Analysis of Measurement Changes in the Pelvic Incidence According to Pelvic Rotation using a 3-dimensional Model

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Abstract

Background: Pelvic incidence (PI) is used as a key parameter in surgical correction of adult spinal deformity (ASD) patients. However, there is a limitation to reflecting the exact center or inclination of 3-dimentional anatomical structures in a 2-dimensional (2D) sagittal radiographs, and these can lead to the measurement errors. Therefore, we evaluated whether there is a change in PI measurement according to the actual rotation of the pelvis, and conducted a study on a more accurate method of measuring PI in a 2D sagittal radiograph.

Methods: From 2014 to 2015, 30 patients who visited our outpatient clinic were analyzed retrospectively. CT scan images including the lower lumbar spine, pelvis, and both femurs in DICOM format were imported to Mimics Research 17.0 (Materialise NV, Belgium), Solidworks (Dassault systems, France), and AutoCAD 2014 (AUTODESK, US), and the changes in PI according to vertical and horizontal pelvic rotations were evaluated.

Results: The average PI according to the horizontal pelvic rotations measured on AutoCAD with 0º, 5º, 10º, 15º, 20º, 25º, 30º, 35º, and 40º was 48.8º, 48.7º, 48.3º, 47.8º, 46.9º, 45.6º, 44.0º, 42.2º, and 39.9º, respectively. The PI of an acceptable error of 6º on radiographs was 35º in the horizontal pelvic rotation. The average PI according to the vertical pelvic rotations measured on AutoCAD with 0º, 5º, 10º, 15º, 20º, 25º, 30º, 35º, and 40º was 48.8º, 49.0º, 49.5º, 50.2º, 51.3º, 52.7º, 54.4º, 56.6º, and 59.4º, respectively. The PI of an acceptable error of 6º on radiographs was 30º in the vertical pelvic rotation.

Conclusions: This study revealed that the PI value could differ from the actual anatomical value due to the horizontal and vertical rotation of the pelvis while acquiring the radiograph. In whole-spine lateral radiographs, errors in PI measurement may occur due to rotation of the pelvis or nonvertical projection of X-rays. In the standing pelvic lateral radiographs, placing the overlapping femoral heads at the center and obtaining the straight sacral endplate as much as possible by referring to CT or magnetic resonance imaging would be a more accurate measurement method to define the PI.

Background

Optimal sagittal balance is an important factor in maintaining a stable posture with minimum energy, absorbing the load on the spine effectively, and maximizing the efficiency of the paraspinal muscles [1]. The sagittal balance of the spine is influenced by the spinal curvature, including thoracic kyphosis (TK) and lumbar lordosis (LL), and the position and angle of the spine, pelvis, hip joint, and knee joint. Notably, as the key component of the overall sagittal balance is the compensation cascade in the pelvis, an understanding of the relationship between the pelvis and the spine is essential [1]. The importance of restoring the optimal sagittal balance of adult spinal deformity (ASD) patients has been also well recognized [2–4]. In the surgical treatment of ASD patients, the restoration of the optimal sagittal balance requires preoperative radiological measurement of the sagittal curvature and dynamic factors such as the correlation between the pelvis and the hip joint [1].

The spine and the pelvis are closely related and show a chain of correlation with each other [5]. The pelvis is the foundation of the spine. The importance of evaluating the spinopelvic balance based on pelvic morphology has been highlighted in previous studies [6]. In ASD surgery, the assessment of the pelvic parameters that define the sagittal pelvic alignment can be broadly divided into two categories: an anatomic parameter, the pelvic incidence (PI), and two positional parameters, the pelvic tilt (PT) and the sacral slope (SS). PT is defined as the angle between the vertical reference line and the line connecting the midpoint of the coxofemoral joint axis and the center of the S1 endplate, and SS is the angle between the horizontal reference line and the line parallel to the S1 endplate [7]. In other words, they are the parameters determined by the vertical or horizontal reference line associated with the position or orientation of the pelvis. The PI was first described by Duval-Baupère et al. [7], and it is the most commonly used anatomical parameter of the pelvis. The PI is defined as the angle between the perpendicular line from the sacral plate and the line connecting the midpoint of the sacral plate to the midpoint of the bicoxofemoral axis [7]. Legaye et al. [8] stated that the PI is the fundamental pelvic parameter for 3-dimensional (3D) regulation of sagittal spinal curves, and as it is a stably maintained anatomical parameter even in an arbitrary position and orientation [9], it serves as the key parameter in the surgical treatment of ASD patients [10].

Nevertheless, the pelvic parameters measured in most previous studies have been assessed in 2-dimensional (2D) sagittal radiographs in the standing position [8], thus limiting the reflection of the accurate center or inclination in 3D anatomical structures [11]. In particular, due to the rotation of the pelvis or nonvertical projection of the X-ray in whole-spine lateral radiographs, it is difficult to obtain the superposition of two femoral heads in practice [12], which could lead to errors in PI measurements as they are taken based on the midpoint on the line connecting the centers of the femoral heads as the reference point of the hip axis [12]. The accuracy of radiologic measurements such as the spinopelvic parameters, especially the PI, is crucial in the preoperative or postoperative evaluation of patients with ASD. Therefore, in this study, the CT scan images in DICOM format of the pelvic CT for the treatment and diagnosis of ASD patients were analyzed using Mimics Research 17.0 for ×64 (Materialise NV, Belgium), Solidworks (Dassault Systems, France), and AutoCAD 2014 (AUTODESK, US), with two objectives: evaluation of the PI changes according to the actual pelvic rotation and determination of the more accurate method of measuring PI in 2D sagittal radiographs.

Methods

Patient Selection

The subjects in this study were 84 patients who visited the outpatient clinic at the present hospital between February 2014 and March 2015 for surgical or nonsurgical treatment.

The inclusion criteria were as follows: (i) patients aged ≥ 20 years, (ii) patients with radiographs and 3D CT scan images of the spine and pelvis for diagnosis and treatment. And the exclusion criteria were as follows: patients with a deformity resulting from coxofemoral pathology, neuromuscular deformity, spinal infection, inflammatory disease such as ankylosing spondylitis, and tumorous condition.

