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Sacroiliac Joint Morphological Changes from Infancy to Adulthood

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Keywords : sacroiliac, growth, pelvic incidence, morphological analysis

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Abstract

Background context: Report of sacroiliac morphology changes during growth is limited in the literature and the interest of such morphology and its consequence for surgery is increasing.

Purpose: Aims of this work are 1) to anatomically define the sacroiliac joint (SIJ), 2) to assess the influence of growth on the sacroiliac morphology and the pelvic parameters.

Study design: Forty-nine young subjects from 6 months to 18 years old (y/o) and 20 adults aged from 18 to 50 y/o were selected from our institutional patient database.

Methods: They underwent a CT examination on a 128-MDCT (GE Healthcare Optima CT660). Transverse CT image datasets were reconstructed, anonymized and segmented with ITK-SNAP. Landmarks and surfaces were selected and a SIJ orientation analysis was performed using costumed Python scripts.

Results: The subjects were divided into four groups: infants (1.9 ± 1 y/o), children (6.9 ± 1.7 y/o), adolescents (13.7 ± 1.8 y/o) and adults (27.3 ± 5.6 y/o). Differences between SIJ orientation were found significant between young subject groups for synovial sacrum SIJ orientation ($p < 0.001$) and iliac total SIJ orientation ($p = 0.036$). Both orientations of younger subjects were found significantly different from the adult group ($p < 0.035$). SIJ synovial sacrum and iliac total orientations correlated significantly with age ($p < 0.03$). All orientations correlated with pelvic incidence (PI) ($p < 0.04$) except for synovial sacrum SIJ orientation ($p = 0.2$). No gender or symmetrical differences were found significant in any group.

Conclusion: Morphological definition of the SIJ confirmed the independency of the gender during growth. Such results will be beneficial for the analysis and management of vertebral pathology.

Keywords: Sacroiliac joint, pelvic incidence, spine, growth

1 INTRODUCTION

2 The sacroiliac joint (SIJ) is an important bilateral articulation of the pelvic girdle. It transfers weight
3 from the upper body to the lower limbs via the spine and serves as a shock absorber. The SIJ is the
4 most direct anatomical link between the pelvis (iliac bones) and the spine (sacrum). Such articulation
5 has been described by anatomists as having a cartilaginous anterior part (synovial) and a fibro-
6 ligamentar posterior synarthrosis. This unique configuration leads to its classification as a
7 diarthrodial/synovial joint¹.

8 It has limited mobility but a high stability due to different mechanisms of force-closure (muscles) and
9 form-closure². The form-closure mechanisms include the ligaments and the self-locking pelvic
10 configuration caused by the wedged shape of the sacrum. Moreover, the articular surface on the
11 sacrum is mostly concave while the iliac surface is mostly convex, adding to the stability of the SIJ.

12 Many changes were reported with aging, one of them being the formation of complementary ridges
13 and grooves on the articular surfaces that increase friction². Such changes are reported to first happen
14 with locomotion³. On the iliac side, a groove (ventro-caudally to the iliac articular surface) is reported
15 to appear in the second decade in women^{4,5}. During growth, the correlation between pelvis widening
16 and age is reported to be 0.333 mm/year (p<0.001)⁶. Even after skeletal maturity, the pelvic width was
17 found to increase by 20 mm. [ref Berger 2011] For the sacrum, three intersegmental fusions of the
18 sacral vertebral segments (S1, S2, S3) occur: S1-S2 fusion occurs between 6 and 13 years old (y/o),
19 while S2-S3 fusion occurs between 9 to 18 y/o⁷. Anthropology and archeo-biology have been defining
20 SIJ and bridging for skeleton age assessment^{8,9}. SIJ anatomy has been studied in evolution: neonatal
21 subjects presented smaller angle of the sacral incidence when compared to adult subjects¹⁰. Such
22 angle was found to be inversely correlated with sacro-acetabular distance (between middle of the
23 sacral plate and middle of the bi-acetabular distance). Lateral and caudal to the first sacral vertebrae
24 are the two main elevations that describe the SIJ, the first being the most prominent. There is a saddle
25 shaped depression between the two elevations that appear during growth and changes with aging.
26 Some gender differences have been reported. Men of 14 years of age and older have a larger articular
27 bony tubercle in the middle of the auricular surface whereas women have a groove at the iliac SIJ
28 surface. Current description of the joint is limited while description of the shape was reported without
29 real quantitative measurements¹¹.

30
31 Articular surface was reported to range from 10.7 to 18cm² depending on gender¹²⁻¹⁴. It is composed
32 of hyaline and fibrocartilage, has a rough and coarse texture suggesting a functional adaptation¹⁵. The
33 SIJ surface is divided into three parts as ventral, middle and dorsal (S1, S2, S3), with 40°, 25° and 10°
34 angle of the surfaces respectively¹⁶. While assessed by MRI, ossification of apophyses of the sacral
35 wings show differences between genders in juvenile population¹⁷. Specificities of the auricular surface

1 morphology contribute to the stability of the joint against shearing with a highest coefficient of friction
2 compare to any diarthrodial joint ¹⁸. Mitchell et al. defined three horizontal axes within the SIJ (iliac
3 and sacral) and a right and left diagonal ¹⁹. Additionally, SIJ kinematics has been studied in-vitro and
4 is mainly characterized by a sagittal rotation and an inferior translation of the sacrum (compared to the
5 ilium) ²⁰.

6
7 A large portion of low back pain (10 to 40% ⁷) is reported to come from the SIJ ²¹. Report of the SIJ
8 morphology changes during growth in the literature is limited and the interest of such morphology and
9 its consequence for surgery is increasing with the 310% increase of interventions per 100 000 insured
10 person from 2000 to 2011²². Stabilization of the SIJ is then becoming an economic and societal
11 burden.

12
13 Bipedal gait differentiates human being from the rest of the mammalian and such bipedal gait is highly
14 influenced by the SIJ anatomy ¹⁰. Pelvic anatomy is defined in the spine adaptability (static and
15 dynamic) to gait by three angles: the pelvic incidence (PI), sum of sacral slope and pelvic tilt. The PI
16 changes with growth and has been reported to stagnate after the puberty. After puberty, PI is mostly
17 fixed for a given patient ²³, although it can change slightly following surgery ²⁴. Predictors of lordosis
18 have been previously described from sagittal alignment of the spine and pelvis ²⁵. Additionally,
19 different posture types have been defined and correlated to pelvis, lordosis and kyphosis
20 measurements ^{18,26,27}. However, such definition did not enable to explain completely the spine static
21 and dynamic equilibrium and SIJ morphology has not be taken into account in such theories.

