Influence of size and shape of the auricular surfaces on subchondral bone density distribution in the sacroiliac joint

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Abstract

The sacroiliac auricular surface is morphologically variable. The impact of morphology variations on subchondral mineralization distribution has not been investigated.

Sixty-nine subject datasets were subjected to CT-osteosorptiometry for chronic loading visualization. Auricular surface morphologies were sorted into three types based on posterior angle size: $>160^\circ$, $130-160^\circ$ and $<130^\circ$. Mineralization was qualitatively classified into four patterns: two marginal (M1, M2) and two non-marginal patterns (N1, N2), and each surface was assessed.

The auricular surfaces averaged $15.4 \pm 3.6 \text{ cm}^2$, with higher values in males. Sacral and iliac areas were significantly different between sexes. Type 2 was the most common (75%) and type 3 the least common morphology (9%). M1 was the most common pattern (62% of surfaces) by sex (males 60%, females 64%) with the anterior border as the maxima region in all three morphologies. Sacra have a majority of surfaces with patterns from the marginal group (98%). Iliia have mineralization concentrated at the anterior border (patterns M1+N2=83%).

Load distribution differences related to morphological diversity seems to have little effect on stress-related bone adaptation visualized with CT-osteosorptiometry. Higher iliac side mineralization was observed in larger joints potentially related to cartilage distribution. Chronic loading adaptation might account for age-related morpho-mechanical size alterations in males.

Introduction

The morphology of the sacroiliac (SIJ) auricular surfaces has been explored in the literature in relation to the changes occurring in response to natural degeneration of the joint¹⁻⁷ and sexual dysmorphism in the pelvis^{1,3,5,7,8}. Regarding the role of the auricular surface in joint mobility and bipedal force transmission, some studies have looked into the influence of the morphological differences and placement of the auricular surfaces in relation to the bony anatomy^{2,9,10}. However, few studies have looked into whether the general shape and size of the SIJ auricular is associated with SIJ pain and what differences there may be between sexes^{5,11,12}.

The osseous part of the auricular surface below the sacral and iliac cartilage is morphologically inconstant, varying inter-individually, as well as side-dependently even within the same individual¹³. It is often reported as made up of two 'limbs', one extending dorso-caudally, the other dorso-cranially situated at varying angles from one another¹³⁻¹⁵. Its shape has been described using a myriad of terms including: "L", "C", "V"-shaped, auricle-shaped, crescent-shaped, wedge-like, propeller-shaped, elliptical, triangular or rectangular^{2,4-6,8,10,13,14,16-18}, supporting the claim that the shape of the auricular surface varies considerably^{13,17-21}. A number of morphological studies have mapped the shape of the surfaces in relation to the limb shapes and sizes and have reported the angles of the posterior border in an attempt to categorize the general shapes based on the posterior angle^{5,6,11,14,15}. Specifically, three morphology types

have been described¹¹ where type 1 has a wide posterior angle ($>160^\circ$), type 3 a narrow posterior angle ($<130^\circ$) and type 2 is in between ($130-160^\circ$).

A previous paper by Poilliot, et al.²² reported the subchondral bone (SCB) density distribution in control SIJs and in joints with sacroiliac joint dysfunction (SIJD) using computed tomography osteoabsorptiometry (CT-OAM). CT-OAM is a radiological-numerical method to identify bone regions which adapt to chronic loading differently when compared to regions loaded to lower extent²³. Applying the same methods for the creation of SCB densitograms, this study aims to compare the mineralization distribution between the three morphological types. This will also be looked at when comparing joint size to see if that has an influence on mineralization. The densitograms will allow the visualization of the mineralization pattern across the surface which corresponds to the continuous loading conditions the joint endures. It will highlight the areas of high/low stress within the joint and thus provide information on the load dissipation between morphology variations and size.

