventral forces applied to the acetabula. In all probability this leads to increased compression and friction in part of the SI joints. It might well be that the decrease in displacement seen in the other specimens is also caused by increased compression between the ilium and sacrum. When starting this study, loading of the ST ligament was primarily used to diminish nutation of the sacrum with respect to the ilium. The results of specimens 5 and 6 raise, however, the question of whether the loading of the ST ligament in this experiment simulates real life situations. Considering the data obtained from specimens 5 and 6, a better method of simulation of loading may be a transverse cut of the ST ligament and then pulling the sectioned parts to each other.

The gluteus maximus muscle is orientated approximately perpendicular to the ventral and middle part of the SI joint. Therefore, we assume that this strong muscle can compress the SI joint in real life situations and enlarge F_N. The connection of the gluteus maximus muscle with the ST ligament is relatively unimportant, since the muscle is extensively connected to the sacrum. We speculate that training of the gluteus maximus muscle can influence rotation in the SI joints, because of the direct connections with the sacrum and ST ligament. This means that the muscle is dynamically influencing F_N.

In some individuals, the long head of the biceps femoris muscle is partly or totally connected with the ST ligament, as in the (female) pelvis of specimens 5 and 6. When present in women it is mostly bilateral[6]. In individuals with such a connection, shortened hamstrings can directly influence movement in the SI joints. Therefore, stretching or strengthening the hamstrings could influence the kinematic behaviour of the SI joints.

We will speculate on the effect of the surgical techniques of Smith-Peterson[8] which were shown to be sometimes successful in treating ischialgia. First of all, the SI joints are innervated by the same nerves as the lower spine. Therefore, abnormal function of the SI joint may lead to ischialgic pain. Secondly, Smith-Peterson was surprised that ischialgia was cured before arthrodesis of the joint was completed. However, by operating on the SI joint, parts of the joint ligaments, as well as the gluteus maximus muscle, will be affected also. In this way the SI joint can be decompressed, creating another kinematic behaviour of SI joint and lower spine. As a result of this surgical technique, compression of an intervertebral disc might have been changed. This speculation serves, at least in part, as an answer to the question of why this operation might have been effective.

On the basis of this and former studies we want to finish with a general statement on diagnosis and therapy. Obviously, the low back region is characterized by large intra- and inter-individual variety. This carries the implication that, apart from the clear pathology usually leading to neurosurgery, it is extremely difficult to reach a well-founded absolute diagnosis in cases of low back pain. Therefore, we consider it wise to evaluate the outcome of kinematic tests during non-operative treatment especially when tests of the SI joints are involved; the therapy has to be continuously adjusted to this evaluation. This approach can preclude one specific, and often unwanted, diagnosis and therapy. Even in the case of an obvious lesion the question remains whether this is the primary cause or just reflects a disturbance in the complex kinematic chain.

At the moment we consider it impossible, with the technology available, to forecast for an individual patient the precise nature and function of the SI joints (see Sturesson et al.[12] and our comments on this study[7]). With the standard methods available, increased or decreased compression in these joints is particularly difficult to judge.

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Summary and conclusions

This study is concerned with clinical-anatomical, biomechanical, and radiological properties of the sacro-iliac joints. It was initiated in order to acquire a better understanding of these 'enigmatic' joints.

We started with researching the macroscopic anatomy of the auricular surfaces of the sacro-iliac joint. Macroscopic alterations of these surfaces have been described by several authors. Generally, such changes are considered to be pathological (Sashin, 1930; Bowen & Cassidy, 1981). If that were true, it could be expected that such changes would cause pain or sacro-iliac problems in (older) men since the changes become gradually more apparent from puberty onwards and are more prominent in men than in women. However, in the view presented in this study, macroscopic changes such as coarse texture and the appearance of ridges and grooves, reflect adaptations to stability, promoted by the increase in weight during the adolescent growth spurt.

One reason for our view is the presence of coarse texture and ridges and grooves in, practically, all male sacro-iliac joints (chapter I). Another reason is the observation that the ridges and grooves in the sacro-iliac joint are complementary, and as a rule covered by intact cartilage, even in specimens of old age. All these features are more outspoken in men than in women. Differences between men and women may be attributed to child-bearing and to differential localization of the centre of gravity in relation to the sacro-iliac joints (chapter I).