Radiographic Measurements

Sagittal alignment was evaluated by lateral 14 × 36-inch full spine X-rays, for which the patients stood in an unsupported neutral position with their arms in the clavicle position [13]. All digital radiographs were measured using a picture archiving communication system (PACS) (Infinitt, Seoul, Korea), a software developed to accurately calculate parameters by magnifying anatomic landmarks of the spine and pelvis on lateral views. On radiography, we evaluated the PI, SS, PT, TK, LL, and sagittal vertical axis (SVA).

Sagittal Vertical Axis

The SVA was defined as the horizontal distance between the posterosuperior corner of the sacrum and the C7 plumb line.

Pelvic Parameters

The PI was measured using a standing lateral radiograph of the pelvis. The angle was defined as that between a line perpendicular to the sacral plate and a line connecting the midpoint of the sacral plate to the bicoxofemoral axis. SS corresponds to the angle between the horizontal reference line and the line parallel to the S1 endplate. PT corresponds to the angle between the vertical reference line and the line connecting the midpoint of the coxofemoral joint axis and the center of the S1 endplate [14].

Sagittal Cobb Angles

The Cobb angle is defined as the greatest angle at a particular region of the vertebral column when measured from the superior endplate of the superior vertebra to the inferior endplate of the inferior vertebra [15]. The sagittal Cobb angle is measured in the sagittal plane, such as on lateral radiographs. Sagittal Cobb angles were measured for TK (T5–12) and LL (T12–S1) [16, 17].

Pelvic Incidence Evaluation according to Pelvic Rotation (Fig. 1)

We imported CT scans including the lower lumbar spine, pelvis, and both femurs in DICOM format to Mimics Research 17.0 for ×64 (Materialise NV, Belgium). We performed and modified 3D reconstruction images using the 3-Matic program. First, the program was used to segment the left and right femoral heads into halves based on the coronal, sagittal, and axial planes (Fig. 2). After segmentation along the coronal and sagittal planes on the axial plane of the S1 endplate, the left sacrum and lower lumbar areas were deleted (Fig. 3). The resulting 3D reconstruction model was applied in SolidWorks (Dassault Systems, France) software to produce 3D CAD drawings and measure the distances. First, the 3-point method was used in circle drawings along the segmented left and right femoral heads (Fig. 4-A and B), and a 3D sketch was drawn for the line connecting the center points of the circles (Fig. 4-C). Next, a line was drawn along the segmented endplate of the sacrum on the sagittal plane, and the vertical line was drawn at the center point of the line (Fig. 4-D). The center point of the line connecting the center of the S1 endplate and the center of the femoral head was defined using a 3D sketch (Figure 5-A). The planes were tilted to 5° angular intervals (the horizontal and vertical rotation of the pelvis: 0º, 5º, 10º, 15º, 20º, 25º, 30º, 35º, and 40º) for the sagittal plane based on the vertical and horizontal reference lines (Fig. 5-B and C). These planes in the interval of 5° angles were used to adjust the view in Solidworks' vertical and horizontal directions. Each captured screen was imported to AutoCAD 2014 (AUTODESK, US) to measure the angle of the PI (Fig. 6).

Statistical Analysis

All statistical analyses were performed using the SPSS software (version 20.0, SPSS Inc., Chicago, IL, USA). To evaluate the interobserver reliability for the measurement, analyses and measurements of the 3D models were made by two engineers specializing in spinopelvic imaging trained by orthopedic and radiologic professors at our clinics. The intraclass correlation coefficients (ICCs, 2-way mixed model for consistency) were calculated to evaluate the consistency between observers and between measurements of a single observer, and the reliability was measured on a scale of 0 to 1, with >0.75 considered as excellent, 0.40 to 0.75 as fair to good, and <0.40 as poor [18].

Results

Baseline Characteristics of the Patients (Tables 1 and 2)

Table 1
Demographics and Baseline Data (30 cases) †

Variable	Mean ± SD or number
Gender	
Male	11
Female	19
Age (years)	50.1±0.8
Degenerative spondylosis	11
Spinal stenosis	8
Degenerative disc disease	6
Compression fracture	5
† Data are presented as mean ± standard deviation or number.	

Table 2
Baseline Radiologic Parameters (30 cases) †

Parameter	Mean ± SD or number
PI (°)	48.8±10.0
SS (°)	37.1±8.5
PT (°)	11.8±7.7
C7SVA (mm)	43±46.6
TK (°)	27±11.5
TL (°)	11.3±11.1
LL (°)	-37.5±19.9
LS (°)	-27.5±14.2
SA (°)	61.6±9.7
AT (°)	24.5±7.7
FHD (mm)	176.5±9
PR (mm)	101±9.2

† Data are presented as mean ± standard deviation.

PI, pelvic incidence; SS, sacral slope; PT, pelvic tilt; C7SVA, C7 plumb line sagittal vertical axis; TK, thoracic kyphosis; TL, thoracolumbar junctional angle; LL, lumbar lordosis; LS, lumbosacral junctional angle; SA, sacro-acetabular angle; AT, acetabular tilt; FHD. Femur head distance; PR, pelvic radius.

At the time of the study, the database included 84 patients. After applying the inclusion criteria, 30 patients were identified for analysis. The patients included 11 men and 19 women. The mean age was 50.1 years. The mean PI, SS, and PT were 48.8 ± 10.0°, 37.1 ± 8.5°, and 11.8 ± 7.7°, respectively. The mean SVA was 43 ± 46.6 mm, while the TK and LL were 27 ± 11.5° and -37.5 ± 19.9°, respectively. Eleven patients were diagnosed with degenerative spondylolisthesis, 8 patients had spinal stenosis, 6 patients had degenerative disc disease, and 5 patients had a compression fracture.

Pelvic Incidence according to Horizontal Pelvic Rotation (Table 3)

Table 3
Effect of horizontal pelvis rotation on PI †

Horizontal rotation	0º	5º	10º	15º	20º	25º	30º	35º	40º
Pelvic incidence	48.8	48.7	48.3	47.8	46.9	45.6	44.0	42.2	39.9
Change (%)		-0.31	-1.01	-2.18	-4.05	-6.56	-9.82	-13.62	-18.20
† Data are presented as mean values.									

