Validity of the EOS-determined pelvic parameters and orientation with pelvic positional variation: a phantom study

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The EOS is a medical imaging system that incorporates simultaneous orthogonal images, producing three-dimensional (3D) reconstructions of the whole skeletal system in various functional positions. Despite growing interest in the pelvic 3D position, the validity of the EOS has not yet been well studied. We investigated the trueness and precision of EOS imaging for pelvic parameters and orientation and assessed whether the measurement using the EOS was affected by the pelvic orientation itself. The orientation of the anterior pelvic plane and pelvic parameters of a custom-made pelvic phantom were measured by three raters using the EOS, and the measurements obtained were compared with the true values. The standard deviations of the measurement errors were 3.23°, 0.26°, 2.98°, 0.88°, and 3.22° for flexion, obliquity, rotation, pelvic incidence, spinopelvic tilt, and sacral slope, respectively. The root-mean square averages of the standard deviation of each measurement were 4.05°, 0.41°, 0.28°, 4.80°, 0.99°, and 5.13°, respectively. The measurement errors for sacral slope correlated significantly with geometric means of flexion, obliquity, and rotation ($r = 0.364$, $p = 2.67 \times 10^{-11}$). The EOS rendered accurate and reliable measurements regarding pelvic 3D position, even with positional variation, but positional variation could affect measurements of sacral slope.

The pelvis plays an important role as a link between the spine and the hips; simultaneously, it serves as a mobile unit both in the spinal column and hip joint. The pelvic incidence, which a morphological parameter of the pelvis, affects positional alignment of the spine¹². To emphasize this concept, Dubousset even referred to the pelvis as the "pelvic vertebra"³⁴. The acetabular orientation is a determining factor in pathologies of native joints and complications of replaced joints⁵–⁸. The acetabulum in the native joint, which is a part of the pelvis, and the acetabular cup in the replaced joint, which is inherently fixed to the pelvis, are influenced by the pelvic orientation⁹,¹⁰. With markedly increased interest in the interplay between the spine and the hips, the need for accurate measurements of three-dimensional (3D) pelvic orientation and parameters, in various functional positions of the pelvis, is also growing¹¹–¹⁷.

Because of its deep location and structural and functional complexity, 3D orientation of the pelvis is difficult to measure. Although conventional radiography and computed tomography have been utilized, both have their limitations. Conventional radiographs, which use a cone-beam X-ray, significantly magnifies the subject to varying degrees¹⁸–²⁰. The degree of magnification is dependent on the distance of the cassette from the X-ray source, divergence of the X-ray beam, size of the object, and distance from the center of projection field. Moreover, with uniplanar conventional radiography, it is difficult to evaluate the 3D pelvic orientation accurately. Computed tomography (CT) with 3D reconstruction precisely depicts the structure of the pelvis. However, with commonly available CT scanners, the pelvis can be scanned only in the supine position; this prevents evaluation of

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Table 1. Trueness of EOS measurements in terms of pelvic parameters and orientation. RMEPEM rates of measurement errors out of positioning error margin, MAE maximum of absolute error. *Morphologic parameter.

| Parameter                      | Rater 1       | Rater 2       | Rater 3       | Total         |
|-------------------------------|---------------|---------------|---------------|---------------|
| Flexion                       | Bias (δ)      | MAE           | RMEPEM        | Bias (δ)      | MAE           | RMEPEM        | Bias (δ)      | MAE           | RMEPEM        |
| Obliquity                     | 0.14          | 0.12 ± 1.52   | 5.11          | 0.94          | −0.86 ± 5.05  | 17.26         | 0.97          | −0.71 ± 1.77  | 5.00          | 0.90          | −0.48 ± 3.23  | 17.26         | 0.94          |
| Pelvic incidence*             | 2.44 ± 3.41   | 9.60          |               |              | 2.44 ± 3.13   | 9.80          |              | 2.27 ± 2.30   | 7.88          |              | 2.38 ± 2.98   | 9.80          |              |
| Spinopelvic tilt              | −0.09 ± 0.73  | 3.58          | 0.75          | 0.88          | −0.48 ± 0.97  | 3.46          | 0.88          | −0.57 ± 0.84  | 2.87          | 0.90          | −0.38 ± 0.88  | 3.58          | 0.84          |
| Sacral slope                  | 2.53 ± 3.66   | 10.57         | 1.00          | 11.22         | 2.92 ± 3.40   | 11.22         | 0.99          | 2.84 ± 2.51   | 9.02          | 0.96          | 2.76 ± 3.22   | 11.22         | 0.98          |