Since ridges and grooves were seen as functional adaptations, a test construction was developed to determine the amount of friction between the articular surfaces of the sacro-iliac joints. The findings were related to the degree of macroscopic roughening. Results showed that articular surfaces with both coarse texture and ridges and grooves, have high friction coefficients (chapter II). The influence of ridges and grooves tended to be greater than that of coarse texture. This is in agreement with a biomechanical model that was developed.

This biomechanical model shows that a higher friction coefficient as well as a greater 'wedge-angle', i.e., the angle between the sacral and iliac auricular surfaces in the frontal plane, influence the stability of the sacro-iliac joint in the sense that less force in the ligaments is required for bearing the upper part of the body (chapter III). These data are compatible with the view that roughening of the sacro-iliac joint has to be regarded as a physiological process, reflecting dynamic development.

Sacro-iliac joints without ridges and grooves will allow movement. Joints with extensive ridges and grooves in combination with coarse texture can be expected to have limited mobility.

We speculated that abnormal loading conditions of sacro-iliac joints with ridges and grooves could lead to new positions of the articular surface, with new relationships between formerly unrelated ridges and grooves. Such an abnormal position could be regarded as a 'blocked' joint. In the literature, however, there is (as yet) no solid proof for the existence of this phenomenon.

The complex nature of the sacro-iliac joints renders it difficult to radiologically assess the joint. The physical nature of conventional radiography as well as tomography renders it impossible to delineate parts of the body without distinct borders. An object that is oblique to tomographic movement will reveal itself as having indistinct borders. For this reason, an adapted radiological method was tested for diagnosing sacro-iliac afflictions. This method was developed in order to differentiate between physiological adaptations and sacro-iliac pathology. For this purpose, an anatomical approach was combined with conventional radiology, complex motion tomography, and computer tomography (chapter III).

Complex motion tomography is suggested as the method of choice in the examination of the sacro-iliac joint. Because of its sinusoidal form and assumed physiological adaptations (ridges and grooves), every part of the joint has to be photographed perpendicular to the joint surface. This implies that the dorsal aspect of the joint has to be tomographed in frontal projection, and the middle and ventral aspects in oblique projection. In 56 patients, referred for probable ankylosing spondylitis, 72 sacro-iliac joints were investigated. Based on plain radiography, six, and on frontal tomography, five sacro-iliac joints were diagnosed as being normal. However, based on oblique tomography, 31 joints were diagnosed as being normal (chapter III).

Obviously, oblique tomography of the sacro-iliac joints gives superior results in comparison with frontal tomography and plain radiography. By way of practical implementation, it is suggested to combine frontal tomography for the dorsal aspect of the sacro-iliac joint with oblique tomography at an angle of about 25° for the middle and ventral aspect.

Since large variations occur in the configuration of the sacro-iliac joints, this approach has to be adapted to the specific requirements of certain patients. For instance, in patients with only a slight inclination of the middle aspect of the joint, or with a more angular dorsal aspect, tomography has to be tailored to the special configuration, which implies an angle different from 25°. For a good diagnosis, knowledge of the detailed anatomy of the sacro-iliac joints, including the presence of grooves and ridges, is a prerequisite. Otherwise, the presence of grooves and ridges may mislead one into believing that the patient suffers from osteophytosis.

If, indeed, the described macroscopic alterations at higher ages are physiological, then the question remains if mobility of the sacro-iliac joints is possible in persons of high age. In several textbooks the opinion is expressed that mobility is impossible.

A test construction was developed to measure movement in the sacro-iliac joints in embalmed preparations of elderly people, and the data were correlated with a radiological survey. The connections between sacrum and fifth lumbar vertebra were spared, as were the surrounding ligaments. To induce movement, forces were exerted on the acetabula (chapter IV).

In the sagittal place, both ventral rotation (as part of nutation) and dorsal rotation (as part of contranutation) could be demonstrated. Most sacro-iliac joints were mobile, allowing up to 4° total rotation, i.e., the combination of nutation and contranutation. In younger people, more rotation can be expected. The sacro-iliac joint with the lowest mobility showed radiologically marked arthrosis. In some sacro-iliac joints a limited amount of 'creep' was demonstrated.

Attention was paid to intra-individual differences in the mobility of the sacro-iliac joints. The impact of the findings on kinematic chain and clinical diagnosis, was discussed (chapter IV). The data of this mobility study support the idea that small movements are possible in the sacro-iliac joints, even at a high age. Ankylosis of the sacro-iliac joint is even at high age not the normal situation. This is in agreement with the morphological study of Stewart (1984) and the biomechanical study of Miller et al. (1987).