The average PI according to the horizontal pelvic rotation measured on AutoCAD with 0º, 5º, 10º, 15º, 20º, 25º, 30º, 35º, and 40º were 48.8º, 48.7º, 48.3º, 47.8º, 46.9º, 45.6º, 44.0º, 42.2º, and 39.9º. Based on the 3D model with 0º horizontal rotation, the percent (%) change of each angle was -0.31, -1.01, -2.18, -4.05, -6.56, -9.82, -13.62, and -18.20. In a study by Lazennec et al. [19], which was conducted on 81 patients, a mean of 6º variability was reported for satisfactory reproducibility for repeated angle measurements, which is suggested as an acceptable error in numerous studies involving radiological measurements [12]. In our study, the PI of an acceptable error of 6º on radiographs [12, 19] was 35º in the horizontal pelvic rotation.

The ICCs of PI measurements according to the horizontal pelvic rotation were classified as excellent, with an intraobserver ICC of 0.97 and with an interobserver ICC of 0.94.

Pelvic Incidence according to Vertical Pelvic Rotation (Table 4)

Table 4
Effect of vertical pelvis rotation on PI †

Vertical rotation	0º	5º	10º	15º	20º	25º	30º	35º	40º
Pelvic incidence	48.8	49.0	49.5	50.2	51.3	52.7	54.4	56.6	59.4
Change (%)		+0.38	+1.28	+2.73	+5.02	+7.88	+11.45	+15.98	+21.55
† Data are presented as mean values.									

The average PI according to the vertical pelvic rotation measured on AutoCAD with 0º, 5º, 10º, 15º, 20º, 25º, 30º, 35º, and 40º was 48.8º, 49.0º, 49.5º, 50.2º, 51.3º, 52.7º, 54.4º, 56.6º, and 59.4º, respectively. Based on the 3D model with 0º vertical rotation, the percentage (%) change of each angle was +0.38, +1.28, +2.73, +5.02, +7.88, +11.34, +15.98, and +21.55. The PI of an acceptable error of 6º on radiographs [12, 19] was 30º in the vertical pelvic rotation.

The ICCs of PI measurements according to the vertical pelvic rotation were classified as excellent, with an intraobserver ICC of 0.95 and with an interobserver ICC of 0.96.

Discussion

There has been increasing recognition of the “chain of correlations” extending from the pelvic alignment to the spine [5], and the PI is a standard measurement for the surgical treatment of ASD patients. Various formulas related to the PI have been proposed for the surgical treatment of ASD [20, 21], and Schwab et al. [22] suggested a simplistic formula (LL=PI+9 [±9]) to estimate the mean lumbar lordosis from the mean PI. Accurate PI measurement is thus a prerequisite for spine surgeons in the treatment of patients with ASD.

Pelvic Incidence and Pelvic Rotation

The PI is generally measured as the angle between the perpendicular line from the sacral plate and the line connecting the midpoint of the sacral plate to the midpoint of the bicoxofemoral axis in 2D sagittal radiographs of standing whole-spine lateral radiographs [7]. However, an image of the 3D pelvis on 2D radiographs can be influenced by the pelvic position and orientation [12], for which there is a difficulty in precisely identifying the sacral endplate and the bicoxofemoral axis [23]. In addition, radiological measurements, including those of the PI, may be influenced by the surgeon’s knowledge and consequent experience of the anatomical landmarks [6].

In clinical practice, malposition or malorientation of the pelvis is commonly observed in standing whole-spine lateral radiographs because of factors such as the patient’s incorrect standing position, pelvic obliquity due to leg length discrepancy, and divergent X-ray beam, which could cause an error in the measurement of spinopelvic parameters [24, 25]. Thus, in 1998, Jackson et al. [24] highlighted the need for an accurate imaging technique for the pelvis to achieve more precise radiological measurements, including those of the PI, and subsequently proposed the geometrical rules to show that all of the radiographs presented 15° or less vertical pelvic rotation with simultaneous 20º or less tilt in the horizontal plane.

Tyrakowski et al. [12], using a single radiological phantom, defined 0º rotation as the complete overlapping of the femoral heads in the anteroposterior direction on lateral radiographs and produced radiographs through rotation at 5º intervals up to 45º along the vertical axis. As a result, the PI was shown to vary according to the pelvic position on the axial plane. The proper maximal angle of rotation of the pelvis for a reliable PI measurement on lateral radiographs was reported to be 30°. They also reported 2 years later in a study on PI measurements based on horizontal pelvic rotation that the PI may be influenced by the pelvic rotation on the coronal plane upon radiography and that a substantial error of PI measurements may occur upon 20º or more horizontal rotation [25]. In our study, similar results were obtained that the PI of an acceptable error of 6º on radiographs [12, 19] was 35º in the horizontal pelvic rotation and 30º in the vertical pelvic rotation.

This study agrees with the two previous studies by Tyrakowski et al. [12, 25] in that the changes in the PI according to the horizontal and vertical rotation of the pelvis were analyzed. However, the key difference lies in the PI measurement method. Through the conventional measurements based on simple radiological images, as in the studies by Tyrakowski et al. [12, 25], the measured values cannot be accurately reproduced by repeated measurements with a constant probability of both intra- and inter-rater errors. In this study, on the contrary, a higher reliability of result values could be achieved by using CT scans and conducting 3D measurements using a 3D model based on several specialized programs, including AutoCAD. Another notable difference from the studies by Tyrakowski et al. [12, 25], where a single radiological phantom was used, is that the measurements in this study were taken from 30 actual patients. Through such highly reliable data from analyzing actual patients, we revealed that the measurement of the PI could be influenced by the horizontal and vertical rotation (0º, 5º, 10º, 15º, 20º, 25º, 30º, 35º, and 40º, respectively) of the pelvis while acquiring the radiograph.

Optimal Pelvic Incidence Evaluation

For an ideal assessment of pelvic parameters, including the PI, it is crucial to acquire radiographs that allow precise identification of the sacral endplate in a straight line with two overlapping femoral heads [6]. Despite this, spinopelvic parameters are usually measured on 36-inch-long cassette lateral radiographs of the spine, and the projection of whole-spine radiographs is centered on the 12th vertebra [23]. Therefore, obtaining the perfect superposition of the two femoral heads and precisely identifying the sacral endplate are usually impossible using whole-spine radiographs. In particular, the sacral endplate could show an overlap of the lumbar spine and the pelvic bony structures on whole-spine radiographs. At the same time, the presence of a buttock or ilium shadow could interfere with the precise evaluation of the sacral endplate. The rotation of the pelvis could also deform the shape of the sacral endplate to an oval on the radiograph [25].