The following hypothesis was investigated:

- Individual difference in subchondral bone density at the auricular surface depends on sacroiliac joint morphology

Materials And Methods

Specimens

A total of 69 specimens (29 females, 40 males; mean age 54 ± 15 years) from bodies subjected to anatomy were included to constitute a representative SIJ control cohort. These included 40 specimens (20 females, 20 males; mean age 53 ± 20 years) from a public hospital in Dunedin (New Zealand) acquired for clinical purposes to diagnose pathologies, or to rule out injury related to acute trauma. Twenty-nine cadavers (9 females, 20 males; mean age range 56 ± 7 years) donated to the University of Basel (Switzerland) between 2009 and 2021. All specimens underwent computed tomography (CT) upon reception at the Anatomy Institute of the University of Basel. None of these cases had a current or past history of low back pain, SIJ-related pathology or abnormalities on previous medical records and visible SIJ conditions visible on the CT-scans.

The ethical committee of the University of Otago, Dunedin, New Zealand approved this study. Ethical approval was acquired for the use of patient datasets used in research studies for diagnostic and therapeutic purposes. These specimens were used in previous studies for the completion of a student thesis by the author^{22,24}. Approval was granted on the grounds of existing patient datasets. Informed oral consent was obtained from all living subjects of this study. All methods were carried out in accordance with relevant guidelines and regulations. All the data were analyzed anonymously.

CT osteoabsorptiometry (CT-OAM)

Data sets for patients CT-OAM were acquired by means of a conventional clinical CT (SOMATOM as64 open, Siemens, Munich, Germany) according to a previous study²⁵. The slices were 0.6 mm thick. The cadaveric specimens were CT scanned (Somatom Emotion 16SL, Siemens, Munich, Germany) upon arrival at the University of Basel in an un-embalmed state. All datasets were evaluated using image analysis software (Analyze, v7.4, Biomedical Imaging Resource, Mayo Foundation, Rochester, NY, USA). The ilia and sacra were first outlined manually within the CT scans (segmentation) to reconstruct a three-dimensional lateral disarticulated view of the bones before the SCB plate of both the sacrum and the ilium of each specimen was isolated as a two-dimensional image. The maximum intensity projection revealed the HU of each pixel²⁶ so that for every image point, each maximum density value of the underlying bone plate was projected onto the surface. Threshold values were chosen according to previous studies to be ≤ 200 to ≥ 1200 HU²⁷. To display the mineral density distribution as densitograms, these data were false color coded and superimposed on the three-dimensionally reconstructed ilia and sacra for anatomical localization.

Classification into morphology types

The three-dimensional renderings of the bones were aligned to face the auricular surfaces. Inkscape v1.0.2-2 (The Inkscape Project, NY, USA; <https://inkscape.org>) was then used to calculate the alpha angle for the classification of the surface into the three different morphology types based on the method developed by Jesse, et al.¹¹ (Figure 1). The process involved two lines through the center of each limb and a third through the cross over point of the first two lines and the 'center' of the angle at the posterior border. The mean angle between the two limbs was then measured via the three points A, B and C (Figure 2) using the 'measurement tool' in Inkscape. For each specimen, this process was carried out three times and a mean value of the three angles was calculated as the result.

Pattern classification

Patterns were firstly identified belonging to two main groups: the marginal (M) and non-marginal groups (N). This assessment was done based on a qualitative analysis of the entire surface region. A pattern was marginal if 60-70% of the surface was less mineralized compared to the highly dense regions constituting the remaining 30-40%. The classification of the non-marginal patterns was the opposite criteria. To identify specific patterns for the qualitative analysis, four main patterns were identified. Two were marginal patterns: M1 had mineralization located around the anterior border which could include the superior corner and/or apex and pattern M2 had mineralization scattered around the borders with no specific maxima, the center region demineralized. The other two were non-marginal patterns: pattern N1 had mineralization spread over the whole superior region, pattern N2 had mineralization spread over the superior and anterior regions (Figure 3).

Pattern M1 was further subdivided into four sub-patterns (Figure 4) based on the distribution of the maximum points of highest mineralization (maxima) at the anterior border. Pattern A had mineralization across the anterior border. Pattern B had a maximum located in the superior corner only. Pattern C had maxima in the superior corner and apex. Pattern D had a maximum at the apex.

