Three-dimensional evaluation of the coccyx movement between supine and standing positions using conventional and upright computed tomography imaging

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Currently, no three-dimensional reference data exist for the normal coccyx in the standing position on computed tomography (CT); however, this information could have utility for evaluating patients with coccydynia and pelvic floor dysfunction. Thus, we aimed to compare coccygeal parameters in the standing versus supine positions using upright and supine CT and evaluate the effects of sex, age, and body mass index (BMI) on coccygeal movement. Thirty-two healthy volunteers underwent both upright (standing position) and conventional (supine position) CT examinations. In the standing position, the coccyx became significantly longer and straighter, with the tip of the coccyx moving backward and downward (all \( p < 0.001 \)). Additionally, the coccygeal straight length (standing/supine, 37.8 ± 7.1/35.7 ± 7.0 mm) and sacrococcygeal straight length (standing/supine, 131.7 ± 11.2/125.0 ± 10.7 mm) were significantly longer in the standing position. The sacrococcygeal angle (standing/supine, 115.0 ± 10.6/105.0 ± 12.5°) was significantly larger, while the lumbosacral angle (standing/supine, 21.1 ± 5.9/25.0 ± 4.9°) was significantly smaller. The migration length of the tip of the coccyx (mean, 7.9 mm) exhibited a moderate correlation with BMI (\( r = 0.42, p = 0.0163 \)). Our results may provide important clues regarding the pathogenesis of coccydynia and pelvic floor dysfunction.

The coccyx comprises the terminal vertebral segments of the human vertebral column and provides weight-bearing support in the sitting position and positional support to the anus. Many ligaments and muscles are attached to the coccyx, supporting the pelvic floor and contributing to voluntary bowel control1. Previous studies have shown that assessments of coccygeal movement play an important part in evaluations of coccydynia2 and pelvic floor dysfunction3. Some authors4,5 have used plain radiography to demonstrate that individuals with greater ventral angulation of the coccyx are at a higher risk of developing idiopathic coccydynia. In addition, coccydynia has been reported to be aggravated by standing and/or walking6. Furthermore, it has been reported that the development of coccydynia is related to both obesity and vaginal delivery due to luxation and hypermobility7,8. However, in previous studies, the coccyx was assessed only by plain radiography in the standing and sitting positions2,7,8, computed tomography (CT)/magnetic resonance imaging (MRI) in the supine position9–16, or MRI in the sitting position17.

Since humans spend the majority of their time in the upright position, and the effects of gravity and intrapelvic pressure are reduced in the supine position, understanding the morphology, morphometry, and movement of the coccyx in the standing position likely has clinical utility. However, to the best of our knowledge, no reference data for the normal coccyx in the standing position on CT imaging exist at present. In addition, as far as we know, no clinical studies to date have compared coccygeal morphology in the supine versus standing positions. Recently,
position was calculated by $((x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2)^{1/2}$, where the coordinates of the tip of
with reference to the sacral vertebra, S1. The migration length of the tip of the coccyx in the standing to supine
and qualitative and quantitative parameters of the coccyx were assessed. Table 1 and Figs. 1 and 2 describe the
3D23.

CT. Image reconstruction was performed using Adaptive Iterative Dose Reduction
with 0.5 s of gantry rotation, a helical scan mode (80-row detector), a noise index of 15 for 5 mm, and a helical
CT. Body trunk scans were acquired in the standing and supine positions. Scanning was performed at 120 kVp,
in the standing position on the same day.

upright CT has been developed based on conventional 320-detector row CT to clarify the effects of gravity on
the human body18.

Thus, this study aimed to compare coccygeal parameters in the standing versus supine positions using upright
and supine CT imaging and to evaluate the effects of sex, age, and body mass index (BMI) on coccygeal move-
ment in healthy volunteers.