Vrtovec et al. [11] reported that, for PI measurements, 2D radiographic images showed approximately 5° overestimation compared to 3D CT images and that the manual measurements through 2D cross-section could not reflect the precise center and inclination of the 3D anatomical structure. In addition, Yamada et al. [26] analyzed the reliability of measuring spinopelvic parameters, including the PI, on standing whole-spine lateral radiographs and standing lateral pelvis radiographs, and reported that PI also tends to be larger approximately 5º due to a large projection angle to the sacral endplate in standing whole-spine lateral radiographs compared with standing lateral pelvic radiographs. Chen et al. [27] also reported that, as the vertical projection point is positioned higher than the spinopelvic area in the whole-spine radiograph, the femoral heads failed to form an alignment and the sacral endplate could not be sharply defined. However, in the pelvic radiograph, the vertical projection point of the radiograph tube falls in the spinopelvic area so that the femoral heads are aligned and an accurate identification of the sacral endplate is possible, and the optimized radiographic intensity in the pelvic area contributes to a more precise visualization of the femoral heads and the sacral endplate through increased signals in the pelvic area. Thus, compared to whole-spine radiographs, standing pelvis radiographs would be more effective in analyzing spinopelvic parameters, including the PI.

In treating ASD patients, the measurement of the spine Cobb’s angle using whole-spine radiographs should be performed, however, a greater emphasis is placed on standing lateral pelvic radiographs than whole-spine radiographs in evaluating spinopelvic parameters, including the PI. To minimize measurement errors according to the horizontal and vertical rotation of the pelvis, the following methods are suggested for PI measurements: In producing the standing pelvic lateral radiographs, the pelvis should first be adjusted horizontally by placing the feet above a block in the case of pelvic obliquity on the whole-spine radiographs. After checking the greater trochanter (GT) of the femur through palpation, the center points of the X-ray tube and cassette should be positioned approximately 3 cm above the GT at 150º to produce maximum overlapping of the two femoral heads so that they are positioned at the center of the produced images (true pelvis lateral radiograph, Fig. 7-A). And even in the case of complete overlap of the two femoral heads, the first sacral endplate boundary may be unclear. In such cases, the proximal and distal boundaries of the upper endplate should be precisely identified in reference to the sagittal cut on CT or MRI of the sacral endplate, and the drawings can be made on the standing pelvic lateral radiographs (Fig. 7-B). The subsequent PI measurement is anticipated to be more accurate based on the angle between the key line from the center of the sacral endplate and the line connecting the identified center of the sacral endplate and the center of the two femoral heads in maximum overlap (Fig. 7-C).

Limitations

This study has some limitations. First, as the study was conducted retrospectively, several confounding variables may exist. Second, the PI measurements were taken using only the 3D model of special mechanical programs, including AutoCAD, to prevent direct comparison with 2D radiographs. Nevertheless, more precise PI measurements using the 3D model are thought to differentiate this study from previous studies. A comparative analysis between 3D and 2D radiographs was conducted in a follow-up study. Third, with the recent advancement of novel imaging techniques, including EOS imaging (Biospace Med, France), far more accurate angle measurements have become possible. However, considering that most clinics have not yet acquired the EOS, the method based on true pelvic lateral radiographs suggested in this study is anticipated to serve as a useful guideline for spine surgeons planning surgical treatment for ASD. Fourth, the level of radiation exposure may increase owing to the additional radiological imaging to obtain standing pelvic lateral radiographs together with whole-spine radiographs. However, as the PI is a critical parameter in treating ASD patients and one that sets the standard in the surgical treatment, the potential increase in additional radiation exposure for more accurate PI measurements is a risk outweighed by therapeutic benefits for ASD patients. This coincides with the recommendations of the International Commission on Radiological Protection (ICRP) [28]: *In conditions where the source of exposure is subject to control, it is desirable and reasonable to set specific dose limitations so that the associated risk is judged to be appropriately small in relation to the benefits resulting from the practice*.

Conclusions

This study revealed that the value of the PI could differ from the actual anatomical value because of the horizontal and vertical rotation of the pelvis while acquiring the radiograph. In lateral whole-spine radiographs, errors in PI measurement may occur due to rotation of the pelvis or nonvertical projection of X-rays. Therefore, the PI should be measured using standing pelvic lateral radiographs instead of whole-spine radiographs to minimize measurement errors. In the standing pelvic lateral radiographs, placing the overlapping femoral heads at the center and obtaining the straight sacral endplate as much as possible by referring to CT or MRI would be a more accurate measurement method to define the PI.

Abbreviations

thoracic kyphosis: TK; lumbar lordosis: LL; adult spinal deformity: ASD; pelvic incidence: PI; pelvic tilt: PT; sacral slope: SS; 3-dimensional: 3D; 2-dimensional: 2D; picture archiving communication system: PACS; sagittal vertical axis: SVA; intraclass correlation coefficients: ICCs; greater trochanter: GT; International Commission on Radiological Protection: ICRP.

Declarations

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Availability of data and materials

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

Authors' contributions

KYL, JHL: conception and design. SKI, WYL: acquisition of data. KYL: drafting the article. All authors have made substantial contributions to the interpretation of data and the critical revision of the article. All authors have read and approved the final manuscript.

Ethics approval and consent to participate

The current study was approved by the Institutional Review Board (IRB) in Kyung Hee university hospital (KMC IRB 2020-11-022) before data collection and analysis. All methods were performed in accordance with the Declaration of Helsinki and the ethical standards of the institutional research committee. Signed informed consent was obtained from all patients in this study.