22
23 Hypothesis of this work is that the SIJ parameters are changing during growth (Figure 1), and that
24 morphological definition of such joint will enable a better understanding of the spinal growth
25 mechanism. The SIJ is believed to take part in the spinal equilibrium and insure the transmission of the
26 loading from the spine to the lower limb. Thus, the orientation of the SIJ articular facets intervenes in
27 biomechanical static and dynamic equilibrium of the spine. Aims of this work are to anatomically
28 define the SIJ in terms of orientation and to assess the influence of the sacroiliac morphology on
29 pelvic parameters.

30 **Methods**

31 Population

32
33 We searched in our institutional database patients who had undergone CT examinations for traumatic
34 or oncologic purposes including the pelvic area. We selected 69 subjects from 6 months to 50 y/o (49

1 young: 7.4 ± 5.1 y/o; 20 adults: 27.3 ± 5 y/o). The CT examinations were performed on 128-MDCT (GE
2 Healthcare Optima CT660). The tube current was modulated according to the patient's body size and
3 shape. In all cases, transverse CT image datasets were reconstructed with a section thickness inferior
4 to 1 mm for the anatomic area from the 4th lumbar vertebra to the ischial tuberosity. The images were
5 anonymized.

6 Data processing

7 Pelvic bones were segmented with the ITK-SNAP software ²⁸ using a threshold adapted to the
8 patient's scan and a snake-based segmentation growing tool. Seven manually located landmarks and
9 10 surfaces were selected using Paraview (BSD License, NY 12065, USA) with definition of anterior
10 superior iliac spine (ASIS), pubis, ischial spine, synovial SIJs (global and caudal) and femoral heads.
11 Documentation for using Python in ParaView can be found in ParaView source documentation
12 (<https://www.paraview.org/documentation/>).

13 *SIJ Angle Analysis*

14 ASIS landmarks were selected from the anterior view of the iliac bone. Two points were selected in
15 the centre of the right and left pubic facets and the central pubic landmark was defined as the middle
16 of those two points (Figure 2A). Ischium bone landmarks selection was set at the ischial tuberosity of
17 each ischium. Those three landmarks were selected for left and right iliac crests (Figure 2A). A
18 medium plane was computed based on the midpoints of those three pairs of landmarks (ASIS, pubic
19 and ischium). Additionally, a landmark was set to the first sacral backbone (spinous process) to define
20 an additional plane as the normal to the sacral plate in its midpoint crossing such landmark (Figure
21 2B).

22 Selection of the SIJ surfaces was performed in two parts: a total surface representing contact between
23 the sacrum and the face of each iliac bone and a synovial surface defined as the partial higher surface
24 (Figure 3). Since sacral vertebrae are not merged in younger subjects, two to three joints were selected
25 on the sacral side. In those cases, the synovial surface was then defined as the sum of the second and
26 third joints while total joint area was the sum of all surface areas. Planes were fitted on each surface.
27 Additionally, sacral plate was selected as a surface. Computation of the fitted planes was performed
28 using customized Python scripts with numpy and matplotlib libraries (minimum least squares method as
29 an example).

30 The midpoint (defined as the point with coordinates being the average of all point coordinates by axis)
31 of the sacral plate was considered to be the center of reference. A plane was defined between the
32 midpoint of the sacral plate and femoral heads in order to compute PI.

1 The medium plane was considered as the reference plane and SIJ surfaces formed by points were used
2 to fit planes. Incidences between SIJ fitted planes and the reference plane were defined for each
3 selected surface. Incidence difference between synovial and total SIJ surfaces on both iliac bones and
4 sacrum were computed.

5 *Morphological SIJ Analysis*

6 Areas were computed for each surface. Ratios between areas from synovial and total surfaces were
7 computed. Widths were defined at three locations of the joints and a cumulative width was provided as
8 the sum of all the widths (Figure 4).

9 Statistical analysis

10 Surface area differences between synovial and total surfaces were tested symmetrically to highlight
11 differences between left and right SIJ if any. Age groups were defined as different growth categories:
12 0 to 4 y/o (group 1), 4 to 10 y/o (group 2) and 10 to 18 y/o (group 3). Such definition enables to
13 provide reference average? values with standard deviations. Correlations between SIJ parameters and
14 age used to depict the continuous? changes of the parameters in aging and between SIJ parameters and
15 PI were tested using R software²⁹ . Growth phases and group differences were analysed using an
16 ANOVA and Wilcoxon test. Coefficient of variation (CV) was computed as the standard deviation of
17 the differences between two measurements divided by the mean to assess reproducibility of the
18 quantification of the morphology of SIJ on the 20 adults.

19

1 **Results**

2 ***Reproducibility of the methods***

3 CV of the four SIJ orientation angles varies from 14.9 to 31.5% (surface angles (SA) Sacrum Total:
4 29.7%, synovial: 24.4%; SA Iliac Total 31.5%, synovial 14.9%). Such reproducibility measurement
5 concerned only the definition of landmarks and did not include the segmentation reproducibility or
6 multiple-observer variability.

7 ***SIJ angular orientation***

8 Average values for sacrum and iliac total and synovial angles with the reference plane were compared
9 between the three growth categories (0-4 y/o /4-10 y/o old /10-18 y/o) and with the adult group (Table
10 1). In the 0 to 18 y/o population, the synovial sacrum and total iliac SA were found to be influenced by
11 the growth category ($p<0.001$ and $p=0.036$ respectively). When compared to the adult population,
12 differences were found significant for synovial sacrum and total iliac SA ($p=0.035$ and $p=0.044$) but
13 not for total sacrum and synovial iliac SA.

14 ***Morphological analysis as areas and widths of the SIJ***

15 Areas and widths by growth category are reported in Table 2. Significant differences were found
16 between young groups? for all values. When compared to adults, only synovial/total sacrum ratio was
17 found not significant while all widths except cumulative widths were significantly different between
18 young groups and adults ($p<0.011$).

19 ***Changes during growth***

20 Correlations between the SIJ morphological parameters (angles, areas and widths) and age or PI are
21 reported (Table 3 and Figure 5). Clear correlations with age were found for synovial sacrum SA
22 ($p<0.001$) and total iliac SA ($p=0.03$). Similarly, areas and widths also strongly correlate with age
23 ($p<0.001$).