Methods
This prospective study was approved by the Keio University School of Medicine Ethics Committee (#20160384),
and written informed consent was obtained from all participants. All methods were performed in accordance
with the relevant guidelines and regulations. Asymptomatic male and female volunteers were recruited from a
volunteer recruitment company. To evaluate normal whole-body anatomy, volunteers were excluded if they had a
history of smoking, diabetes, hypertension, dyslipidemia, an awareness of dysuria, vertebral pain, diseases of the
vertebral column, or its developmental defects, as well as those who had undergone surgeries or were currently
undergoing treatment. A total of 32 healthy volunteers (16 men and 16 women; with four men and four women
in the third, fourth, fifth, and sixth decades of life, mean age 48.4 ± 11.5 years [range, 30–68 years]) participated
in this study conducted between April 2018 and October 2018. Among the 16 women, nine had given birth (all
vaginal deliveries) and seven had not. The 32 enrolled volunteers had been analyzed for different purposes in
previous studies that evaluated the vena cava, aorta, and pelvic  floor19 as well as the brain20 and lung volume21,22
but did not evaluate movement of the coccyx. All volunteers prospectively underwent conventional 320-detec-
tor row CT imaging (supine CT) (Aquilion ONE, Canon Medical Systems Corporation, Japan) in the supine
position, as well as upright CT imaging (prototype TSX-401R, Canon Medical Systems Corporation, Japan)18–22
in the standing position on the same day.

To maintain urinary bladder tension, volunteers were instructed to refrain from urinating before undergoing
CT. Body trunk scans were acquired in the standing and supine positions. Scanning was performed at 120 kVp,
with 0.5 s of gantry rotation, a helical scan mode (80-row detector), a noise index of 15 for 5 mm, and a helical
pitch of 0.8 for abdominal CT. Image reconstruction was performed using Adaptive Iterative Dose Reduction
3D33.

CT images were processed and analyzed by the SYNAPSE VINCENT image analysis system (Fujifilm Inc.),
and qualitative and quantitative parameters of the coccyx were assessed. Table 1 and Figs. 1 and 2 describe the
coccygeal parameters documented in this study11,12. The two types of CT images underwent rigid registration
with reference to the sacral vertebra, S1. The migration length of the tip of the coccyx in the standing to supine
position was calculated by $((x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2)^{1/2}$, where the coordinates of the tip of
the coccyx in the standing position were $x_1$, $y_1$, and $z_1$, and the coordinates of the tip of the coccyx in the supine
position were $x_2$, $y_2$, and $z_2$. Measurements were repeated in the first 16 of the 32 subjects after an interval of
one month to assess intra-observer repeatability; measurements were also repeated by another independent
observer to determine inter-observer reproducibility.

Data are presented as mean ± standard deviation (SD). Data were tested for normality using the Shapiro-
Wilk test. Mean differences between the standing and supine positions were compared using paired $t$-tests.
Comparisons between men and women, as well as between women who had or had not experienced childbirth,
were performed using the Mann–Whitney U test. Correlations between migration length and age, BMI, height,
and body weight were assessed using Pearson’s correlation analyses. The strength of the correlations was defined
as follows according to the Cohen classification24: weak, $0.10 \leq |r| < 0.30$; moderate, $0.30 \leq |r| < 0.50$; and strong,
$0.50 \leq |r| \leq 1.0$. Assessment of the reliability of measurements was performed by calculation of inter- and intraclass
correlation coefficients. Inter- and intra-observer agreements were evaluated by measuring intraclass correlation
coefficients (ICCs). The significance level for all tests was 5% (two-sided), and all data were analyzed using a
commercially available software program (JMP version 15; SAS Institute Inc., Cary, NC, USA).

| Parameter                          | Definition/description                                                                 |
|------------------------------------|----------------------------------------------------------------------------------------|
| Coccygeal straight length11,12     | Measured in a straight line from the middle of the upper border of Co1 to the coccygeal tip (Fig. 1a) |
| Sacral straight length11,12        | Measured in a straight line from the middle of the upper border of S1 to the middle of the inferior border of S5 (Fig. 1a) |
| Sacrococcygeal straight length11,23| Measured from S1 to the tip of the coccyx using the same methods as applied to the coccyx (Fig. 1a) |
| Lumbosacral angle11                | Measured using parallel lines, one to the superior surface of the first sacral segment and a second to the horizontal plane (Fig. 1b) |
| Sacrococcygeal angle11             | Formed by the intersection of a line between the midpoint of the upper borders of S1 and Co1 and a line between the latter and the tip of the coccyx (Fig. 1b) |
| Sacrococcygeal joint angle11       | Formed between lines intersecting the middle of S5 and Co1 (Fig. 1c)                   |
| Intercoccygeal angle11             | Formed between lines intersecting the middle of the first and last coccygeal segments in the median plane (Fig. 1c) |
| Migration length                   | Migration length of the tip of the coccyx between the supine and standing positions when both images were matched for S1 as a standard point |

Table 1. Definitions/descriptions of parameters of the morphology and morphometry of the coccyx.
Figure 1. Coccygeal parameters. (a) Straight lengths. Green, coccygeal straight length; red, sacral straight length; blue, sacrococcygeal straight length. (b) Angles of the sacrum. Red, lumbosacral angle; blue, sacrococcygeal angle. (c) Angles of the coccyx. Green, sacrococcygeal joint angle; orange, intercoccygeal angle.