Consent for publication

Not applicable”

Competing interests

The authors declare that they have no competing interests

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Figures

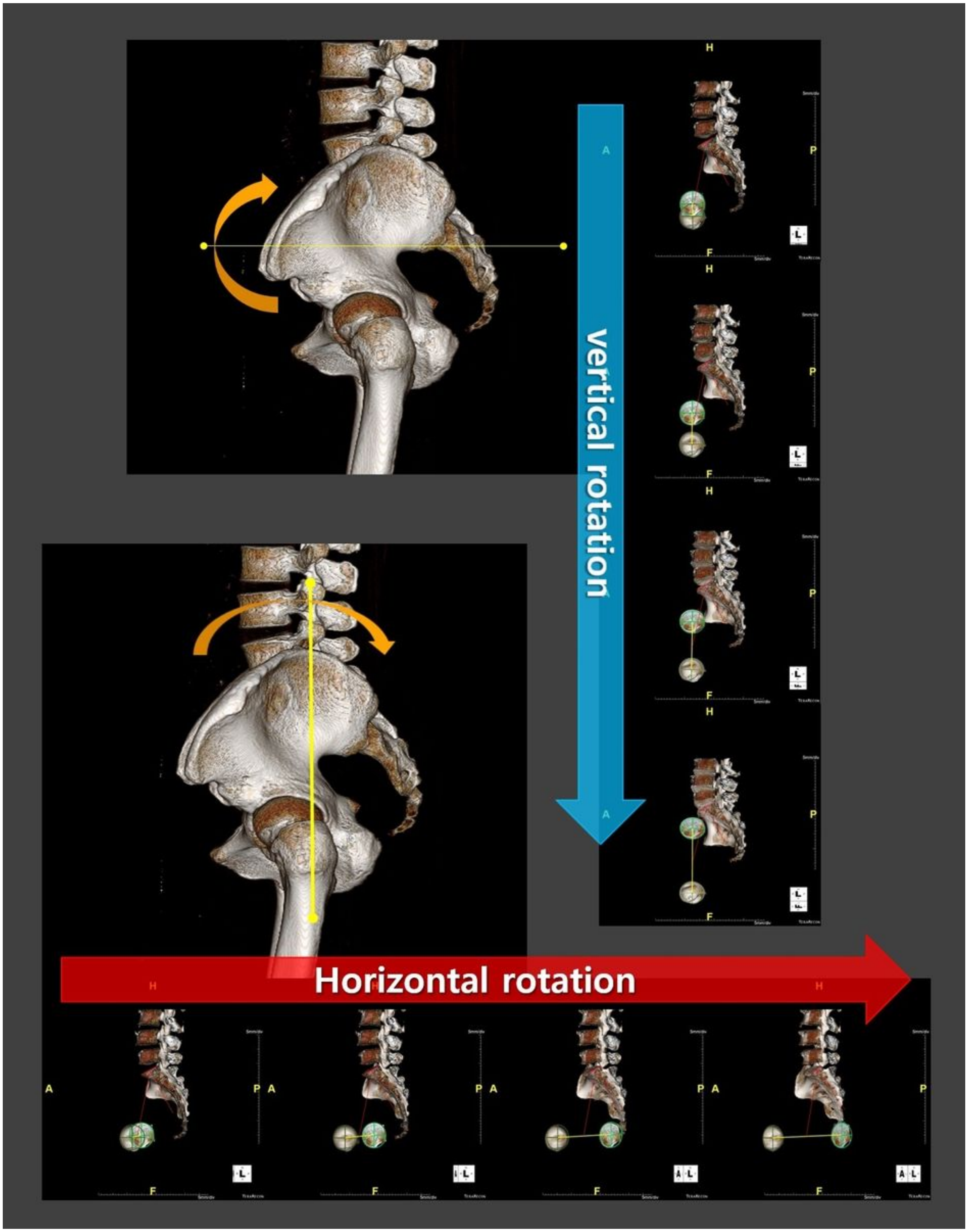

Figure 1

Pelvic incidence evaluation according to the horizontal and vertical pelvic rotation.

