Ishizuka et al. BMC Musculoskeletal Disorders (2025) 26:351
https://doi.org/10.1186/s12891-025-08597-w

BMC Musculoskeletal Disorders

RESEARCH

Open Access

# Age-specific normative values of sacral development and fusion in children and adolescents: a cross-sectional study utilizing multiplanar reconstruction computed tomography imaging

Kyohei Ishizuka[1], Satoshi Nozawa[1*], Daichi Watanabe[2], Takuma Ishihara[2], Kazunari Yamada[1], Chizuo Iwai[1] and Haruhiko Akiyama[1]

## Abstract

**Background** This study aimed to determine the index of the sacral vertebrae fusion period in children and adolescents to diagnose the lesion around the sacral spine accurately.

**Methods** Patients aged 0–40 years who underwent computed tomography (CT), including the normal sacrum for screening abdominal disorders and pan-scan in trauma between 2019 and 2022 were retrospectively examined. There were 402 eligible sacra (385 patients: 206 women and 179 men). We evaluated bony fusion at six parts of the sacral vertebrae (anterior or posterior of each intervertebral and both side lateral masses). The predicted probability of bony fusion obtained from the logistic regression model is depicted graphically by sex.

**Results** The association between bony fusion in each vertebral segment and age was evaluated using a logistic regression model with a Huber–White robust sandwich estimator, including the patient as a clustering variable. Bony fusion of the sacral bodies of S1/S2 was slowest, with 80% of patients achieving bony fusion at 28.7 and 24.6 years of age for men and women, respectively. Compared to men, women exhibited earlier fusion of the intervertebral segments of the sacral vertebrae; however, no significant difference between the sexes in terms of eventual bony fusion at the lateral mass was observed, while the initiation of bony fusion occurred earlier in women.

**Conclusion** The predicted probability of bony fusion could aid pediatricians, orthopedists, radiologists, and other physicians in understanding the normal development of the sacral spine and accurately differentiating the lesion around the sacral spine.

**Keywords** Sacral spine development, Sacrum, Adolescent, Bony fusion

*Correspondence:
Satoshi Nozawa
noza618@yahoo.co.jp
[1] Department of Orthopedic Surgery, Gifu University School of Medicine, 1-1 Yanagido, Gifu 501-1194, Japan
[2] Innovative and Clinical Research Promotion Center, Gifu University Hospital, Gifu, Japan

## Background

Knowledge of the normal CT appearance is important to differentiate the normal appearance from pathology [1]. Normal variants mimicking fractures exist in all regions of the pediatric spine due to not-yet-ossified vertebral apophyses [2]. To accurately differentiate lesions around the sacral spine in pediatric patients, it is crucial to understand the normal development of the sacral spine. However, most physicians are unfamiliar with the normal development of this region. Anatomy textbooks note that the sacral vertebrae are initially formed embryologically as separate structures [3]. The intervertebral spaces fuse gradually from the age of 16–18 years, and all the intervertebral spaces are considered to have fused by 30 years of age [3]. However, in clinical practice, the bony fusion timing varies even among patients of the same age. Under the circumstances, references, such as age-specific normative values of the development, could be helpful guides for physicians. To date, literature on the anatomical development of the lumbar spine, sacrum, and pelvis is extremely limited and small in size [4, 5].

To our knowledge, there are no clear criteria for determining the progress of bony fusion of the sacral vertebrae. In this study, we present age-specific normative values for the bony fusion of the sacral vertebrae, using computed tomography (CT) images of 402 normal sacral bones from individuals aged 0–40 years.

## Methods

### Study design

A retrospective cross-sectional investigation.

### Patient selection

The study comprised patients aged 0–40 years that visited or were transferred to the various departments of our hospital (e.g., pediatrics, emergency unit, internal medicine, surgery, and orthopedics) between February 2019 and November 2022. Inclusion criteria were as follows: cases with a normal sacrum that underwent 1-mm slice thickness CT scans for screening abdominal disorders and pan-scan in trauma. Patients were excluded from the study if they had low back pain (LBP), severe fractures, bone tumors, pelvic inflammatory disease, or genetic disorders such as Marfan syndrome.

### Patient variables

Digital Imaging and Communications in Medicine format was used to store and read CT scans of 1-mm slice thickness. Orthopedic surgeons used the volume-rendering approach using 3D CT scans to assess bony fusion. The region of interest for bony fusion was divided into anterior posterior at the vertebral bodies and both lateral masses, and a score at each of the six locations was maintained. The fusion criteria by Luis Rios et al. [2] were used. Briefly, the absence of bony fusion was assigned value 0; up to 1/3 of the total area, approximately 1/2 and more than 2/3 were assigned the values 1, 2, and 3, respectively, and complete fusion was assigned the value 4. Assessments were performed by the first examiner (K.I.). To test the intra- and interexaminer reliability, the first and second observers (S.N.) assessed the images obtained from 40 patients.

### Statistical analysis

The association between bony fusion in each vertebral segment and age was evaluated using a logistic regression model with a Huber–White robust sandwich estimator, including the patient as a clustering variable. To confirm the hypothesis that the association between sacral fusion and age varies by sex, sex and a two-way interaction term (age * sex) were included in the logistic regression model. A test of the interaction term confirmed the modifying effect of sex on the relationship between sacral fusion and age. The sex-specific predicted probability of bony fusion obtained from the logistic regression model is shown graphically. Patient characteristics were summarized using medians and interquartile ranges (IQR) for continuous variables and frequencies for categorical variables. Only one case had missing values; therefore, complete data were used for analysis. The significance level was set at a $p$-value of $< 0.05$. All $p$-values were two-sided, and the significance level was set at a $p$-value of $< 0.05$. Analyses were performed using R 4.2.2 (The R Project for Statistical Computing). Based on the findings of CT, intra- and interexaminer reliability of the bony fusion assessments was evaluated using intraclass correlation coefficients (ICC).