24 ***Pelvic incidence and correlation***

25 PI ranged in average per groups between 48.3 to 50.8° for infants, children and adolescents and were
26 significantly different from PI in adults ($39.9\pm 13^\circ$, $p=0.002$ -Table 1). PI correlates with total and
27 synovial iliac SA and total sacrum SA ($p<0.04$) (Table 3). It also correlates significantly with sacrum
28 average width and synovial sacrum area ($p<0.01$). Correlation of PI with age was found significant
29 ($p=0.03$).

30 ***Gender differences and symmetry***

1 No significant differences between genders were found even when differentiating adults (p ranged
2 from 0.2 to 0.66 for angles and 0.09 to 0.33 for areas) from infants and adolescents adults (p ranged
3 from 0.61 to 0.96 for angles and 0.12 to 0.3 for areas). SIJ angular orientations in infant, adolescent
4 and adult groups differentiated by gender are reported in Table 1. No symmetrical differences were
5 found between right and left surface SIJ angles in the whole population (p: 0.1 to 0.79) or in sub-
6 groups (infants and adolescents: p: 0.1 to 0.79, adults: p: 0.32 to 0.54).

7 **DISCUSSION**

8 This study improves the understanding of the morphological evolution of the pelvis during growth.

9 Existence of different spinal morphotypes has been shown ²⁶. Such morphology leads each individual
10 to different static and dynamic properties. Accounting for such morphotypes in the physiopathology
11 and management of spinal pathology (including surgical management) is common practice nowadays
12 ¹². The pelvis, considered as the pelvic vertebrae, is closely linked to the spine and even indivisible in
13 terms of biomechanics. Indeed, pelvic parameters (PI, pelvic tilt and sacral slope) determine spinal
14 morphotypes and play a big role in the adaptation of the spine to pathological and mechanical
15 situations (including especially pelvic retroversion ^{8,24}).

16

17 The SIJ is the focus of many research studies. The anatomical description and the biomechanical study
18 of the motion of such structure have been studied at several years of life (childhood, growth, adult and
19 aging) and is still discussed today ¹¹. Two studies of this large literature could be noticed as scan
20 studies of the SIJ anatomy. Postacchini R. et al ³⁷ described the articular and extra-articular areas of
21 the sacroiliac complex in adults. The bone anatomy was provided in order to differentiate the articular
22 and extra-articular areas by CT scan as reported as more efficient for such differentiation than in MRI.
23 Description of the sacroiliac surface in adults was mostly performed from their location relative to the
24 sacral depression and SIJ space in coronal and axial planes. Such values are then difficult to compare
25 to the results presented here. Regarding the paediatric population, Zejden A. and Jurik G. ⁷ studied the
26 bone anatomy of this area by tomodensimetry during growth (124 patients between 9 months and 18
27 y/o) describing mainly the ossification kernel/core and the fusion of segments according with age and
28 gender. Those two studies did not provide 3D-analysis of the morphology of the SIJ. To the best of our
29 knowledge, we did not found any study reporting orientation of the articular sacroiliac surface, the
30 evolution in those orientations with growth and its relationship to PI.

31 Reproducibility of the positioning of the landmarks and computation of the angles was assessed using
32 CV. CV stayed under 35% for angular measurements which could be considered as reasonable and
33 could be explained by the quality of the scan not enabling good segmentation and worsening landmark
34 positioning. Intersegmental fusion assessment reliability was assessed in terms of agreement between
35 two senior radiologists in ⁴ and was of 4%. However, they reported a classification rather than a

1 continuous variable. Reports of similar measurements were not found in literature. However such
2 results did not include the segmentation results as the methodology used for segmenting the SIJ was
3 similar in all cases. Further shape analysis could be performed ³⁰.

4 In defining three sub-groups (0-4 y/o /4-10 y/o /10-18 y/o) and an adult group, significant changes
5 during growth of the SIJ surface orientation have been shown. The angle of the SIJ surface regarding
6 the reference plane to the sacral plate increases significantly with age and such result is more
7 significant for synovial articular surfaces of the sacrum ($p < 0.001$ for synovial sacrum SA and $p = 0.04$
8 for iliac total SA). This could be an adaptation to the weight gained during growth resulting in
9 increased shear forces to the joint. Force resulting from gravitation could then be mostly transmitted
10 through the synovial SA part in comparison with the dorsal part and thus increasing the form closure
11 mechanism. This increase of angle reinforces the self-locking mechanism, therefore increasing the
12 stability of the pelvic girdle. Differences were found significant between the 4-10 y/o group and 10-18
13 y/o group ($p = 0.022$ for synovial sacrum SA and almost significant 0.076 for total iliac SA) while no
14 significant difference was found between the 0-4 y/o and 4-10 y/o groups. Growth of the spine has
15 been reported to occur mostly between 0 and 5 years and during puberty which then leads to more
16 detection of idiopathic scoliosis during puberty ^{31,32}. Similarly, we found that the SIJ morphology is
17 significantly different between the 4 to 10 y/o group and the 10 to 18 y/o group which seems to
18 correspond to a spine growth phase, although such results need to be confirmed with further
19 investigation.

20 The synovial area localized in the antero-superior part of the articulation is more correlated with age
21 than the fibro-ligamentar area localized in the postero-inferior part of the articulation (when synovial
22 and total morphological changes are compared). Indeed, as shear forces increase with age, SIJ surfaces
23 increase to insure stability and to limit stresses at the joint. As the morphology of the pelvis causes the
24 synovial surface to be subjected to higher forces than the fibro-ligamentar area, this part of the joint
25 seems to adapt more over time.

26 The results showed that there is no difference between gender in morphological changes during
27 growth ($p > 0.2$). Such results agree with several studies showing the gender anatomical independency
28 of such articulation particularly before puberty ³³ (no significant different in young and adult groups in
29 our results). While pelvic dimensions have been reported to be larger in male around the 22nd month
30 with the difference decreasing later, consequences of such dimorphism on the SIJ articular surface
31 could be a wider occupation of the sacral base by the fifth lumbar vertebra in male ². In our study, the
32 size of the growth phase population may be too small to show significant changes in the orientation
33 planes of the SIJ between genders.

34 Anatomical widths are also described in the results. It appeared that the changes in angles of the
35 articular surfaces are associated with morphological changes of the structures. This highlights that the

1 changes of the SIJ planes is part of a normal evolution and growth of the osteo-articular structures.
2 This work provided a quantitative definition and reference values of the SIJ in growth.