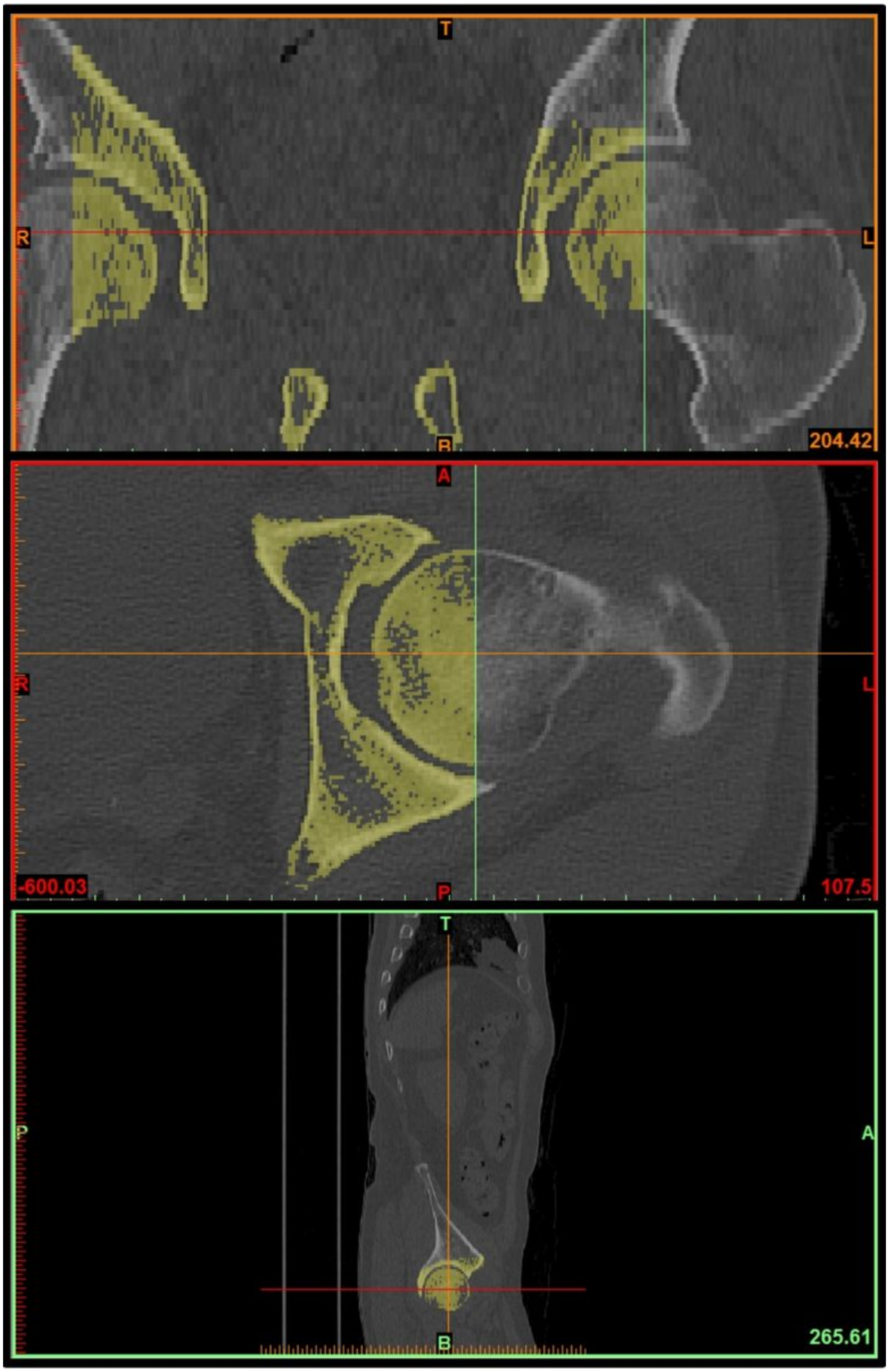

Figure 2

3D reconstruction of femoral head for pelvic incidence; Acquired CT images were performed and modified 3D reconstruction images using 3-Matic program. Segmentation of both femoral heads into halves based on the coronal, sagittal, and axial plane.

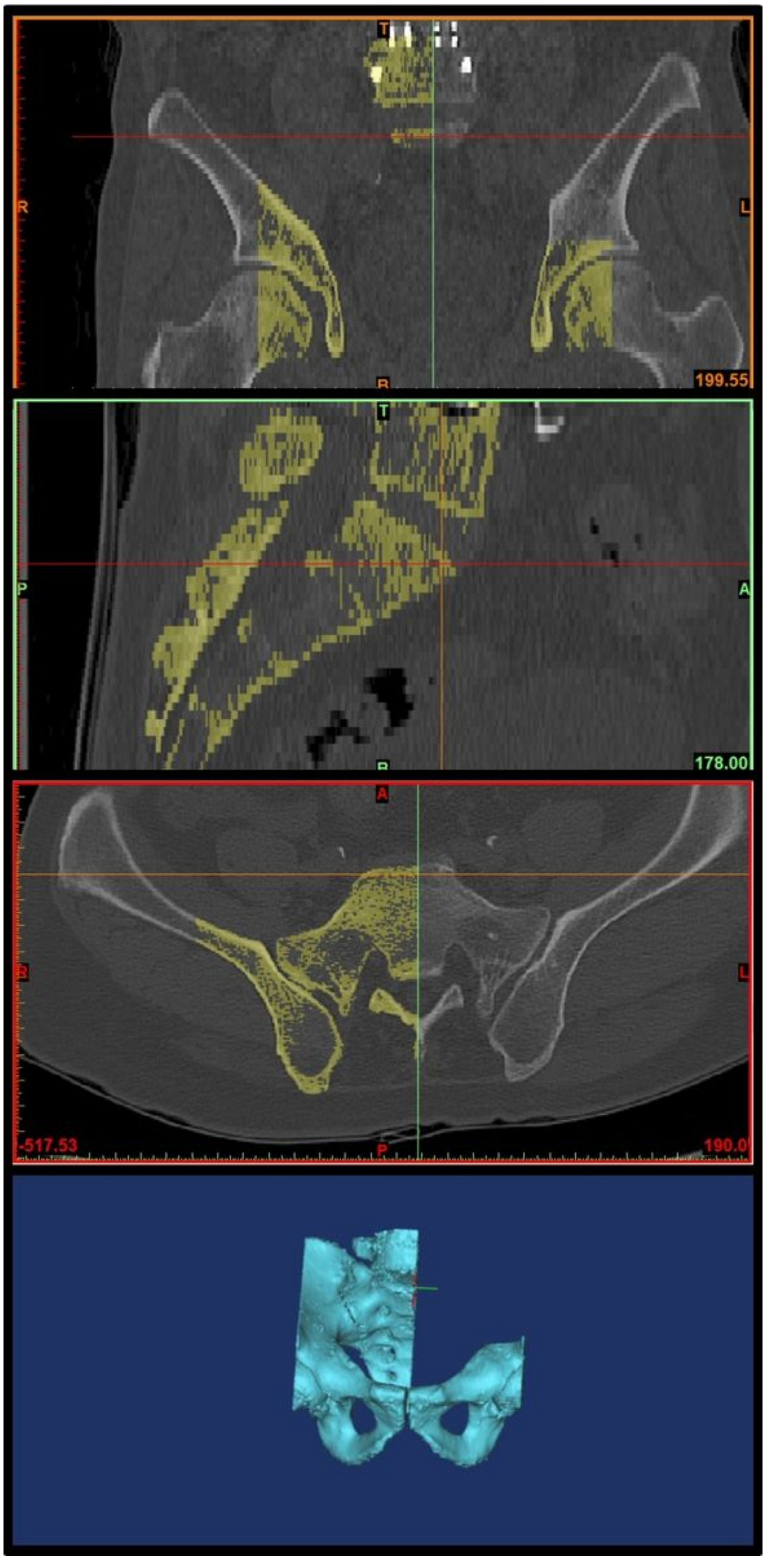

Figure 3

3D reconstruction of sacrum and lower lumbar for pelvic incidence; Segmentation of S1 endplate in coronal, sagittal, and axial plane. Remove left sacrum and lower lumbar images.