### Ethical approval

The Gifu University Graduate School of Medicine Institutional Review Board has accepted this retrospective study under study number #2022–175. Moreover, informed consent was obtained using an opt-out method disclosed on the Gifu University website. For any participants under the age of 16, the consent was obtained using same method from the parents or legal guardians. The research was conducted following the tenets of the Declaration of Helsinki and its later amendments.

## Results

Of all patients who underwent CT scans, 2090 were eligible, and the pelvic regions of 413 of these patients were included. Of these 413 patients, 13 were scanned multiple times, which was > 1 year apart; five sacra were scanned twice within a year and were included only once; and six sacra were excluded because they had apparent morphologic abnormalities owing to tumors or Marfan syndrome. Overall, 402 sacra from 385 patients were used to assess the morphology of the lumbar spine and sacrum in detail (Fig. 1).

The distribution of 402 sacra was as follows: 0–9-year-olds: 25 cases (6.2%); 10–14-year-olds: 32 cases (8.0%); 15–19-year-olds: 43 cases (10.7%);

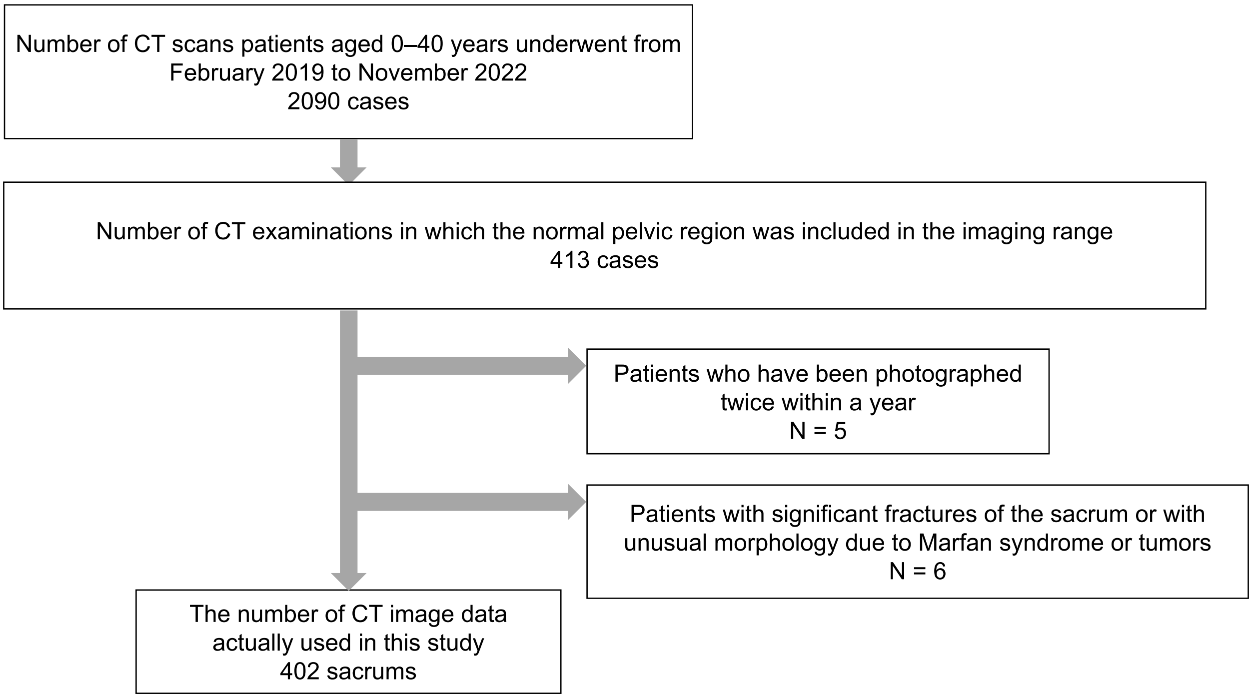


**Fig. 1** Flow diagram of patient selection. Patients undergoing CT between February 2019 and November 2022 were included. The data of patients who underwent imaging of the pelvic region were extracted, and 11 patients were excluded. Finally, 402 eligible CT images were included

20–24-year-olds: 57 cases (14.2%); 25–29-year-olds: 67 cases (16.7%); 30–34-year-olds: 70 cases (17.4%); and 35–40-year-olds: 108 cases (26.9%). The median age was 28 (IQR: 20–35). The detailed distribution of each age group is shown in Fig. 2.

Bony fusion was generally evaluated at the lateral mass and vertebral body separately.