3

4 PI has been shown to be a morphologic parameter, constant and invariable for a given patient. This
5 pelvic parameter is established during growth and stabilizes definitely at the end of puberty. The PI
6 has been shown to increase during growth, particularly during the first ten years ⁹. However the
7 mechanism influencing the value of such parameter are only partially known and understood
8 nowadays. The pelvis, as an osteoarticular structure, changes during growth. To the best of our
9 knowledge, few studies have shown the link between morphological growth of the pelvic ring and the
10 establishment of pelvic parameters. In 2014, the works of Schlösser, et al. ³⁴ reported a lordosis
11 development during a morphological growth and correlation of such parameters with PI. The
12 relationship described between the pelvis and PI makes us think that the morphological evolution of
13 the pelvis plays a crucial part in the definition? of the pelvic parameters and thus, through
14 biomechanical relationship, of the spinal morphotype. In this work, a significant correlation between
15 orientation of the SIJ surface compared to orthogonal reference plane and the value of the PI is
16 reported. Such results are significant for total sacrum SA, total iliac SA and synovial iliac SA (Table
17 3). Thus, the more the SIJ articular plane opens externally, the higher the pelvic incidence ($p < 0.04$, R
18 ranged between 0.2 and 0.44). This is in line with the conclusions from Abola et al. ³⁵ that PI had an
19 influence on the SIJ. They reported that a higher PI was associated with a more angulated and curved
20 sacrum and a more linear SIJ in the sagittal plane. Our study shows that it also has an effect on the
21 orientation of the SIJ in the horizontal plane, through PI correlation with total sacrum and iliac SA.
22 The synovial surface area of the sacrum is also positively correlated with PI. Pelvis with higher PI tend
23 to have a more horizontal sacrum, potentially further increasing forces on the synovial area of the
24 joint, thus leading to an increased surface area and average width of the synovial sacrum part.

25 Statistical power of our study is however limited by the available number of patients as well as by the
26 difficulties of the lengthy post-processing, including segmentation and measurements. However, such
27 results reinforce the hypothesis that the morphological changes of the articular surface of the SIJ is
28 related to the definition of pelvic parameters specific to the individual and thus to the spinal
29 morphotypes.

30 Mac-Thiong et al. ³⁶ showed the interaction forces between the different segments in the pelvic-spinal
31 sagittal equilibrium in the paediatric population. This work enables to include, downstream to such
32 mechanism, the significant correlation between the articular surface SIJ orientation and the PI (Figure
33 6).

34

1 **CONCLUSIONS**

2 The results of this work help us to investigate the constitutive mechanisms of pelvic and spinal
3 morphotypes as well as the relation between pelvic and vertebral structures. They come within the
4 scope of the human's growth process by the acquisition of the biped standing in the development.
5 They also show no difference in the SIJ angular orientation between genders.

6 Thus, they will be beneficial to the analysis and management of spinopelvic pathology (including
7 distortion) of the infant, child and adolescent, at ages when the maturity of the pelvic-spinal base is not
8 yet definitive.

9 It is then necessary and interesting to further study the biomechanical and morphological analysis on a
10 higher number of subjects, and integrate the analysis of the spinal curves (e.g. lumbar lordosis,
11 thoracic kyphosis), together with pelvic parameters (pelvic incidence, pelvic tilt and sacral slope) and
12 spinal morphotype of each patient.

13

1 REFERENCES

- 2 1. Dall BE, Eden SV, Rahl MD (eds). *Surgery for the Painful, Dysfunctional Sacroiliac Joint: A*
3 *Clinical Guide*. Springer International Publishing. Available at
4 <https://www.springer.com/la/book/9783319107257>. 2015, Accessed April 8, 2019.
- 5 2. Vleeming A, Schuenke MD, Masi AT, et al. The sacroiliac joint: an overview of its anatomy,
6 function and potential clinical implications. *J Anat* 2012;221:537–67.
- 7 3. Solonen KA. The sacroiliac joint in the light of anatomical, roentgenological and clinical studies.
8 *Acta Orthop Scand Suppl* 1957;27:1–127.
- 9 4. Brooke R. The Sacro-Iliac Joint. *J Anat* 1924;58:299–305.
- 10 5. Vleeming A, Van Wingerden JP, Dijkstra PF, et al. Mobility in the sacroiliac joints in the
11 elderly: a kinematic and radiological study. *Clin Biomech Bristol Avon* 1992;7:170–6.
- 12 6. Berger AA, May R, Renner JB, et al. Surprising evidence of pelvic growth (widening) after
13 skeletal maturity. *J Orthop Res Off Publ Orthop Res Soc* 2011;29:1719–23.
- 14 7. Zejden A, Jurik AG. Anatomy of the sacroiliac joints in children and adolescents by computed
15 tomography. *Pediatr Rheumatol Online J*;15. Epub ahead of print November 25, 2017. DOI:
16 10.1186/s12969-017-0210-0.
- 17 8. Boulay C, Tardieu C, Hecquet J, et al. Sagittal alignment of spine and pelvis regulated by pelvic
18 incidence: standard values and prediction of lordosis. *Eur Spine J Off Publ Eur Spine Soc Eur*
19 *Spinal Deform Soc Eur Sect Cerv Spine Res Soc* 2006;15:415–22.
- 20 9. Kendall HO, Kendall FP, Wadsworth GE. Muscles, Testing and Function. *Am J Phys Med*
21 *Rehabil* 1973;52:43.
- 22 10. Tardieu C, Bonneau N, Hecquet J, et al. How is sagittal balance acquired during bipedal gait
23 acquisition? Comparison of neonatal and adult pelvis in three dimensions. Evolutionary
24 implications. *J Hum Evol* 2013;65:209–22.
- 25 11. Hens SM, Godde K. Auricular Surface Aging: Comparing Two Methods that Assess
26 Morphological Change in the Ilium with Bayesian Analyses. *J Forensic Sci* 2016;61:S30–8.
- 27 12. Miller J a. A, Schultz AB, Andersson GBJ. Load-displacement behavior of sacroiliac joints. *J*
28 *Orthop Res* 1987;5:92–101.
- 29 13. Sashin D. A CRITICAL ANALYSIS OF THE ANATOMY AND THE PATHOLOGIC
30 CHANGES OF THE SACRO-ILIAC JOINTS. *JBJS* 1930;12:891.
- 31 14. Ebraheim NA, Biyani A. Percutaneous computed tomographic stabilization of the pathologic
32 sacroiliac joint. *Clin Orthop* 2003;252–5.
- 33 15. Bowen V, Cassidy JD. Macroscopic and microscopic anatomy of the sacroiliac joint from
34 embryonic life until the eighth decade. *Spine* 1981;6:620–8.
- 35 16. Dijkstra PF, Vleeming A, Stoeckart R. Complex motion tomography of the sacroiliac joint. An
36 anatomical and roentgenological study. *ROFO Fortschr Geb Rontgenstr Nuklearmed*
37 1989;150:635–42.