Biomechanically, a free body diagram of the symmetrical sacrum was introduced in order to acquire a better understanding of the function of the ridges and the depressions (chapter II). The resulting bone to bone contact force was given by F_T. The force F_T can be resolved into a force perpendicular to the joint surface (F_N) and a tangential force (F_W). We looked for possibilities in the anatomy of the sacro-iliac joint, to dynamically influence F_N. For this purpose, a study was performed on embalmed specimens (chapter V and VI).

The sacrotuberous ligaments are considered to be important structures in the kinematic chain between pelvis and vertebral column. Muscles attached to these ligaments, such as the gluteus maximus, and in some individuals the piriformis and the long head of the biceps femoris, may influence movement in the sacro-iliac joints (chapter V). We speculated that, especially, the sacrotuberous ligament and its connections with the biceps femoris and the gluteus maximus could play an important role in enlarging F_N.

The material prompted us to perform a new biomechanical study to substantiate the anatomical data. In this study, the hypothesis was tested that small changes in the tension of the sacrotuberous ligament influence (the range of) motion in the sacro-iliac joint (chapter VI).

Load application to the sacrotuberous ligament was performed in order to study its effect on sacro-iliac rotation. It was shown that even light load application along the hamstrings and the gluteus maximus, significantly diminished ventral rotation of the sacrum. The results imply that loading the sacrotuberous ligament restricts nutation of the sacrum. Consequently, muscles which attach to the sacrotuberous ligaments, such as the gluteus maximus and in certain individuals the long head of the biceps, can dynamically influence movement and stability of the sacro-iliac joints (chapter VI).

The importance of the sacrotuberous ligaments and sacro-iliac joints as parts of the kinematic chain, was emphasized. Increased or decreased compression of the sacro-iliac joints could be an important factor in the kinematics of the low back region.

Since the sacro-iliac joints were demonstrated to be mobile, and the joints differ extremely both inter- and intra-individually, these joints deserve more attention when kinematic disturbances of the low back are studied. Even in the case of an obvious lesion of the lumbar vertebrae, the question remains whether this is the primary cause or a reflection of a disturbance in the complex kinematic chain which includes the sacro-iliac joints.

New studies will have to be undertaken in order to develop standard methods to test increased or decreased sacro-iliac compression. The effect of specific biomechanical stimuli to the sacro-iliac joints of living persons, has to be correlated with the movement patterns of, especially, the lower vertebral column. The development of a motion analysis laboratory in our department could be extremely helpful in testing this relationship.

Samenvatting en konklusies

Deze studie betreft klinisch-anatomische, biomechanische en radiologische aspecten van de sacro-iliacale gewrichten. De studie werd ondernomen teneinde een beter begrip van deze 'raadselachtige gewrichten' te verkrijgen.

In eerste instantie onderzochten wij de macroscopische anatomie van de auriculaire oppervlakken van het sacro-iliacale gewricht. Verscheidene auteurs hebben macroscopische veranderingen van deze gewrichten beschreven. Over het algemeen worden dergelijke veranderingen als pathologisch opgevat (Sashin, 1930; Bowen & Cassidy, 1981). Indien dat juist zou zijn, zou men moeten verwachten dat die veranderingen met name bij (oudere) mannen aanleiding zouden geven tot pijn of andere sacro-iliacale klachten aangezien de genoemde veranderingen vanaf de puberteit steeds duidelijker aanwezig zijn en wel vooral bij mannen. In de visie die hier gepresenteerd wordt moeten deze macroscopische veranderingen—zoals verruwing van het oppervlak of het verschijnen van richels en groeven—opgevat worden als functionele aanpassingen: aanpassingen gericht op verhoogde stabiliteit, uitgelokt door de gewichtstoename gedurende de groeispurt.

Eén argument ten gunste van die visie betreft de verruwing van het oppervlak en de aanwezigheid van richels en groeven in bijna alle mannelijke sacro-iliacale gewrichten (hoofdstuk I). Een ander argument is gelegen in de waarneming dat de richels en de groeven complementair zijn en doorgaans bedekt worden door intact kraakbeen, zelfs bij oudere personen. Al deze aspekten zijn bij mannen meer uitgesproken aanwezig dan bij vrouwen. Verschillen tussen mannen en vrouwen kunnen worden toegeschreven aan de zwangerschap en aan de differentiële localisatie van het zwaartepunt ten opzichte van het sacro-iliacale gewricht (hoofdstuk II).