Area based size classification

Classification of 'large' and 'small' joints was arbitrarily categorized based on the mean area of all the joints. 'Small' surfaces had an area lower than the mean area, 'large' joint surfaces had an area higher than the mean area.

Statistical analysis

Prism (version 9.0.2, GraphPad, San Diego, CA, USA) was used for statistical analyses. Normal distribution of the data was determined using the Shapiro-Wilk test. Based on distribution, an ANOVA or a Kruskal-Wallis test was used to compare size differences and HU values between left and right sides as well as iliac and sacral sides between sexes. Age correlations were determined using a Pearson-r test as the data was not normally distributed. Dunn's post hoc correction was applied. *P* values of 0.05 or less were considered statistically significant. Values are given as mean values $\pm$ standard deviations with a 95-% confidence interval (CI). Correlations were defined as follows: strong ≥ 0.7 , moderate $0.7 > r \geq 0.5$, weak $0.5 > r \geq 0.1$. For qualitative analyses, the patterns were classified into the 5 groups and percentages were formulated based on the amount in each category.

Results

Surface area differences were observed between males and females as well as positive correlations with age

The auricular surface area of all control specimens averaged $15.4 \pm 3.6 \text{ cm}^2$ (95% CI: 15.0-15.9 cm^2). Mean area was rounded down to 15.0 cm^2 for the subsequent classification of 'large' and 'small' joints.

A significant difference was found in the mean areas between sexes ($p < 0.01$): mean areas for males were $16.2 \pm 3.9 \text{ cm}^2$ (95% CI: 15.6 - 16.8 cm^2) and $14.3 \pm 2.9 \text{ cm}^2$ (95% CI: 13.7 - 14.8 cm^2) for females. No significant difference in size was found between all sacral and all iliac auricular surfaces ($p = 0.7$) nor between sides ($p > 0.9$). However, a significant difference was found between sexes in sacral ($p < 0.01$, males $15.7 \pm 3.5 \text{ cm}^2$ [95% CI: 15.0 - 16.5 cm^2]; females $14.0 \pm 2.7 \text{ cm}^2$ [95% CI: 13.3-14.7 cm^2]) and iliac areas ($p = 0.02$, males $16.6 \pm 4.3 \text{ cm}^2$ [95% CI: 15.7-17.6 cm^2]; females $14.6 \pm 3.1 \text{ cm}^2$ [95% CI: 13.8-15.4 cm^2]) (Figure 5A). Auricular joint surface areas varied more in males than in females among individuals, and more in the sacrum compared to the ilium (Figure 5A). When separating males and females by size, larger joint sizes trended towards male specimens (sacrum 69%, ilium 65%), as indicated by the medians (Figure 5B). The opposite was true for smaller joint sizes with a dominance of female joints (51% ilium, 53% sacrum) (Figure 5B).

Age yielded weak positive correlations in the sacral ($p = 0.03$; $r = 0.18$), and iliac sides ($p = 0.02$; $r = 0.19$; Figure 6A, B). When subdividing this further by sex, a weak correlation with age was found in males in both the sacral ($p = 0.02$; $r = 0.26$) and iliac ($p < 0.01$; $r = 0.36$) sides (Figure 6C, D). This correlation was not found in females ($p > 0.7$).

Morphology types are unequally distributed between sexes and bones

Type 2 was the most common morphology (75% of all surfaces) and type 3 the least common (9% of surfaces). Within type 2, both sexes and bones were more or less equally represented. However, types 1 and 3 showed inequalities in the distribution of sacra and ilia as well as male and female specimens (T1: sacra 58%, ilia 42%, males 78%, females 22%; T3: sacra 29%, ilia 71%, males 37%, females 63%) (Figure 7).

Pattern M1 was the most common pattern with the apex and superior regions (M1A) as the most prevalent maxima zones.

Of the 276 auricular surfaces, 62% of all joints had pattern M1. When separated by sex and size, all had a majority of joints from pattern M1, with sub pattern M1A being the most frequent sub pattern (67% for males; 54% in females, 54% in small joints, 68% in large joints).