- 1 17. Bollow M, Braun J, Kannenberg J, et al. Normal morphology of sacroiliac joints in children:
2 magnetic resonance studies related to age and sex. *Skeletal Radiol* 1997;26:697–704.
- 3 18. Weisl H. The movements of the sacroiliac joint. *Acta Anat (Basel)* 1955;23:80–91.
- 4 19. Mitchell FL, Moran PS, Pruzzo NA, et al. *An evaluation and treatment manual of osteopathic
5 muscle energy procedures*. 1st ed. Valley Park, Mo. : Mitchell, Moran and Pruzzo, Associates.
6 Available at <https://trove.nla.gov.au/version/45422031>. 1979, Accessed June 5, 2018.
- 7 20. Hammer N, Scholze M, Kibsgård T, et al. Physiological in vitro sacroiliac joint motion: a study
8 on three-dimensional posterior pelvic ring kinematics. *J Anat* 2019;234:346–58.
- 9 21. Sembrano JN, Polly DW. How Often Is Low Back Pain Not Coming From the Back? *Spine*;34.
10 Epub ahead of print January 1, 2009. DOI: 10.1097/BRS.0b013e31818b8882.
- 11 22. Gras F, Hillmann S, Rausch S, et al. Biomorphometric Analysis of Ilio-Sacro-Iliac Corridors
12 for an Intra-Osseous Implant to Fix Posterior Pelvic Ring Fractures. *J Orthop Res* 2015;33:254–
13 60.
- 14 23. Le Huec JC, Aunoble S, Philippe L, et al. Pelvic parameters: origin and significance. *Eur Spine J*
15 2011;20:564–71.
- 16 24. Place HM, Hayes AM, Huebner SB, et al. Pelvic incidence: a fixed value or can you change it?
17 *Spine J*. Epub ahead of print June 2017. DOI: 10.1016/j.spinee.2017.06.037.
- 18 25. Alderink GJ. The sacroiliac joint: review of anatomy, mechanics, and function. *J Orthop Sports
19 Phys Ther* 1991;13:71–84.
- 20 26. Roussouly P, Gollogly S, Berthonnaud E, et al. Classification of the normal variation in the
21 sagittal alignment of the human lumbar spine and pelvis in the standing position. *Spine*
22 2005;30:346–53.
- 23 27. Laouissat F, Sebaaly A, Gehrchen M, et al. Classification of normal sagittal spine alignment:
24 refounding the Roussouly classification. *Eur Spine J Off Publ Eur Spine Soc Eur Spinal Deform
25 Soc Eur Sect Cerv Spine Res Soc* 2018;27:2002–11.
- 26 28. Yushkevich PA, Piven J, Hazlett HC, et al. User-guided 3D active contour segmentation of
27 anatomical structures: significantly improved efficiency and reliability. *NeuroImage*
28 2006;31:1116–28.
- 29 29. R Core Team R: A Language and Environment for Statistical Computing. R Foundation for
30 Statistical Computing. 2013.
- 31 30. Márquez EJ, Cabeen R, Woods RP, et al. The Measurement of Local Variation in Shape. *Evol
32 Biol* 2012;39:419–39.
- 33 31. DiMeglio A, Dimeglio A, Canavese F, et al. Growth and adolescent idiopathic scoliosis: when
34 and how much? *J Pediatr Orthop* 2011;31:S28-36.
- 35 32. Dimeglio A, Canavese F. The growing spine: how spinal deformities influence normal spine and
36 thoracic cage growth. *Eur Spine J Off Publ Eur Spine Soc Eur Spinal Deform Soc Eur Sect Cerv
37 Spine Res Soc* 2012;21:64–70.
- 38 33. Klein P, Sommerfeld P. *Biomécanique des membres inférieurs: bases et concepts, bassin,
39 membres inférieurs*. Elsevier Masson; 2008.

- 1 34. Schlösser TPC, Janssen MMA, Vrtovec T, et al. Evolution of the ischio-iliac lordosis during
2 natural growth and its relation with the pelvic incidence. *Eur Spine J* 2014;23:1433–41.
- 3 35. Abola MV, Teplensky JR, Cooperman DR, et al. Pelvic Incidence Is Associated With Sacral
4 Curvature, Sacroiliac Joint Angulation, And Sacral Ala Width. *Spine*. Epub ahead of print April
5 12, 2018. DOI: 10.1097/BRS.0000000000002679.
- 6 36. Mac-Thiong JM, Wang Z, de Guise JA, et al. Postural model of sagittal spino-pelvic alignment
7 and its relevance for lumbosacral developmental spondylolisthesis. *Spine Phila Pa 1976*
8 2008;33:2316–25.
- 9 37. Postacchini R, Trasimeni G, Ripani F, et al. Morphometric anatomical and CT study of the
10 human adult sacroiliac region. *Surg Radiol Anat SRA* 2017;39:85–94.

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1 **FIGURES LEGEND**

2

3 **Figure 1.** Illustration of the hypothesis: orientation of the SIJ is changing during growth and is
4 correlated to the pelvic incidence's evolution.

5 **Figure 2.** SIJ Angular Analysis: **A)** SIJ selections, **B)** central plane in dark grey (based on landmarks
6 on sacroiliac crests, pubis and ischium), sacrum plate fitted plane in light grey and pelvic incidence
7 plane in transparent light green (based on midpoint of sacrum plate and centres of femoral heads); **C)**
8 fitted plane on sacral SIJ on a young subject (2.4 y/o, female).

9 **Figure 3.** Illustration of the different joint surfaces of the SIJ analysed in our study

10 **Figure 4.** Morphological analysis of the SIJ: **A)** widths defined on each sacral and iliac SIJ, **B)**
11 Landmarks definition.

12 **Figure 5.** SIJ correlations with age and PI.

13 **Figure 6.** Schematic relationship between spine parameters according to ³⁶ and with the SIJ addition.