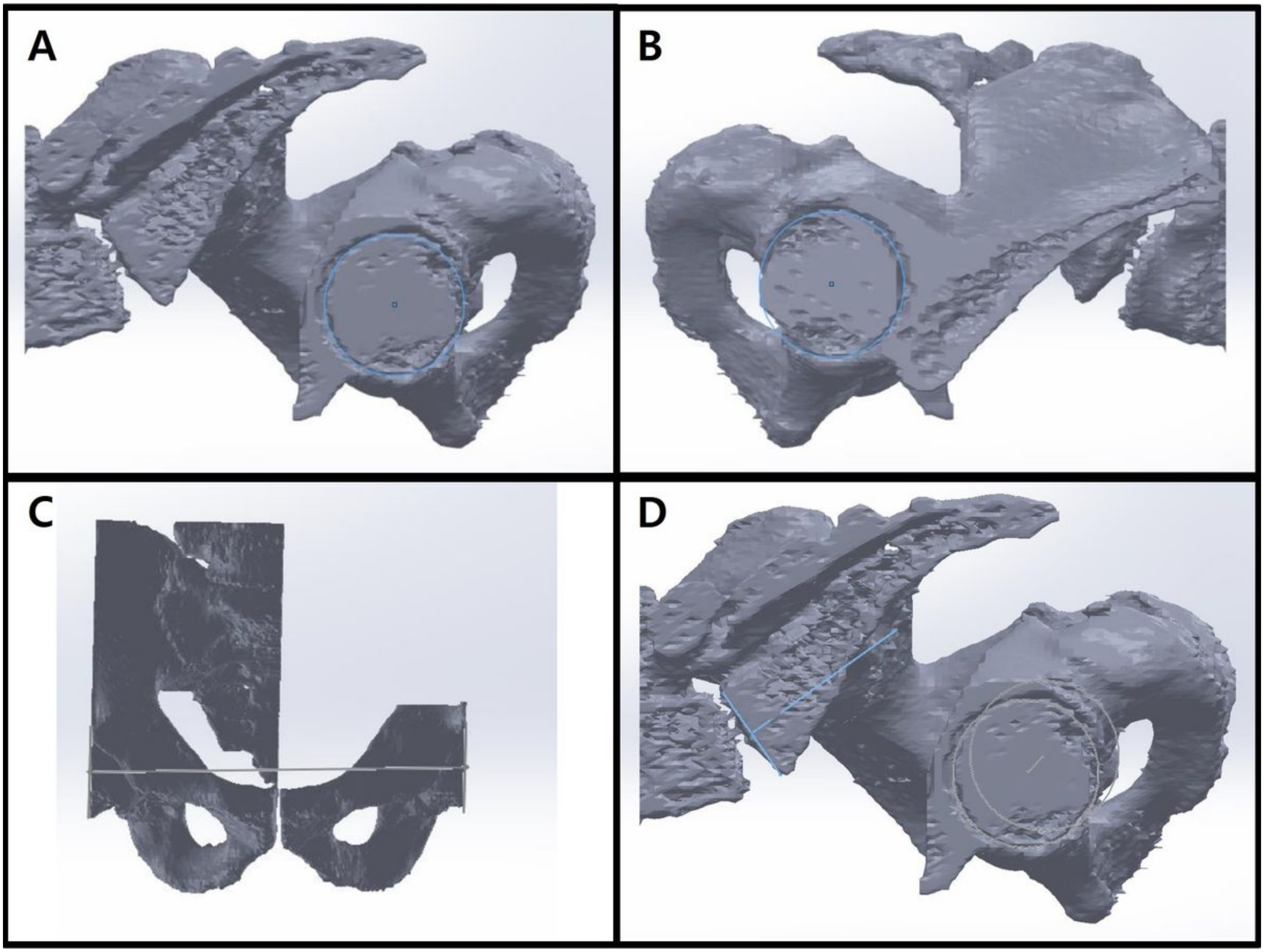

Figure 4

3D sketch of both femoral heads and S1 end plate; The completed 3D reconstruction model was applied in Solidworks (Dassault systems, France) software to produce 3D sketch of the 3D model. (A and B) Circle drawings along the segmented left and right femoral heads. (C) Drawing line connecting the center points of the circles. (D) Drawing line along the segmented endplate of the sacrum on the sagittal plane and vertical line at the center point of the line