Regarding the mineralization maxima, the anterior region mineralization was the most common pattern (pattern M1A, 61% of joints), followed by the apex only (pattern M1C, 25% of joints), with the lowest being the superior corner only (pattern M1B, only 14% of joints). Refer to supporting information tables S1-S4.

Sacral auricular surfaces trend toward marginal patterns, whilst the iliac side has more characteristic anterior region mineralisation patterns, with no influence by joint morphology

The iliac side commonly had a majority of specimens belonging to patterns M1 and N2 (total of 83%), whilst the sacral side had a combined percentage of marginal patterns M1 and M2 (98%) (Figure 8). These patterns are consistent in all three morphology types; patterns M1 and M2 for the sacral side (T1:100%, T2:99%, T3:86%) and patterns M1 and N2 for the iliac side (T1:95%, T2:83%, T3:88%).

Anterior border mineralization (M1A) was a common finding in all three morphology types as well as between large and small joints

For all three morphology types, pattern M1 was the most common (T1: 56%, T2: 64%, T3:58%). Pattern M1 sub patterns showed that all three types joints had a high percentage of M1A pattern (T1: 68%, T2: 68%, T3: 50%) (Figure 9). When dividing the joints by size, 66% of small joints and 59% of large joints had pattern M1. Pattern M1A was also the most common in both large (68%) and small (54%) joints (Figure 9).

Mean HU values were higher in larger ilia with no sex nor auricular surface morphology difference.

When looking at the mean HU values of the overall surface, a significant difference ($p < 0.01$) was found when comparing small ilia vs. large ilia (small ilia: mean 598 ± 147 HU; 95% CI: 560-637 HU, large ilia: mean 704 ± 137 HU; 95% CI: 673-734 HU). This was not found on the sacral side ($p = 0.6$). No significant difference was found when comparing HU values of each morphology type ($p > 0.5$) nor between both sexes ($p > 0.9$).

Despite a majority of morphology resemblance there was low conformity between patterns of corresponding ilia and sacra

When comparing patterns of corresponding ilia and sacra from the same joint, there was low conformity: 38% conformity when both bones differed between patterns M1 to N2 and 8% conformity when adding the M1 sub patterns. When comparing matching morphologies between sacra and ilia from the same SIJ, there was a 67% conformity that both bones had the same morphology type.

Discussion

This study qualitatively analyzed the mineralization patterns of the sacral and iliac auricular surfaces of the SIJ in a cohort representing a 'control' population. It provides insights into the influence of surface size and shape with related morpho-mechanical difference between individuals. The results presented here are likely representative of the long-term loading conditions of the individuals which demonstrate the biomechanical stresses applied to the SIJ during life.

Load-induced mineralization patterns seem to differ between the sacral and iliac side

The area of the auricular surface has commonly been quoted on the values reported by Brooke¹⁶: approximately 1.5 cm² at birth, 7 cm² during puberty and up to 17.5 cm² as an adult^{19–21,28}. Further studies have specifically measured the auricular surface size in adults between the sexes, sides and bones with results ranging from 10.0 to 12.8 cm²^{1,5,10,29}. No significant difference was found between the sacral and iliac sides nor between left and right sides, but there is a significant difference between sexes^{1,5}. Additionally, greater variability was noted in the surface area sizes in males when compared to females and in the iliac side rather than the sacral side. This given study reflects a higher mean auricular surface area than previously reported (15.4 cm²), with a statistically significant difference between males and females where the former tended to have larger, more variable joints. Previous studies describe a male particularity of the SIJ surface extending over two and in many cases three sacral segments, whilst females were restricted to only two sacral segments in the majority of cases³⁰. This phenomenon is partly explained by females being more restricted in SIJ development, as they must retain a more 'primitive' structure for birthing, whilst the male pelvis has inclined inferior-posteriorly³⁰.