14 **TABLES LEGEND**

15 **Table 1.** Normal value in different growth categories (0 to 4 y/o, 4 to 10 y/o and 10 to 18 y/o), in
16 adults and in the whole population. Significativity: *: $p < 0.05$, **: $p < 0.005$, ***: $p < 0.001$

17 **Table 2.** Shape Analysis of the SIJ including area: widths and spline analysis. Significativity: *:
18 $p < 0.05$. **: $p < 0.005$. ***: $p < 0.001$

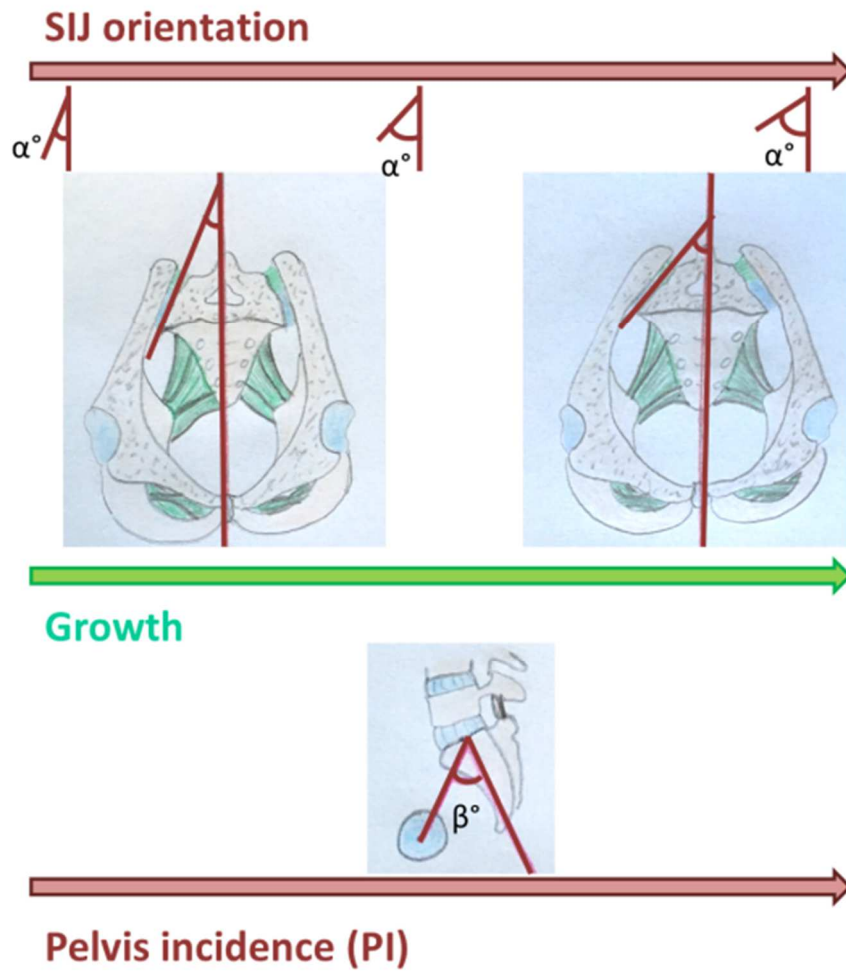
19 **Table 3.** Pearson correlations between SIJ characteristics and age or PI.

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1 **FIGURES**

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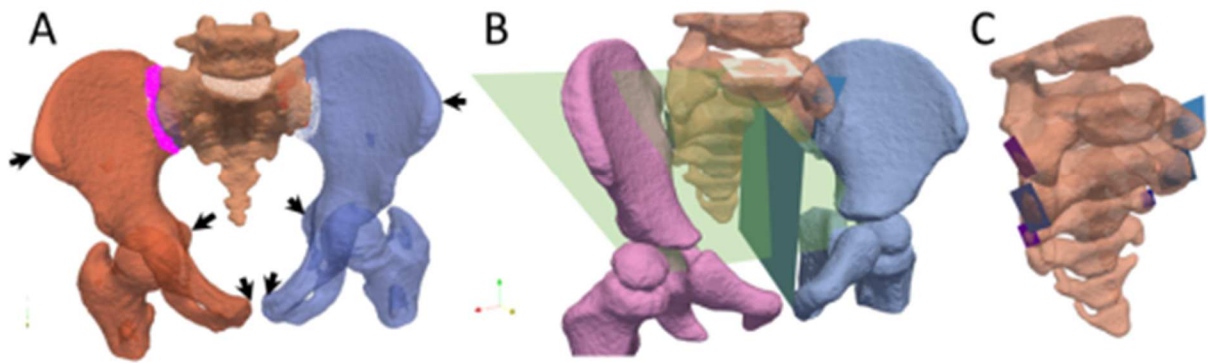


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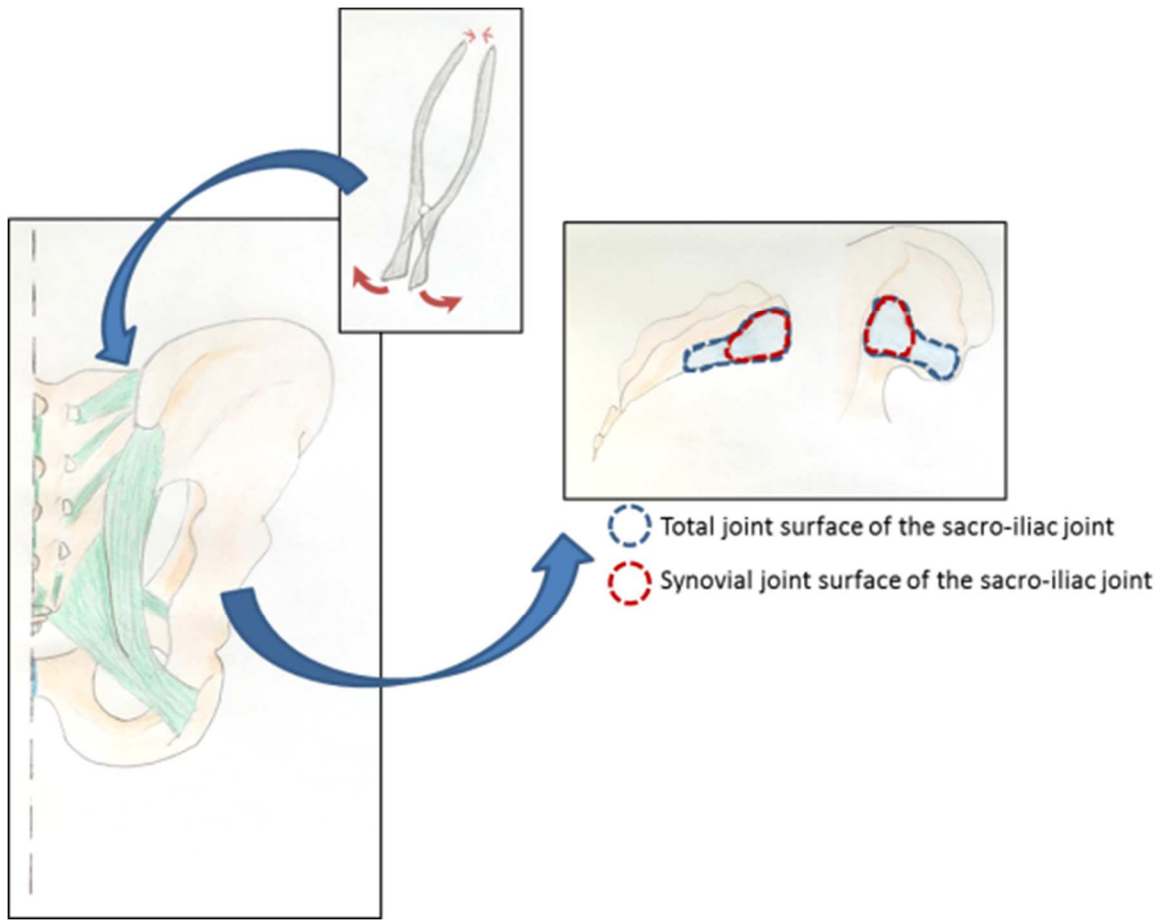
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1 **Figure 3.** Illustration of the different joint surfaces of the SIJ analysed in our study