Intra- and interexaminer reliabilities were tested by randomly selecting 40 cases (10% of all cases). To determine bony fusion, the intraexaminer reliability was ICC 0.94 (95% confidence interval [CI], 0.93–0.94), and the interexaminer reliability was ICC 0.86 (95% CI, 0.84–0.88). The degree of fusion was associated with age at both locations ($p$-value $=0.001$). The predicted probability of sacral fusion (score $=4$) for age in each lateral mass stratified by sex is shown in Fig. 3a–d. The line representing 80% of the fusion probability is represented by a dotted line. The gray zone depicts the 95% CI (Fig. 3e). Most lower vertebrae showed bony fusion by age 13, with 80% of men and women showing bony fusion in all vertebrae by age 16 and 15, respectively. The S1 and S2 vertebrae showed the slowest bony fusion compared with the other vertebrae. Both S2/S3 and S4/S5 bony fusion showed significant differences between the sexes, with fusion initiating earlier in women than in men (interaction $p$-value of $<0.001$ and 0.006, respectively).

Figure 4a–c demonstrates the bony fusion process of the anterior surface of the lateral masses, and Fig. 4d–f depicts the bony fusion process of the posterior surface of the lateral masses. In all vertebral segments, the age at the beginning, progress, and completion of bony fusion were not different between the anterior and posterior surfaces. Figure 5a–d shows the relationship between sacral fusion (score $=4$) and age in the anterior region of the vertebral body of each vertebral segment, stratified by sex. The calculated age at which 80% of people attained bony fusion is shown in Fig. 5e. Cranial intervertebral spaces above S3/S4 exhibited slower fusion. Results showed that women attained earlier bony fusion at all vertebral elevations. In 80% of the patients, bony fusion was confirmed at the S1/S2 vertebrae at 28.7 and 24.6 years of age for men and women, respectively. The S2/3 vertebrae and lateral masses, the association between age and bony fusion differed significantly by sex (interaction $p$-value $=0.022$). In S3/S4 vertebrae, there was no difference in the onset of bony fusion between the sexes; however, women showed a rapid progression of bony fusion in the 10-year age group.

Figure 6a–d shows the relationship between sacral fusion (score $=4$) and age at the posterior segment of the vertebral body, stratified by sex. The age at which 80% of people attain bony fusion is shown in Fig. 6e. Posterior fusion at the S1/S2 vertebrae and the anterior

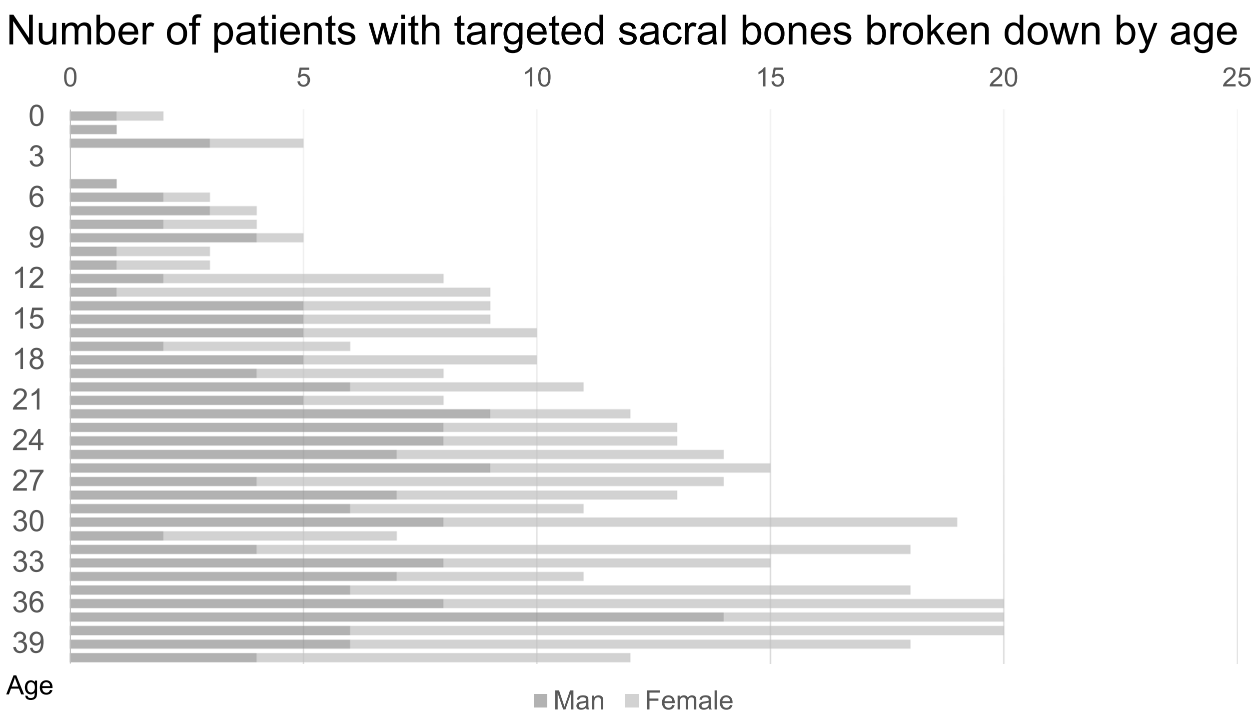


**Fig. 2** Sex and age distribution of the 402 sacra. This figure depicts the sex and age data for the 402 study patients