Figure 2. Computed tomography imaging of the coccyx in healthy volunteers. The coccyx of a 36-year-old man in the standing position (A) and the supine position (B), and the coccyx of a 47-year-old parous woman in the standing position (C) and supine position (D) in the mid-sagittal plane. As demonstrated, the coccyx becomes longer and straighter, with the tip of the coccyx (white arrow) moving backward and downward relative to the supine position.
Results

Characteristics of the volunteers are presented in Table 2.

The mean straight lengths of the coccyx, sacrum, and sacrococcygeal segment; the mean coccygeal, sacral, and sacrococcygeal curvatures; and the mean differences between the standing and supine positions are shown in Table 3. The coccygeal straight length (mean difference 2.1 mm, [95% confidence interval (CI), 1.2–2.9], \( p < 0.0001 \)) and the sacrococcygeal straight length (mean difference 6.7 mm, [95% CI, 5.4–8.1], \( p < 0.0001 \)) were significantly longer in the standing position than in the supine position. The sacrococcygeal angle (mean difference 10.0°, [95% CI, 7.9–12.1], \( p < 0.0001 \)) and the intercoccygeal angle (mean difference 9.0°, [95% CI, 4.3–13.7], \( p = 0.0005 \)) were significantly larger in the standing position than in the supine position. The lumbosacral angle (mean difference − 4.0°, [95% CI, − 4.9 to − 3.0], \( p < 0.0001 \)) was significantly smaller in the standing position than

Table 2. Characteristics of the study population. BMI body mass index, SD standard deviation.

| Variables              | Overall (n = 32) | Men (n = 16) | Women (n = 16) |
|------------------------|-----------------|--------------|----------------|
| Mean ± SD (range)      | Mean ± SD (range) | Mean ± SD (range) |
| Age, years             | 48.4 ± 11.5 (30–68) | 48.4 ± 12.9 (30–68) | 48.4 ± 10.2 (33–63) |
| BMI, kg/m²              | 22.5 ± 3.0 (16.7–30.6) | 23.3 ± 3.4 (18.9–30.6) | 21.7 ± 2.4 (16.7–25.7) |
| Height, cm              | 163.3 ± 7.7 (147.7–177.0) | 168.1 ± 6.3 (155.2–177.0) | 158.6 ± 6.0 (147.7–170.7) |
| Weight, kg              | 60.3 ± 10.8 (41.6–88.0) | 65.9 ± 10.8 (47.6–88.0) | 54.3 ± 7.5 (41.6–66.2) |

Table 3. Summary statistics for parameters in the standing and supine positions.
in the supine position. There were no significant differences in the sacral straight length or the sacrococcygeal joint angle. The mean migration lengths of the tip of the coccyx were 0.15 mm (95% CI, −0.82–1.13) to the left in the x-axis, 4.3 mm (95% CI, 3.12–5.53) backward in the y-axis, and 5.2 mm (95% CI, 4.15–6.29) downward in the z-axis in the standing position. The mean migration length of the tip of the coccyx was 7.9 mm (95% CI, 6.7–9.1), and all coccyges migrated backward and downward. The migration length exhibited a moderate correlation with increased body weight (r = 0.48, p = 0.0054) and increased BMI (r = 0.42, p = 0.0163) (Fig. 3). There was no significant difference in migration length between men and women (p = 0.486), and migration length was correlated with neither height (r = 0.31, p = 0.0873) nor age (r = −0.06, p = 0.756).

Differences in any coccygeal parameter between the standing and supine positions did not differ significantly between men and women. Analyses for parous and nulliparous women are described in the supplementary Table.

Inter- and intra-observer correlation coefficients were between 0.82 and 0.94 and between 0.91 and 0.97, respectively, for all quantitative measurements.