Op basis van de gedachte dat richels en groeven functionele aanpassingen zijn, werd een nieuw onderzoek ontworpen. Een proefopstelling werd ontwikkeld waarbij de wrijving tussen de sacro-iliacale gewrichts-oppervlakken gemeten kon worden. De bevindingen bleken samen te hangen met de mate van verruwing van het oppervlak. Een gewrichts-oppervlak met zichtbare verruwing èn met richels en groeven, heeft een hoge wrijvingscoëfficiënt (hoofdstuk II). In dit opzicht lijkt de betekenis van richels en groeven over het algemeen groter dan die van de verruwing van het oppervlak. Dit is in overeenstemming met een biomechanisch model dat werd ontwikkeld.

Dit biomechanische model maakt duidelijk dat zowel een hogere wrijvingscoëfficiënt als een grotere 'wighoek', d.w.z. de hoek tussen het sacrale en het iliacale auriculaire gewrichtsoppervlak in het frontale vlak, de stabiliteit van het sacro-iliacale gewricht in die zin beïnvloeden, dat geringere ligamentaire krachten benodigd zijn om het gewicht van het bovenlichaam te dragen (hoofdstuk II).

Deze gegevens zijn in overeenstemming met de gedachte dat de verruwing van het sacro-iliacale gewrichtsoppervlak gezien moet worden als een fysiologisch proces, als de weerspiegeling van een dynamische ontwikkeling. Sacro-iliacale gewrichten zonder richels en groeven laten bewegingen toe. Gewrichten met uitgebreide richels en groeven, in combinatie met verruwing van het oppervlak, hebben naar alle waarschijnlijkheid een geringe beweeglijkheid.

Wij speculeerden dat een abnormale belasting van sacro-iliacale gewrichten met richels en groeven kan leiden tot een nieuwe positie van de gewrichtsoppervlakken, met nieuwe relaties tussen voorheen ongerelateerde richels en groeven. Een dergelijke afwijkende stand zou gezien kunnen worden als een 'geblokkeerd' gewricht. In de literatuur bestaat er echter nog geen bewijs voor het bestaan van dit fenomeen.

Gezien de complexe bouw van de sacro-iliacale gewrichten is het buitengewoon moeilijk, het gewricht radiologisch te onderzoeken. De fysieke aard van zowel conventionele radiografie als van tomografie impliceert dat duidelijke grenzen nodig zijn wil men lichaamsdelen scherp kunnen afbakenen. Maar een objekt dat scheef staat ten opzichte van de beweging van de tomograaf, zal zichtbaar worden als een object met onscherpe grenzen.

Om deze reden werd een aangepaste radiologische methode ontwikkeld om wille van de diagnostiek van sacro-iliacale aandoeningen. Verwacht werd dat met behulp van deze methode onderscheid gemaakt kon worden tussen fysiologische aanpassingen en sacro-iliacale pathologie. Een anatomische benadering werd gecombineerd met conventionele radiologie, complexe bewegingstomografie en computer tomografie (hoofdstuk III).

Voor onderzoek van het sacro-iliacale gewricht wordt complexe bewegingstomografie aanbevolen. Vanwege de sinusoïdale vorm van het gewricht en de aanwezigheid van fysiologische aanpassingen (richels en groeven), moet elk gedeelte van het gewricht loodrecht op het oppervlak gefotografeerd worden. De dorsale zijde van het gewricht moet dus getomografeerd worden in frontale projektie, het centrum en het ventrale gedeelte in schuine projektie.

Bij 56 patiënten, verwezen wegens vermoedelijke spondylitis ankylopoëtica (morbus Bechterew), werden 72 sacro-iliacale gewrichten onderzocht. Op basis van conventionele radiografie bleken er 6 als normaal te moeten worden beschouwd, bij frontale tomografie 5. Bij oblique tomografie echter, konden 31 gewrichten als normaal worden aangewezen (hoofdstuk III).