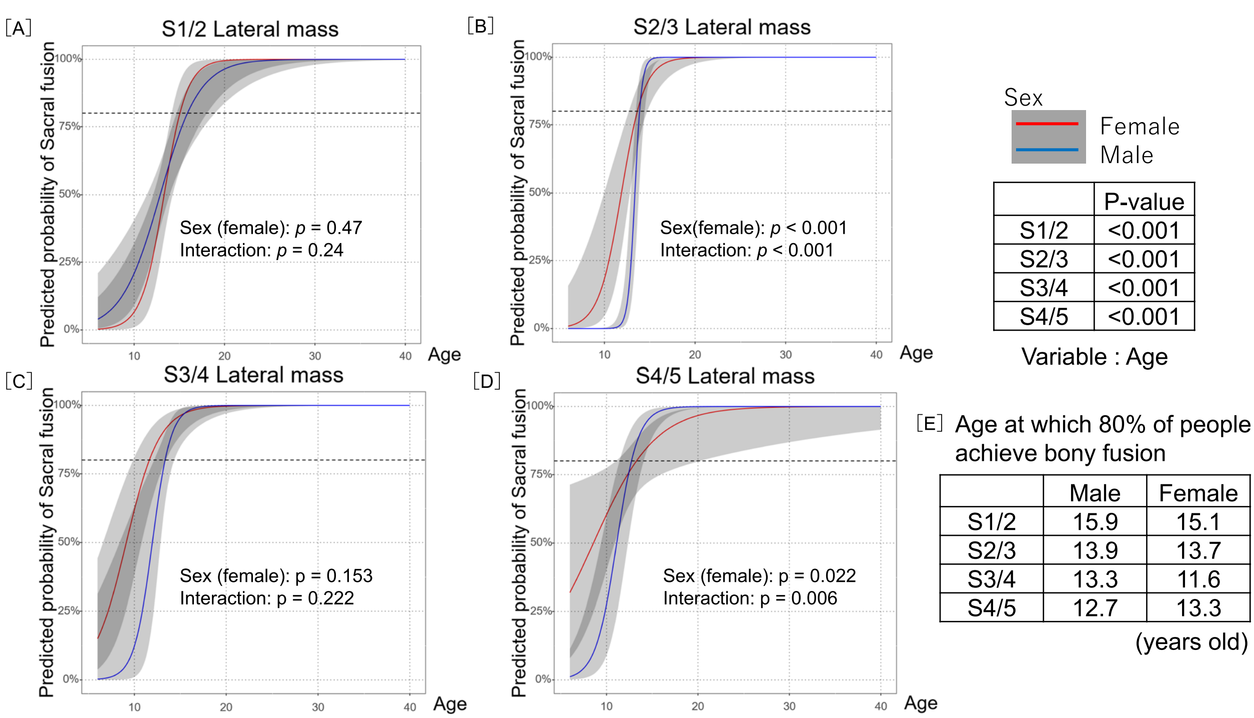


**Fig. 3** Predicted probability of sacral fusion by age for each lateral mass. The S1/S2 vertebrae fusion showed the slowest bony fusion progression compared with the other vertebrae. Significant changes by sex were observed in S2/S3 and S4/S5, indicating that the initiation of bony fusion is earlier in female vertebrae than in male vertebrae (interaction *p*-values of < 0.001 and 0.006, respectively)

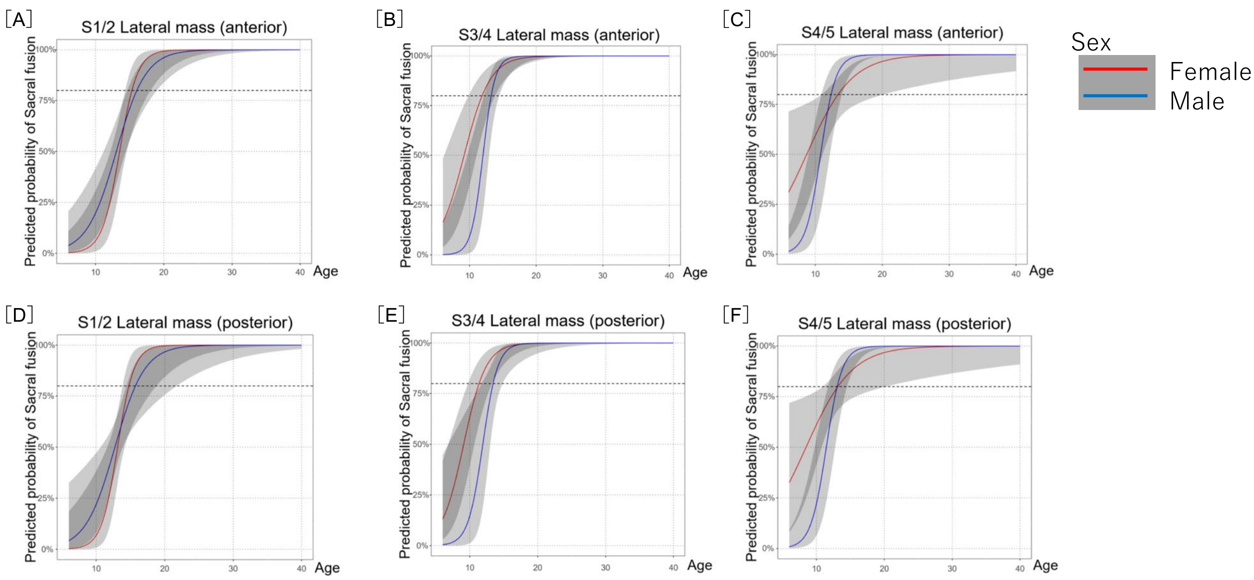


**Fig. 4** Predicted probability of sacral fusion by age and lateral mass segment. The process of bony fusion of the anterior surface of the lateral masses is depicted in **a**–**c**, while **d**–**f** illustrates the process of bony fusion of the posterior surface of the lateral masses. In all vertebral segments, the age at the beginning, progress, and completion of bony fusion remained consistent between the anterior and posterior surfaces