Discussion
In this prospective study, we demonstrated that the coccyx became longer and straighter in the standing position, with the tip of the coccyx moving backward and downward in this position. Coccydynia has previously been reported to be associated with obesity and vaginal delivery and to be aggravated by standing and/or walking. In our study, there were positive correlations between BMI, body weight, and the mobility of the coccyx. We believe our findings are important because, although we included only asymptomatic volunteers, the coccyx was shown to move in a similar manner to what can lead to coccydynia; therefore, our results may provide potentially important clues regarding the pathogenesis of coccydynia. Additionally, our study identified normal reference values for coccygeal measurements in the standing position using upright CT imaging.

Our study showed no significant differences in coccygeal parameters between men and women. In contrast, Karadimas et al. reported that coccydynia development is approximately four times more likely in women than in men. In addition, other studies have demonstrated that the coccyx is significantly longer in male individuals while being more ventrally angulated in female individuals. These findings may seem contradictory; however, this discrepancy may have resulted from the small number of volunteers in our study (only 16 male volunteers and 16 female volunteers). Therefore, these differences may not have been determined to statistically significant. Further research should be conducted to compare coccygeal parameters between men and women. Our study also showed that women with a history of vaginal deliveries tended to have a longer coccygeal migration length. However, the study design was too small to analyze the differences between parous and nulliparous women.

Some authors have investigated coccygeal movement using open dynamic MRI or plain radiography. During dynamic MRI, images can be obtained when patients are either contracting or squeezing the pelvic muscles or when these muscles are relaxed. MRI can effectively evaluate pelvic floor morphology; however, dynamic MRI generally requires 15–30 min, whereas upright CT takes less than 3 min for two scout scans and one main scan. In addition, dynamic MRI uses unnatural abdominal pressure during scanning, while upright CT imaging permits scanning in a natural position, as gravity is automatically applied in the vertical direction. In contrast, plain radiography can be performed more easily than CT imaging with less radiation exposure; however, evaluable parameters are restricted using this imaging modality.

This study had several limitations. First, our sample size was small and restricted to only a single Japanese center. Previous studies have suggested that racial differences do exist in the morphology and morphometry of the coccyx. Thus, further studies including more ethic groups and larger patient populations are necessary. Second, our study focused solely on the standing and supine positions. However, since a previous study has...
shown that individuals with coccydynia show transient exacerbation of pain when standing up from a sitting position, assessment in the sitting position is also important. Finally, although the observers independently evaluated images in a blinded and randomized manner, they may have recognized the positioning of subjects in some cases due to the presence or absence of a CT table. The inter- and intra-observer agreements (ICCs), however, were relatively high in this study.

Conclusions
Our study demonstrated that the coccyx becomes longer and straighter in the standing position, with the tip of the coccyx moving backward and downward relative to the supine position. Furthermore, the migration length exhibited a moderate correlation with increased BMI and body weight.