In relation to specific pattern differences between 'small' and 'large' joints, there were no significant differences between the two; both small and large joints had a majority of pattern M1 with maxima points at the apex and superior corner regions (M1A). However, mean surface mineralization between small and large joints was significant only on the iliac side. It has been suggested that larger joints may be predisposed to withstanding higher loads in proportion with the height/weight of the individual¹¹, however this is unrealistic. 'Smaller' joints have, by definition, smaller two-dimensional surface areas for force dissipation. This would result in higher loading conditions to the surface than if the surface area was 'larger'. It is important to highlight the anatomy of the auricular surface in its three-dimensional state where the surface is not flat but is composed of ridges and grooves^{31–33}, which 'increases' the true three-

dimensional contact-area when compared to the two-dimensional appearance of the auricular bone surface. This allows perhaps more surface dissipation for forces in 'smaller' joints if these ridges and grooves are greater than those in larger joints and would explain why larger joints have higher mineralization than smaller ones. For this theory to be tested, a volumetric analysis of the SCB plate would need to be undertaken in order to account for the unevenness of the auricular surface. Or, this result might be related to other compensation mechanisms such as cartilage thinning or sacral displacement. In fact, studies have reported that the iliac fibro-cartilage degenerates faster than the contralateral sacral hyaline one³⁴, which might account for the higher mineralization seen on the iliac side²³. This may be more pronounced in larger joints as they require less dampening of forces than smaller joints, but this theory would have to be investigated further.

Subchondral bone lamellae show age-related morpho-mechanical size alterations in males.

Age correlated weakly to auricular surface size, specifically in males. Developmental changes at puberty mediated by hormonal changes allow the female pelvis to retain joint elasticity and a shape fit for childbirth, whilst the male pelvis is freer to alter over time³⁵. For example, ankylosis can be seen in males as early as 30 years, with 75% of males with ankylosed joints after 50 years, which doesn't apply to females^{13,16}. This 'degenerative freedom', seemingly limited to the male pelvis, would explain the correlations here described as ankylosis would visibly alter the size of the joint on the three-dimensional reconstruction. Shape however is retained, as previously reported in Nishi, et al.⁴, as it could be determined by other intrinsic factors like genetics. The structure of the auricular surface is known to alter with age^{15,36}, and related changes in loading patterns by the spine and lower extremities. Ziegeler, et al.³⁷ reported substantial difference in the degeneration between both sexes where males exhibit a steady linear increase of osteophyte development with higher values than females after 50 years of age which might account for the size increase in males.

Mineralization patterns and mean density were non-different between morphology types.

Type 2 morphology was previously described as the most common morphology in both sexes and was termed the 'normal morphology'¹¹. This study echoes this assumption showing a close to equal distribution of ilia and sacra and males and females with type 2 morphology. The other two morphology types had a more biased distribution where males and sacra were more common in type 1 and females and ilia in type 3. Indeed, reports have similarly observed larger angles in males than in females as well as more acute angles in the ilia than the sacra^{1,7,38}.

The patterns identified in this study could be explained by the concept 'integration' kinematics of the pelvis. Force and form-closure result in the compression of the ilia and sacra as a consequence of axial loading, achieved via the muscular system, the ligaments and bony structure of the auricular surfaces^{28,31,39,40}. Under physiological loading conditions, the fifth lumbar vertebra is transposed anterior-inferiorly relative to the sacrum⁴¹ and small anterior rotations occur at the pubic symphysis anchoring both pubic bones together^{41,42}. As a result, the interosseous, sacrotuberous and sacrospinous

ligaments are tensed³⁹, pulling the iliac bones together in direction of the sacrum, thereby constraining nutation mostly on the cranial side whereas the caudal aspect tends to gape^{31,39}. In this scenario, the anterior-superior regions of the auricular surfaces are more tightly connected than the inferior posterior-regions thus revealing the tendency for the mineralization to be located in the anterior-superior regions: as seen in patterns M1, N1 and N2. However, in cases of border mineralization, as seen in pattern M2, this suggests that loads are dissipated across the surface specifically at the borders. As this is seen principally in the sacral side, this suggests the dissipation of forces into the surrounding structures (musculature, ligaments, fat and other connective tissues) which are located around the borders^{43,44}.