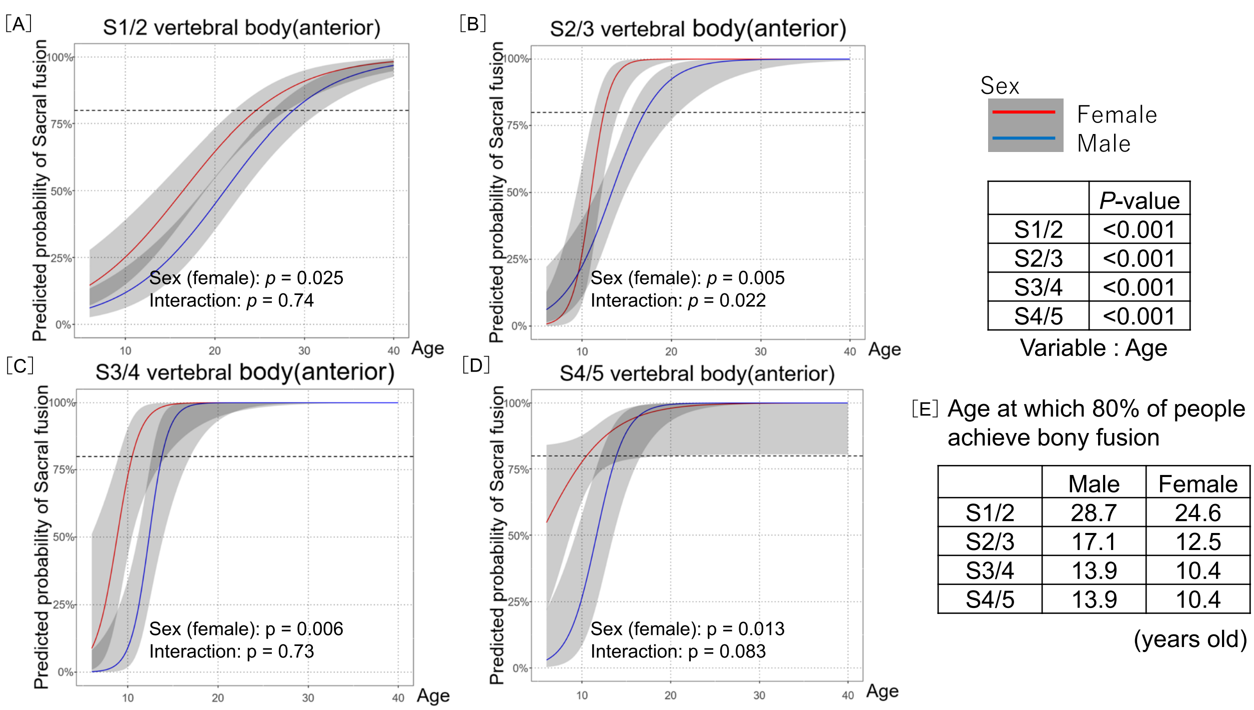


**Fig. 5** Predicted probability of sacral fusion by age for each vertebra on the anterior surface. This figure illustrates the relationship between intervertebral space and sacral fusion rate, showing that a higher intervertebral space from S3/S4 results in slower fusion. It also demonstrates a significant interaction between age and sex, with women completing bony fusion earlier at the S2/S3 level and in the lateral masses