Oblique tomografie van de sacro-iliacale gewrichten geeft betere resultaten dan frontale tomografie of conventionele radiologie. Met het oog op de praktische implementatie wordt voorgesteld om frontale tomografie voor het dorsale gedeelte van het gewricht te combineren met schuine tomografie onder een hoek van 25° voor het centrum en het ventrale gedeelte (hoofdstuk III).

Aangezien de bouw van de sacro-iliacale gewrichten aan grote variabiliteit onderhevig is, moet deze benadering aangepast worden aan de individuele bouw. Bijvoorbeeld bij patiënten met een slechts geringe helling van het centrum van het gewricht, of met een dorsaal deel welk een grote hoek maakt t.o.v. het ventrale en het centrale deel, moet tomografie precies worden toegesneden op die situatie. Dit impliceert dat de hoek niet altijd 25° moet zijn.

Teneinde goede diagnostiek te kunnen bedrijven, is gedetailleerde kennis van de anatomie van de sacro-iliacale gewrichten, met inbegrip van de aanwezigheid van groeven en richels, een vereiste. Zonder die kennis zou bijvoorbeeld de aanwezigheid van richels en groeven ten onrechte tot de diagnose 'osteophytose' kunnen leiden.

Indien het inderdaad zo is dat de beschreven macroscopische veranderingen op hogere leeftijd fysiologisch zijn, dan blijft de vraag of op hogere leeftijd enige beweeglijkheid mogelijk is in de sacro-iliacale gewrichten. In diverse anatomische leerboeken wordt namelijk gesteld dat beweging onmogelijk is.

Een proefopstelling werd ontwikkeld teneinde sacro-iliacale beweeglijkheid te meten in preparaten, afkomstig van oudere mensen. De gegevens werden vergeleken met de resultaten van radiologisch onderzoek. Bij het prepareren werden de verbindingen tussen het sacrum en de vijfde lumbale wervel gespaard, evenals de omringende ligamenten. Beweging werd opgewekt door kracht uit te oefenen op de acetabula (hoofdstuk IV).

In het sagittale vlak kon zowel ventrale rotatie (als onderdeel van nutatie) als dorsale rotatie (als onderdeel van contranutatie) worden aangetoond. De meeste sacro-iliacale gewrichten waren beweeglijk, met een maximale bewegingsmogelijkheid van 4° rotatie, dat wil zeggen voor nutatie en contra-nutatie samen. Het sacro-iliacale gewricht met de minste beweeglijkheid vertoonde radiologisch duidelijke tekenen van arthrosis. In sommige sacro-iliacale gewrichten werd een zekere mate van 'kruip' aangetroffen. Aandacht wordt besteed aan intra-individuele verschillen in sacro-iliacale beweeglijkheid. De kinematische en klinische consequenties van de bevindingen worden besproken (hoofdstuk IV).

De gegevens van deze mobiliteitsstudie suggereren dat kleine sacro-iliacale bewegingen ook op hoge leeftijd nog mogelijk zijn. Zelfs op hoge leeftijd is ankylose niet de normale situatie. Deze conclusie komt overeen met Stewart's (1984) morfologische studie en met de biomechanische studie van Miller et al. (1987).

Teneinde de functie van de richels en de groeven beter biomechanisch te kunnen begrijpen, gebruikten wij een vrijlichaamsdiagram van het symmetrische sacrum. De kontakt-kracht tussen de botten werd aangeduid als F_T. De kracht F_T werd ontleed in een component loodrecht op het oppervlak (F_N) en een tangentiële kracht (F_W). We zochten naar mogelijkheden om op basis van de sacro-iliacale anatomie de normaalkracht F_N te beïnvloeden. Met dit doel werd een onderzoek verricht aan anatomische preparaten (hoofdstuk V en VI).

De sacrotuberale ligamenten worden als belangrijke schakels gezien in de kinematische keten tussen het bekken en de wervelkolom. De aan deze ligamenten bevestigde spieren, zoals de m. gluteus maximus en, bij sommige individuen, de m. piriformis en de lange kop van de m. biceps femoris, kunnen de bewegingen in de sacro-iliacale gewrichten beïnvloeden. We speculeerden dat met name het sacrotuberale ligament en de verbindingen ervan met de m. biceps femoris en de m. gluteus maximus, een belangrijke rol kunnen spelen in het vergroten van F_N (hoofdstuk V).