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

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References
1. Lirette, L. S., Chaiban, G., Tolba, R. & Eissa, H. Coccydynia: an overview of the anatomy, etiology, and treatment of coccyx pain. *Ochsner J.* 14, 84–87 (2014).
2. Maigne, J. Y. & Tamalet, B. Standardized radiologic protocol for the study of common coccygodynia and characteristics of the lesions observed in the sitting position. Clinical elements differentiating luxation, hypermobility, and normal mobility. *Spine (Phila Pa 1976)* 21, 2588–2593 (1996).
3. Fujisaki, A., Shigeta, M., Shimoinaba, M. & Yoshimura, Y. Influence of adequate pelvic floor muscle contraction on the movement of the coccyx during pelvic floor muscle training. *J. Phys. Ther. Sci.* 30, 544–548 (2018).
4. Kim, N. H. & Suk, K. S. Clinical and radiological differences between traumatic and idiopathic coccygodynia. *Yonsei Med. J.* 40, 215–220 (1999).
5. Postacchini, F. & Massobrio, M. Idiopathic coccygodynia. Analysis of fifty-one operative cases and a radiographic study of the normal coccyx. *J. Bone Jt. Surg. Am.* 65, 1116–1124 (1983).
6. Karadimas, E. I., Trypisannis, G. & Giannoudis, P. V. Surgical treatment of coccygodynia: An analytic review of the literature. *Eur. Spine J.* 20, 698–705 (2011).
7. Maigne, J. Y., Doursounian, L. & Chatellier, G. Causes and mechanisms of common coccydynia: role of body mass index and coccygeal trauma. *Spine (Phila Pa 1976)* 25, 3072–3079 (2000).
8. Maigne, J. Y., Rusakiewicz, F. & Diouf, M. Postpartum coccydynia: A case series study of 57 women. *Eur. J. Phys. Rehabil. Med.* 48, 387–392 (2012).
9. Kerimoglu, U., Dagoglu, M. G. & Ergen, F. B. Intercoccygeal angle and type of coccyx in asymptomatic patients. *Surg. Radiol. Anat.* 29, 683–687 (2007).
10. Przybylski, P. et al. Evaluation of coccygeal bone variability, intercoccygeal and lumbo-sacral angles in asymptomatic patients in multislice computed tomography. *Anat. Sci. Int.* 88, 204–211 (2013).
11. Marwan, Y. A. et al. Computed tomography-based morphologic and morphometric features of the coccyx among Arab adults. *Spine (Phila Pa 1976)* 39, E1210–1219 (2014).
12. Woon, J. T. K., Perumal, V., Maigne, J. Y. & Stringer, M. D. CT morphology and morphometry of the normal adult coccyx. *Eur. Spine J.* 22, 863–870 (2013).
13. Yoon, M. G., Moon, M. S., Park, B. K., Lee, H. & Kim, D. H. Analysis of sacrococcygeal morphology in Koreans using computed tomography. *Clin. Orthop. Surg.* 8, 412–419 (2016).
14. Tetikler, H. et al. MRI-based detailed evaluation of the anatomy of the human coccyx among Turkish adults. *Niger. J. Clin. Pract.* 20, 136–142 (2017).
15. Zhan, M. J. et al. Estimation of stature and sex from sacrum and coccyx measurements by multidetector computed tomography in Chinese. *Leg. Med. (Tokyo)*. 34, 21–26 (2018).
16. Hekimoglu, A. & Ergun, O. Morphological evaluation of the coccyx with multidetector computed tomography. *Surg. Radiol. Anat.* 41, 1519–1524 (2019).
17. Bo, K., Lilleås, F., Talseth, T. & Hedland, H. Dynamic MRI of the pelvic floor muscles in an upright sitting position. *Neuromol. Urodyn.* 20, 167–174 (2001).
18. Inzaki, M. et al. Development of upright computed tomography with area detector for whole-body scans: Phantom study, efficacy on workflow, effect of gravity on human body, and potential clinical impact. *Invest. Radiol.* 55, 73–83 (2020).
19. Narita, K. et al. Pelvic floor morphology in the standing position using upright computed tomography: Age and sex differences. *Int. Urogynecol. J.* 31, 2387–2393 (2020).
20. Yokoyama, Y. et al. Effect of gravity on brain structure as indicated on upright computed tomography. *Sci. Rep.* 11, 392 (2021).
21. Yamada, Y. et al. Differences in lung and lobe volumes between supine and standing positions scanned with conventional and newly developed 320-detector-row upright CT: Intra-individual comparison. *Respiration* 99, 598–605 (2020).
22. Yamada, Y. et al. Comparison of inspiratory and expiratory lung and lobe volumes among supine, standing, and sitting positions using conventional and upright CT. *Sci. Rep.* 10, 16203 (2020).
23. Yamada, Y. et al. Dose reduction in chest CT: Comparison of the adaptive iterative dose reduction 3D, adaptive iterative dose reduction, and filtered back projection reconstruction techniques. *Eur. J. Radiol.* 81, 4185–4195 (2012).
24. Cohen, L. H. Measurement of life events in *Life events and psychological functioning: Theoretical and methodological issues.* (ed. Cohen, L. H.) 11–30 (SAGE Publications, 1988).
25. Grassi, R. et al. Coccygeal movement: assessment with dynamic MRI. *Eur. J. Radiol.* 61, 473–479 (2007).

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Author contributions
F.Y. participated in data analysis and wrote the manuscript. Y.Y. wrote the manuscript and participated in protocol development, data collection and interpretation, and editing of the manuscript. M.Y. participated in protocol development, data collection and interpretation, and editing of the manuscript. Y.Y. participated in data collection, analysis, and interpretation and editing of the manuscript. K.N., K.M., and T.N. participated in data collection and editing of the manuscript. M.J. developed the project and helped write and edit the manuscript. All authors approved the final version to be published and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Competing interests
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Additional information
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