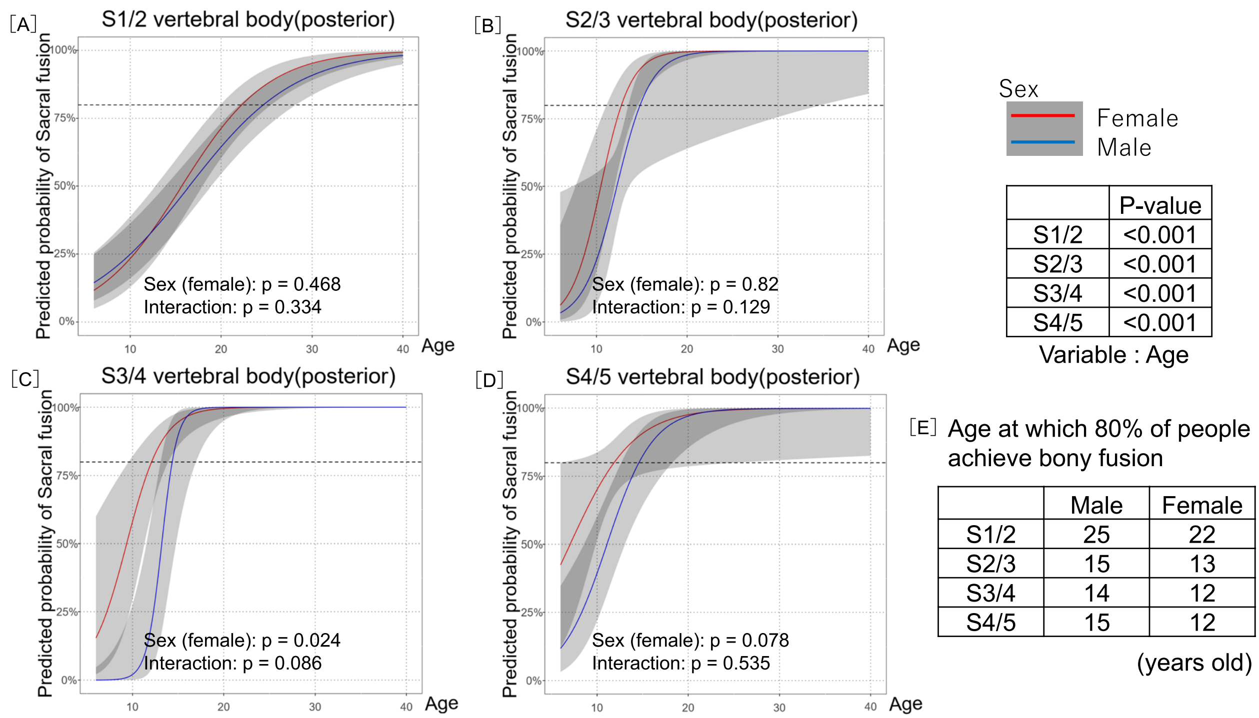


**Fig. 6** Predicted probability of sacral fusion by age at each vertebra on the posterior surface. The posterior and anterior vertebrae require approximately 10 years for the bony fusion of S2/S3 and S1/S2. There is no significant interaction between age and sex in either of the vertebral segments. The female group exhibited significantly faster bony fusion progression in the S3/S4 vertebrae and anterior vertebral body ($p = 0.024$) than male group

vertebrae occurs approximately 10 years of age following the bony fusion at S2/S3. A significant interaction between age and sex was not found for each posterior vertebral segment. The female group had significantly faster bony fusion progression at the S3/S4 and in the anterior vertebral body ($p$-value $= 0.024$).

Based on the results, representative three-dimensional CT (3D-CT) images of the normal development of the sacrum with Risser's sign [6] are presented in Fig. 7. In 6–9-year-old males, there was almost no fusion in any intervertebral space (Fig. 7a). At 10–12 years of age, men had no fusion in any intervertebral space with Risser 0 or 1. In contrast, in women, fusion could be observed in many patients in the lower intervertebral spaces with Risser 2(Fig. 7b-d). In 13–15-year-old females, fusion was observed in the lateral masses of each vertebral intervertebral space with Risser 3 (Fig. 7e), and at 16–18 years of age, fusion was seen in the lateral masses of all vertebral intervertebral spaces in most patients with Risser 4 (Fig. 7f). At approximately 25 years of age, most patients of both sexes exhibited fusion at all intervertebral mass sites with Risser 5 (Fig. 7g, h).

## Discussion

To our knowledge, this is the first study to demonstrate the age-specific normative values of sacral development and fusion based on over 400 sacra using 3D-CT. The present study also shows representative 3D-CT images of the normal development of the sacrum with Risser's sign. Based on the fusion status of the sacrum, it is possible to predict Risser's sign to some extent.

Our study also shows the probability of bony fusion at each site for each age group. It is also shown that in the S1/S2, the most crucial level in clinical practice, bony fusion progresses gradually in the front of the vertebral body and is completed after the age of 25 years. In the lateral mass, bony fusion progresses rapidly after the age of 10 years and is completed around 15 years of age.

Some reports investigate the development of primary/secondary ossification centers using small cases of the sacrum (anterior and posterior epiphysis and endplate ring epiphysis) by CT or MRI. The studies reveal that epiphyses begin to fuse at around the age of 13 and 11 in males and females, respectively, with complete bony fusion at 16–25 years of age, asymmetry in the progression of fusion, and the risk of confusion with a fracture in