Regarding the mineralization patterns, pattern M1 was the most common in all distinctions covered, i.e.: sex, bone, size and morphology type. Maxima zones were most often the anterior border region which include the apex and superior corner (M1A). Furthermore, no significant difference was found in the mean HU values between the three morphology types. These findings reveal that mineralization patterns of the surface are unlikely impacted by size or shape; thus, we can reject our hypothesis. Moreover, sacra have a majority of surfaces with patterns from the marginal group, whilst ilia have concentrated mineralization in the superior and anterior regions, with low pattern conformity between corresponding sacra and ilia. This corroborates with previous findings where the sacral side is less dense than its corresponding iliac side²² and that although iliac surfaces of the joint are reciprocally shaped, they are not exactly congruent with the sacral surface¹³.

Regarding the limitations of the study, the scans obtained from the control cohort were different to the patients from the SIJD cohort. Therefore, this comparison may not account for population difference and potential variables between the two cohorts, except, age, sex and SIJ pathology. Furthermore, regional analysis may also have included some pixel sub volumes outside of the auricular surfaces, which may have caused a relative underestimation of the regional HU mean. In addition, the manual isolation of the three regions was performed by only one investigator. Consequently, the reproducibility of outlining the exact same regions remains untested to date. However, the regions were defined as being three sections of equal size with the anterior region incorporating the apex of the auricular surface. These are easily reproducible on each specimen regardless of the shape of the auricular surface. Anatomical variants were not accounted for and may have had some influence on joint area³⁷.

Conclusions

Load distribution related to auricular surface morphological differences seems to have little impact on stress-related subchondral bone adaptation visualized here with CT-OAM. Higher mineralization on the iliac side, only observed in larger joints, might relate to cartilaginous changes in joints with larger surface areas. Chronic loading adaptations might account for age-related morpho-mechanical size alterations.

Declarations

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Author contributions

A.P.: Data curation, Formal analysis, Writing—original draft, Investigation, Conceptualization. T.D.: Resources. M.T.: Data curation, Software. M.G.: Writing—review & editing, N.H.: Writing—review & editing. M.M.: Supervision, Software, Data curation, Writing- review and editing.

Data availability

The data acquired in the course of this study are available from the corresponding author on request.

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Competing interests

The authors have declared that no competing interests exist.

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Figures

Figure 1

Classification of sacroiliac joint auricular surface morphology types of auricular surface based on Jesse, et al.¹¹

Figure 2

Calculation of the alpha angle of the sacroiliac joint. Lines were drawn through the center of each limb (yellow dotted lines), another line (red dashed line) was drawn going through the interception of these two lines and the deepest part of the angle (point B). The measurement tool was used to measure the angle made between points A and C (interception of the yellow line and the tip of the limb). The resulting angle is highlighted within the green circle. A: anterior, I: inferior, P: posterior, S: superior

Figure 3

Sacroiliac joint pattern classification into the marginal (top) and non-marginal groups (bottom). (A) Pattern M1 (low mineralization in >60% of the surface) with anterior border mineralization. (B) pattern M2 with mineralization around the borders. (C) Pattern N1 (high mineralization in >60% of the surface) with mineralization located in the superior corner. (D) Pattern N2 with mineralization located in the superior corner and apex. A: anterior, I: inferior, P: posterior, S: superior

Figure 4

Classification of the morphology types of auricular surface. M1: marginal pattern 1

Figure 5

(A) Box plot of sex differences in auricular surface area by bone in the control cohort. Outlines of the boxes indicate the 25- and 75-percentile, the solid black horizontal line, the median. Whiskers indicate the 5-95 percentiles. The dotted line separates the cohorts in the table. (B) percentages of the distribution of the control cohort by size.

Figure 6

(A) Correlation of ilium auricular surface area with age in both sexes, (B) correlation of sacrum auricular surface area with age in both sexes, (C) age correlation with auricular surface area in male ilia and male sacra (D).

Figure 7

Distribution of bone side and sexes by morphology type I: ilium, S: sacrum, ♂: male, ♀: female.

Figure 8

Two most common patterns by bone type sacrum vs. ilium. M: marginal, N: non-marginal

Figure 9

Sub pattern distribution between each group. Bold shaded boxes represent the highest percentage of specimens

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