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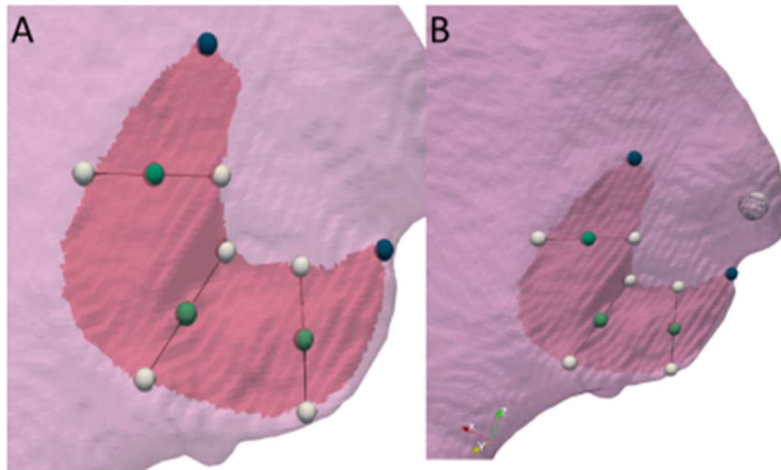
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3 Landmarks definition.

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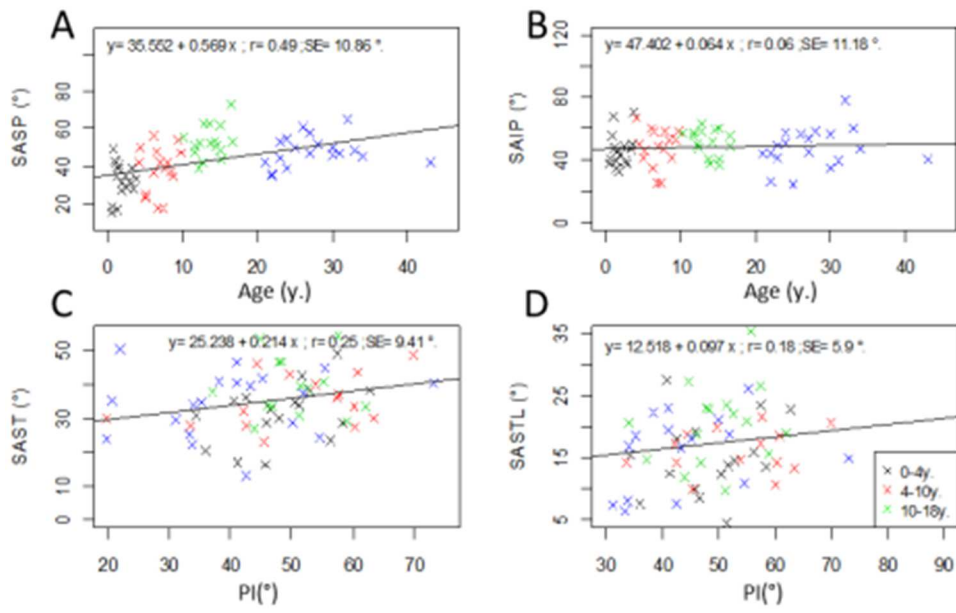


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1 **Figure 5.** SIJ correlations with age and PI.

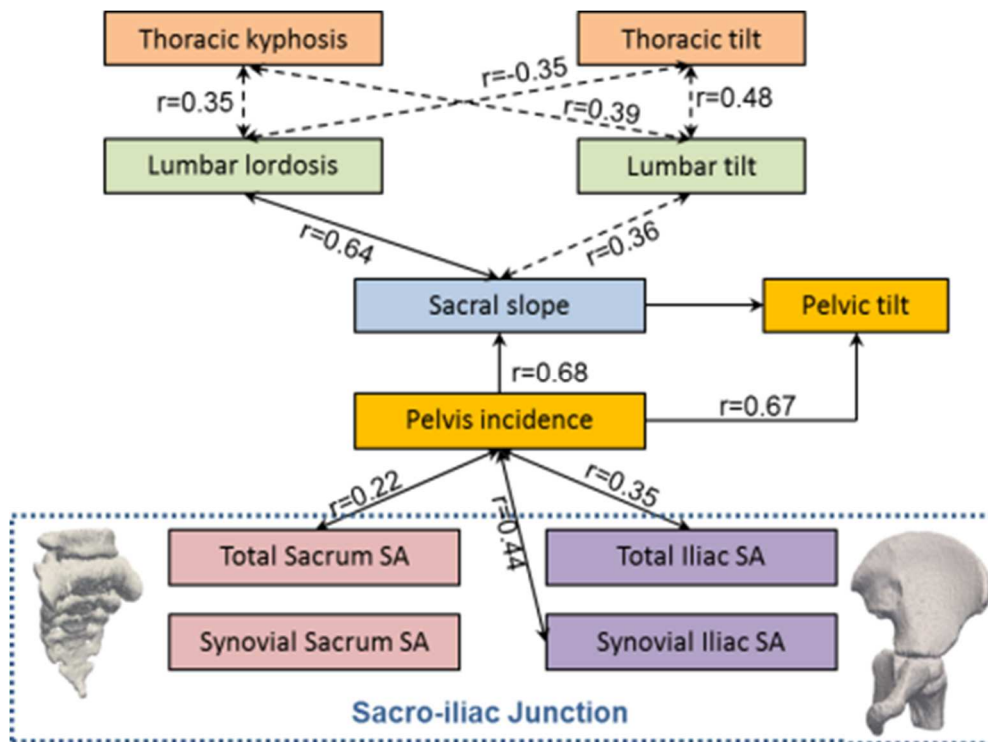
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1 **Figure 6.** Schematic relationship between spine parameters according to ²⁸ and with the SIJ addition.