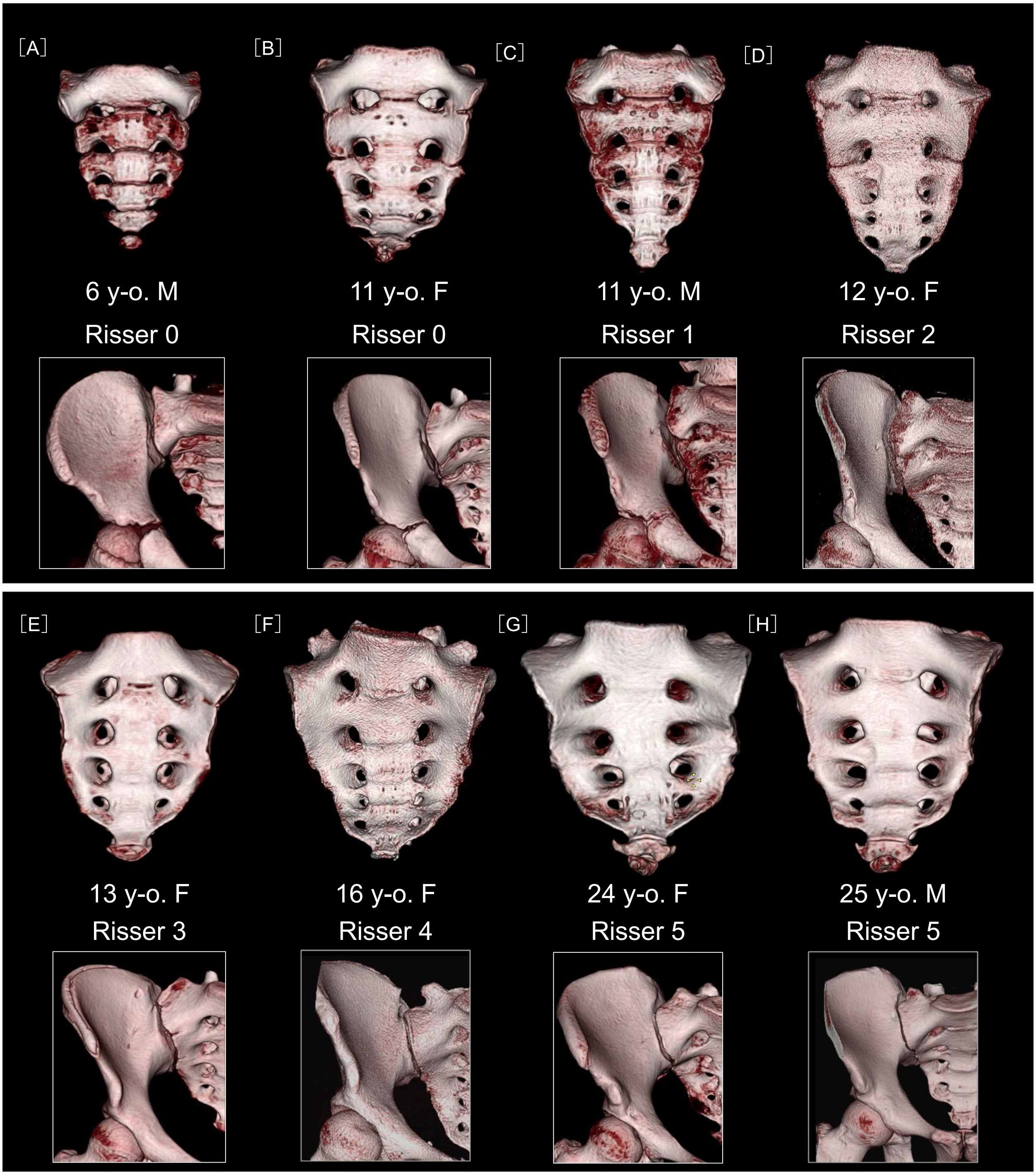


**Fig. 7** Three-dimensional computed tomography (3D-CT) images depicting normal sacral development with Risser's sign. At 6–9 years of age, almost no fusion was observed in any intervertebral space in males. By 10–12 years of age, essentially no fusion was observed in any intervertebral space in males; however, in females, fusion was observed in many cases in the lower intervertebral spaces. At 13–15 years of age, fusion was observed in the lateral masses of each vertebral intervertebral space in females, and at 16–18 years of age, fusion was observed in the lateral masses of all vertebral intervertebral spaces in most patients. At approximately 25 years of age, most patients of both sexes exhibited fusion at all sites of intervertebral masses

the state of partial fusion [1, 7–9]. Broome et al. showed a radiographic description of the postnatal development anatomy of the sacrum with minor cases of 37 CT images (X-ray: 63 cases, MRI: 10 cases). They demonstrated that the ages of fusion are 17–24 years at intervertebral disk spaces and 11–16 years at the costal process on the S1–S2 level; 11–22 years and 2–18 years on the S2–S3 level; 8–15 years and 5–18 years on the S3–4 level, respectively. Our present study investigating 402 sacra from the fusion period aligns with their results. Cardoso et al. reported the chronological data on primary and secondary ossification centers in dry bones using 191 cases. They showed the fusion sequence follows a caudal-cranial and anterior–posterior gradient in the primary centers of ossification [10].

Meijerman et al. investigated the association between sex, socioeconomic status, and ethnicity with bony fusion. They reported the effect of socioeconomic status on bony fusion of the medial clavicular epiphysis, with slower fusion in the absence of economic wealth [11]. An earlier bony fusion in the vertebral body in women has been reported in a previous report, which is consistent with the present study [4, 10]. Reports implicate estrogens and androgens in skeletal sexual dimorphism [4]. Females undergo the growth spurt during puberty approximately two years earlier than males, a difference that we consider reflected in the earlier completion of bony fusion. It has also been suggested that the importance of bipedal walking and weight transfer through the sacrum influences sacral fusion. Bony fusion does not occur in paraplegic patients because of the lack of load on this area [12, 13].

The following reports discuss the impact of insufficient bony fusion between S1/S2 and lower back pain. According to von Brandis et al., it is important not to mistake an unfused growth plate for a fracture line when interpreting sacral images [12]. Lumbarization is the complete or incomplete fusion of the upper sacral vertebrae with the L5 [13]. Previous studies have shown a connection between insufficient fusion in the transitional vertebrae and LBP. Vinha et al. found that patients with lumbosacral transitional vertebrae (LSTV) often experience LBP [14]. Nardo et al. also noted a positive correlation between type II and LBP [15].

This study found sex-specific differences in the bony fusion of S2/S3 and S4/S5 lateral masses. Sex-based differences in the sacroiliac joint (SIJ) begin at approximately 14 years of age, with males demonstrating significant differences from females [14]. In males, the center of gravity is more anterior to the SIJ, and the load on the SIJ is greater. Furthermore, S1/S2 and S2/S3 have significantly deeper curvature in men [15]. These morphological changes might affect bony fusion in their early teens. The involvement with racial variation in sacral kyphosis [16] should be the focus of future investigations.

Our results should be considered alongside several study limitations. A major limitation was that the samples were derived from a single ethnic group. Second, the sample size is a relatively small amount of data, especially for patients below the age of 10, resulting in a large CI for that age group. Third, the association between sacral development and Risser's sign is not well evaluated due to the small number of whole pelvic CT images.