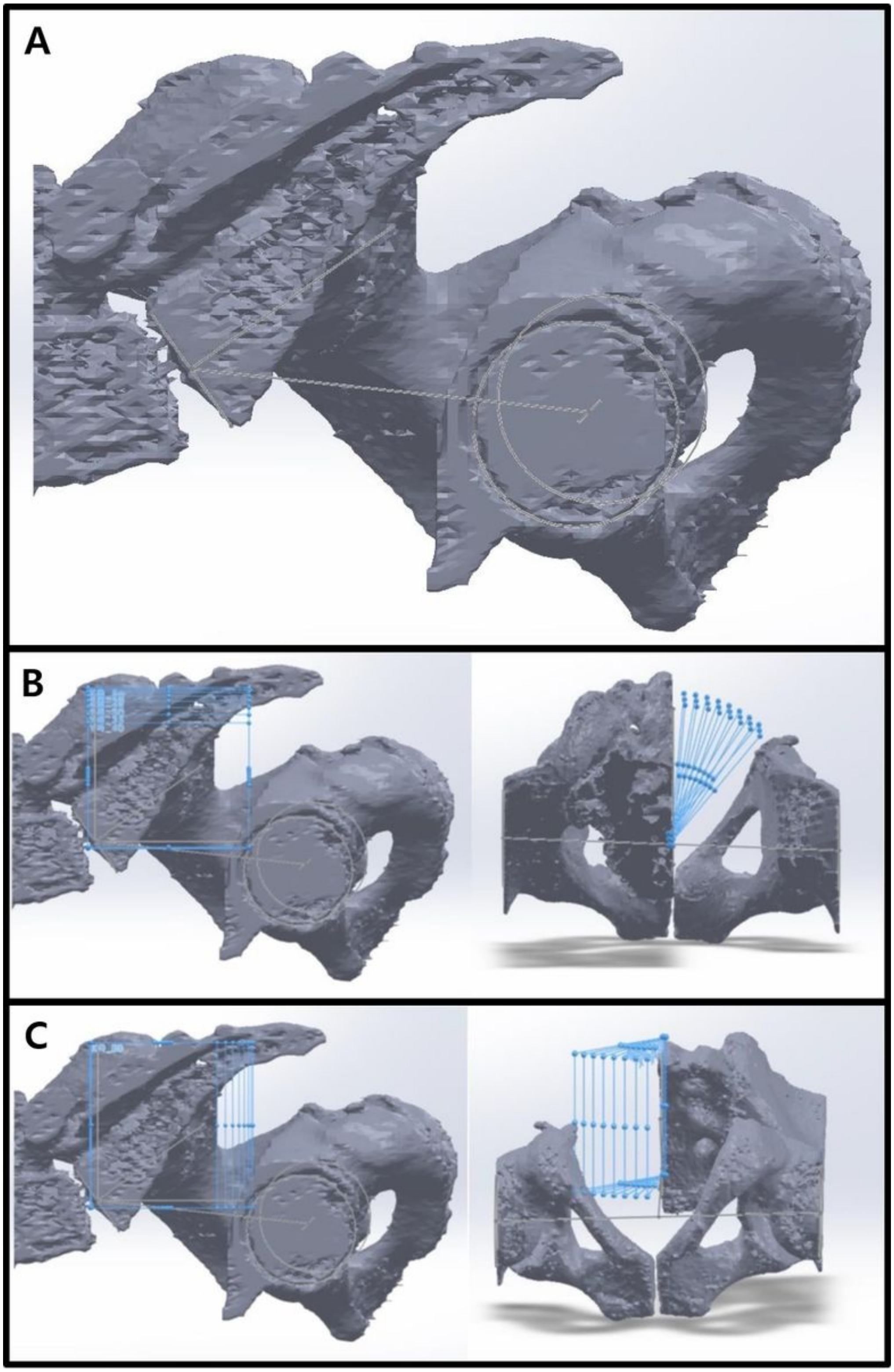

Figure 5

Horizontal and vertical rotation of the sagittal plane with a 3D sketch; (A) The center point of the line connecting the center of the S1 endplate and the center of the femoral head was defined. (B and C) The planes were tilted to 5° angular intervals (the horizontal and vertical rotation of the pelvis: 0º, 5º, 10º, 15º, 20º, 25º, 30º, 35º, and 40º) for the sagittal plane based on the vertical and horizontal reference lines

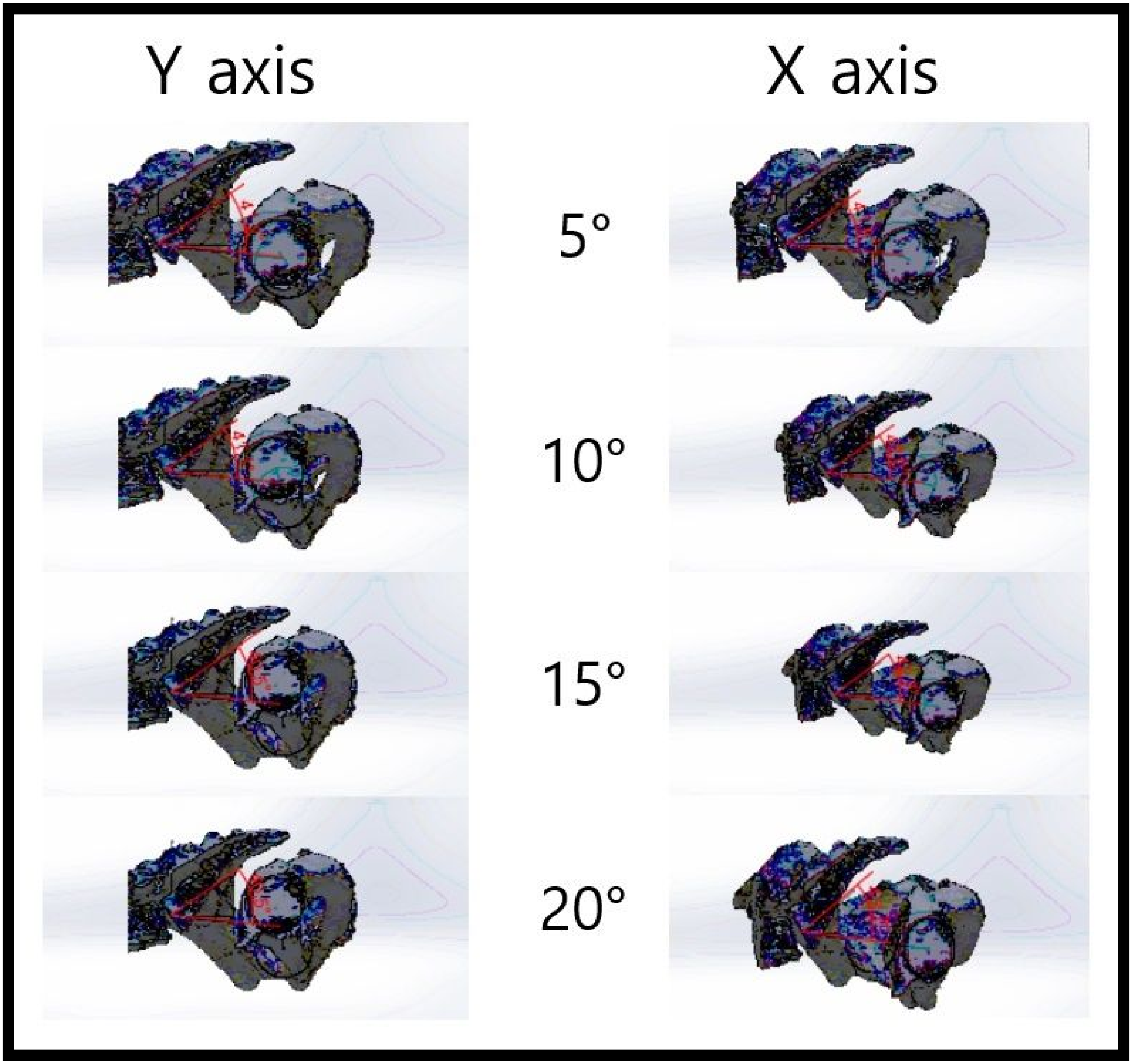

Figure 6

Pelvic incidence measurement in various plane; Planes in the interval of 5° angles were used to adjust the view in Solidworks' vertical and horizontal directions, and each captured screen was imported to AutoCAD 2014 (AUTODESK, US) to measure the angle of the PI

Figure 7

Measurement of pelvic incidence in true pelvis lateral radiographs; (A) Overlapping of both femoral heads. (B) Precise identification of sacral endplate using CT or MRI. (C) More accurate measurement of pelvic incidence.