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TABLES

Table 1. Normal value in different growth categories (0 to 4 y/o, 4 to 10 y/o and 10 to 18 y/o), in adults and in the whole population. Significativity: *: p<0.05, **:p<0.005, ***:p<0.001

Growth phases	1	2	3	Total	p	Female (gr. 1, 2 and 3)	Male (gr. 1, 2 and 3)	Adults	p
Gender (Female)	17(9)	16(7)	16(8)	49(24)		24	25	20(9)	
Age (y.)	1.9±1	6.9±1.7	13.7±1.8	7.4±5.1		7.5±5.4	7.2±4.9	27.3±5.6	
Weight (Kg)	10.9±2.4	24.6±7.4	47.8±6.3	27.4±16.4		28.4±17.2	26.5±15.9	63.7±12.1	
Size (cm)	81.5±10.3	118.7±10.9	156.9±7.6	118.3±32.7		118.5±34.1	118.1±31.9	170.8±11.6	
BMI (Kg/m2)	16.3±1.4	17.2±2.4	19.4±1.7	17.6±2.2		17.7±2.5	17.2±1.9	21.7±2.1	
BSA (m2)	0.5±0.1	0.9±0.2	1.4±0.1	0.9±0.4		1±0.4	0.9±0.4	1.7±0.2	
Total Sacrum SA (°)	31.5±8.7	35.3±7.6	40.5±11	35.7±9.7	0.22	35.9±10	35.5±9.7	34.6±9.4	0.61
Synovial Sacrum SA (°)	32.4±9.5	38.2±12.1	53±8.5	41±13.2	<0.001***	40.9±14.7	41.1±11.9	48.5±8	0.035*
Total Iliac SA (°)	42.9±7.2	42.6±7.5	40.4±6	42±6.9	0.036*	42.1±5.7	41.9±7.9	37.5±11.2	0.044*
Synovial Iliac SA (°)	46.2±10.5	48±12.1	51.3±8.6	48.5±10.5	0.57	47.7±9.9	49.2±11.2	48±12.6	0.78
Pelvic Incidence (°)	48.3±7.9	50.8±12.6	49.6±7.6	49.5±9.5	0.027*	49.0±8.5	50.1±10.4	40±13	0.002* *

Table 2. Shape Analysis of the SIJ including area: widths and spline analysis. Significativity: *: p<0.05. **:p<0.005. ***:p<0.001

Growth phases	1	2	3	Total	p	Adults	p
Gender (Female)	17(9)	16(7)	16(8)	49(24)		20(9)	
Age (y.)	1.9±1	6.9±1.7	13.7±1.8	7.4±5.1		27.3±5.6	

Total Sacrum SA area (cm²)	2.19±0.78	5.59±1.16	9.26±2.37	5.7±3.22	<0.001***	9.86±3.5	<i>0.003**</i>
Synovial Sacrum SA area (cm²)	1.36±0.67	3.63±0.85	5.9±1.66	3.64±2.14	<0.001***	6.69±2	<i>0.009**</i>
Synovial/Total sacrum ratio	0.7±0.06	0.71±0.06	0.7±0.04	0.71±0.05	0.048*	0.66±0.1	<i>0.061</i>
Total iliac area (cm²)	2.43±0.85	5.8±1.84	9.47±2.28	5.9±3.32	<0.001***	9.17±3.85	<0.001***
Synovial iliac area (cm²)	1.72±0.66	4.02±0.95	6.6±1.64	4.13±2.26	<0.001***	6±2.27	<0.001***
Synovial/Total iliac ratio	0.6±0.16	0.65±0.07	0.64±0.06	0.63±0.11	0.006**	0.7±0.05	0.011*
Sacrum long width (mm)	25.7±8.2	42.1±8.1	55.4±6.8	41.3±14	<0.001***	50.8±11.6	0.011*
Sacrum cumulative width (mm)	61.4±18	103.5±26.8	147.8±27.1	104.9±41.8	<0.001***	117.8±37.6	0.24
Sacrum average width (mm)	14.5±3.2	23.8±14.5	34.8±17.2	24.6±15.2	<0.001***	45±13.8	<0.001***
Iliac long width (mm)	20.3±3.1	34.6±6.6	49.4±5.4	34.8±12.8	<0.001***	47.2±10.3	<0.001***
Iliac cumulative width (mm)	70.9±15.2	104.8±25.2	152.7±24.4	109±39.8	<0.001***	125.1±35.9	0.13
Iliac average width (mm)	13.9±4.1	22.2±10.1	36±17.1	24.2±14.5	<0.001***	42.8±10.5	<0.001***

Table 3. Pearson correlations between SIJ characteristics and age or PI.

	Correlations with age	Correlations with PI
	r (p)	r (p)
Total Sacrum SA (°)	0.01(0.6)	0.22(0.04)*
Synovial Sacrum SA (°)	0.47(<0.001) ***	0.21(0.4)
Total Iliac SA (°)	0.24(0.03)*	0.35(0.002)**
Synovial Iliac SA (°)	0.35(0.63)	0.44(<0.001) ***
Total Sacrum SA area (mm²)	0.72(<0.001) ***	0.22(0.11)
Synovial Sacrum SA area (mm²)	0.75(<0.001) ***	0.21(0.046)*
Total Iliac SA area (mm²)	0.63(<0.001) ***	0.15(0.36)
Synovial Iliac SA area (mm²)	0.61(<0.001) ***	0.15(0.34)
Sacrum long width (mm)	0.61(<0.001) ***	0.1(0.35)
Sacrum cumulative width (mm)	0.46(<0.001) ***	0.14(0.88)
Sacrum average width (mm)	0.61(<0.001) ***	0.29(0.01)*
Iliac long width (mm)	0.7(<0.001) ***	0.23(0.44)
Iliac cumulative width (mm)	0.53(<0.001) ***	0.14(0.85)
Iliac average width (mm)	0.64(<0.001) ***	0.75(0.058)