## Conclusion

We have presented the age-specific normative values and predicted probability of sacral fusion based on over 400 sacra examinations. This study will help pediatricians, orthopedic surgeons, radiologists, and other physicians to better understand sacral development and differentiate the lesion around the sacral spine.

#### Abbreviations

| | |
|---|---|
| CI | Confidence intervals |
| CT | Computed tomography |
| ICC | Intraclass correlation coefficients |
| LBP | Low back pain |
| SIJ | Sacroiliac joint |

#### Acknowledgements

We would like to thank Daichi Watanabe and Takuma Ishihara, Ph.D. Centre for Advanced Medical Sciences and Clinical Research, Gifu University Hospital, for their advice on statistics.
This work was supported by Johnson & Johnson Medical Research Grant.

#### Authors' contributions

K.I. was responsible for data collection, literature extraction, manuscript description, and data interpretation. S.N. helped with research design, acquired data, and helped write manuscript. K.Y. and C.I. contributed to clinical aspects of research design and data interpretation. D.W. and T.I. interpreted data and helped write the manuscript. H.A. was responsible for final approval of the manuscript. All authors have read and approved the final submitted manuscript.

#### Funding

This work was supported by Johnson & Johnson Medical Research Grant.

#### Data availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

### Declarations

#### Ethics approval and consent to participate

The Gifu University Graduate School of Medicine Institutional Review Board has accepted this retrospective study under study number #2022–175. Informed consent was obtained using an opt-out method disclosed on the Gifu University website. For any participants under the age of 16, the consent was obtained using same method from the parents or legal guardians. The research was conducted following the tenets of the Declaration of Helsinki and its later amendments.

#### Consent for publication

Not applicable.

#### Competing interests

The authors declare no competing interests.

Received: 7 June 2024 Accepted: 28 March 2025
Published online: 10 April 2025

**References**

1. Grissom LE, Harty MP, Guo GW, Kecskemethy HH. Maturation of pelvic ossification centers on computed tomography in normal children. Pediatr Radiol. 2018;48(13):1902–14.
2. Jaremko JL, Siminoski K, Firth GB, Matzinger MA, Shenouda N, Konji VN, Roth J, Sbrocchi AM, Reed MH, O'Brien MK, et al. Common normal variants of pediatric vertebral development that mimic fractures: a pictorial review from a national longitudinal bone health study. Pediatr Radiol. 2015;45(4):593–605.
3. Grant's Atlas of Anatomy, 16e. Agur AMR, Dalley AFI. agur. Lippincott Williams & Wilkins, a Wolters Kluwer business. 2025. https://premiumbasicsciences.lwwhealthlibrary.com/book.aspx?bookid=3319&sectionid=0. Accessed 04 Apr 2025.
4. Rios L, Weisensee K, Rissech C: Sacral fusion as an aid in age estimation. Forensic Sci Int 2008, 180(2–3):111 e111–117.
5. Mahon TJ, Friedling LJ, Gordon GM: The use of ventral fusion between sacral elements S1 and S2 as an additional age-at-death indicator in a black South African skeletal sample. Forensic Sci Int 2018, 286:267 e261–267 e266.
6. Risser JC. The Iliac apophysis; an invaluable sign in the management of scoliosis. Clin Orthop. 1958;11:111–9.
7. Almeida M, Laurent MR, Dubois V, Claessens F, O'Brien CA, Bouillon R, Vanderschueren D, Manolagas SC. Estrogens and Androgens in Skeletal Physiology and Pathophysiology. Physiol Rev. 2017;97(1):135–87.
8. Broome DR, Hayman LA, Herrick RC, Braverman RM, Glass RB, Fahr LM. Postnatal maturation of the sacrum and coccyx: MR imaging, helical CT, and conventional radiography. AJR Am J Roentgenol. 1998;170(4):1061–6.
9. Zejden A, Jurik AG. Anatomy of the sacroiliac joints in children and adolescents by computed tomography. Pediatr Rheumatol Online J. 2017;15(1):82.
10. Cardoso HF, Pereira V, Rios L. Chronology of fusion of the primary and secondary ossification centers in the human sacrum and age estimation in child and adolescent skeletons. Am J Phys Anthropol. 2014;153(2):214–25.
11. Meijerman L, Maat GJ, Schulz R, Schmeling A. Variables affecting the probability of complete fusion of the medial clavicular epiphysis. Int J Legal Med. 2007;121(6):463–8.
12. Abitbol MM. Evolution of the sacrum in hominoids. Am J Phys Anthropol. 1987;74(1):65–81.
13. Esses SI, Botsford DJ, Huler RJ, Rauschning W: Surgical anatomy of the sacrum. A guide for rational screw fixation. Spine (Phila Pa 1976) 1991, 16(6 Suppl):S283–288.
14. Vleeming A, Schuenke MD, Masi AT, Carreiro JE, Danneels L, Willard FH. The sacroiliac joint: an overview of its anatomy, function and potential clinical implications. J Anat. 2012;221(6):537–67.
15. Plochocki JH. Sexual Dimorphism of Anterior Sacral Curvature. J Forensic Sci. 2011;56(1):161–4.
16. Krenn VA, Webb NM, Fornai C, Haeusler M. Sex classification using the human sacrum: Geometric morphometrics versus conventional approaches. PLoS ONE. 2022;17(4): e0264770.

## Publisher's Note