Eén en ander leidde tot een nieuwe biomechanische studie teneinde de anatomische gegevens te onderbouwen. De hypothese werd getoetst dat kleine spanningsveranderingen in het sacrotuberale ligament de bewegingen en/of bewegingsmogelijkheden van het sacro-iliacale gewricht beïnvloeden (hoofdstuk VI).

Daartoe werd het sacrotuberale ligament belast. Zelfs een geringe belasting in de richting van de ischiocrurale groep en de m. gluteus maximus, bleek een significante vermindering te geven van de ventrale rotatie van het sacrum. De gegevens impliceren dat belasting van de sacrotuberale ligamenten de nutatie-mogelijkheid van het sacrum beperkt. Dientengevolge kunnen spieren die aan de sacrotuberale band aanhechten, zoals de m. gluteus maximus en bij sommigen de lange kop van de m. biceps femoris, bewegingen en stabiliteit van de sacro-iliacale gewrichten op dynamische wijze beïnvloeden (hoofdstuk VI).

Het belang van de sacrotuberale band en de sacro-iliacale gewrichten als onderdelen van de kinematische keten wordt benadrukt. Toegenomen of afgenomen compressie van de sacro-iliacale gewrichten zou een belangrijke factor kunnen zijn in de kinematica van het lage ruggebied.

Aangezien kon worden aangetoond dat de sacro-iliacale gewrichten beweeglijk zijn, en er grote inter- en intra-individuele verschillen bestaan, verdienen deze gewrichten meer aandacht bij de studie van kinematische verstoringen in het gebied van de lage rug. Zelfs wanneer er duidelijk sprake is van pathologie van de lumbale wervels, blijft toch de vraag bestaan of die pathologie primair is of een symptoom van een algemene verstoring van de ingewikkelde kinematische keten waar de sacro-iliacale gewrichten deel van uitmaken.

Nieuw onderzoek zou tot doel moeten hebben, standaard-methoden te ontwikkelen voor het testen van toe- of afname van sacro-iliacale compressie. Het effect van specifieke biomechanische stimuli op de sacro-iliacale gewrichten zal moeten worden bezien in samenhang met bewegingen van, met name, de lumbale wervelkolom. Een goed uitgerust bewegingsanalyse-laboratorium is voor het onderzoeken van dergelijke complexe systemen onontbeerlijk.

Curriculum vitae

Vanaf de vierde klas van de lagere school worden de schoolverplichtingen als een buitengewoon onnodige bezigheid ervaren. De drang om grotere tijdsdelen in de vrije natuur te kunnen spenderen leidt alras tot onvrijwillige verplaatsing naar verscheidende Haagse middelbare scholen. Na een ongeval wordt, grotendeels in bed, op recordwijze het meest minimale b-pakket gehaald—na afrondingen naar boven. Dit ter schande van een beroemde school.

Vanwege multipele ongevallen en daardoor opgelopen afwijkingen aan het bewegingsapparaat wordt een carrière als piloot onmogelijk en veranderd in een opleiding tot fysiotherapeut. Vanaf het tweede jaar van deze studie worden assistentschappen in de anatomie verricht aan de VU. Na voltooiing van deze studie wordt gedurende vier jaar gestudeerd en worden anatomische assistentschappen vervuld aan de Interfakulteit Lichamelijke Opvoeding, Vrije Universiteit te Amsterdam, gekombineerd met docentschappen in de anatomie aan verschillende HBO-instellingen.

Vervolgens wordt gekozen voor het ondernemerschap gekombineerd met een beroep als professioneel zeezeiler in Mediterrane wateren. Deze plannen worden ten dele doorkruist door een aanbod voor een docentschap in de anatomie aan de Medische Fakulteit Erasmus, waarna zeilen en lesgeven gekombineerd worden. In samenwerking met anderen worden twee klinisch anatomische boeken geschreven. Momenteel wordt gewerkt als docent en onderzoeker in een samenwerkingsverband van anatomie en medische technologie.

Docentschappen worden vervuld in het akademisch, postakademisch en vervolgonderwijs aan de Erasmus Universiteit te Rotterdam, de Freie Universität te Berlijn en de Goethe Universität te Frankfurt. In de vrije tijd wordt gezeild.

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Andry Vleeming

Thinking within a fixed circle of ideas tends to restrict
the questions to a limited field.
And if one's questions stay in a limited field,
so do the answers
(David Bohm: Some remarks on the notion of order.
In G.H. Waddington, *Towards a Theoretical Biology.*
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