Results

Trueness (Table 1). The bias (δ) values for each measurement are summarized in Table 1. The means of measurement bias for all three gyrations of pelvic orientation and sPT were within the margins of error of the positioning device. The mean of measurement bias for the sacral slope was outside the error margins of the positioning device. The standard deviation of bias for flexion, obliquity, rotation, PI, sPT, and SS was 3.23°, 0.26°, 0.23°, 2.98°, 0.88°, and 3.22°, respectively. Maximal absolute errors of flexion, obliquity, rotation, PI, sPT, and SS were 17.26°, 0.71°, 0.63°, 9.80°, 3.58°, and 11.22°, respectively. All the maximum errors were outside the error margin. The rates of measurement errors outside the positioning error margin (RMEPEM) for flexion, obliquity, and rotation were 0.94, 0.51, and 0.42. The RMEPEM of sPT and SS were 0.84 and 0.98, respectively.

Precision (Table 2). The ICC of all the parameters revealed excellent reliability (Table 2). The ICC between the measurements of each rater and the reference values showed excellent agreements, with the lower limits of all 95% confidence intervals exceeding 0.95; the ICC among the three raters also had excellent values, approximating to 1.0.

Global uncertainty (Table 2). While flexion was the most uncertain parameter among the pelvic orientations with 11.33° of global uncertainty, SS was the most uncertain parameter among the pelvic parameters with...
13.47° of global uncertainty. For individual raters, the global uncertainty of flexion ranged from 5.37° to 17.44° and that of SS ranged from 9.63° to 13.91°.

**Postural influence (Figs. 1 and 2).** The LOESS plot for measurement errors of each parameters along the sum of pelvic orientation angles depicted that SS and flexion are more error prone than other parameters (Fig. 1). To focus on the measurement errors of these two parameters, we plotted multiple heat maps of measurement errors with positional variance. The heat maps showed that the three positional parameters—flexion, obliquity, and rotation—have a complex impact on measurement errors of SS (Fig. 2).

The heat maps revealed two features of SS measurement errors. First, the sign of SS measurement errors tended to be similar to the sign of the product of flexion, obliquity, and rotation. Second, the absolute values of SS measurement errors correlated with the absolute values of the product of flexion, obliquity, and rotation.
Based on these observations, the correlation between the measurement errors of SS and the geometric means of the positional parameters—flexion, obliquity, and rotation—were tested with Spearman’s correlation analysis, revealing a correlation coefficient of 0.364 \( (p = 2.67 \times 10^{-11}, 95\% \text{ CI } 0.262–0.463) \). As PI is the sum of SS and sPT, measurement errors of sPT were relatively smaller than those of SS. Thus, PI was also markedly affected by the geometric means of the positional parameters of flexion, obliquity, and rotation. The coefficient of correlation between PI measurement errors and the geometric means of flexion, obliquity, and rotation was 0.394 \( (p = 3.65 \times 10^{-13}, 95\% \text{ CI } 0.277–0.489) \). In contrast to SS, we could not identify any patterns in the measurement errors of flexion.

**Discussion**

The present study aimed to measure the accuracy and reliability of the EOS using SterEOS software for measuring pelvic orientation and parameters. The measurements of pelvic orientation and parameters were accurate, with a standard deviation of bias ranging from 0.23° to 3.23°; however, flexion among the pelvic orientations and SS among the pelvic parameters demonstrated the highest measurement errors, with the maximum absolute error reaching 17.26° and 11.22°, respectively. The measurements were reliable, with the average ICC ranging from 0.23° to 3.23°.
from 0.998 to 1.00. Flexion, among the pelvic orientations, and SS, among pelvic parameters, had the highest
RMSD, at 4.05° and 5.13°, respectively. Overall, flexion and SS had the highest global uncertainty, reaching 11.33°
and 13.47°, respectively. The geometric mean of flexion, obliquity, and rotation correlated significantly with SS
measurement errors (r = 0.364, p = 2.67 × 10⁻¹¹).

The limited number of studies available on the validity of the EOS system have focused on the pelvis22,23,53
The measurement error of the EOS system for various pelvic orientations was previously assessed by Bittersohl
et al53. Their analysis was limited in that the positional change did not abide by the standard coordinate system
of pelvic orientation42–44. Rousseau et al. used a pelvic phantom to assess the effect of axial rotation on the
measurement error of the orientation itself. The deviation of axial rotation was − 0.39° ± 0.77°, with a maximal
deviation of 1.1°22, representing less accuracy and reliability of the EOS system than evaluated in the present
study (− 0.01° ± 0.23°, with a maximal deviation of 0.63°). The pelvic phantom used had a unilateral artificial
acetabular cup and was not built to make symmetric shape from the designing stage. Without detailed description
regarding calibration of rotational axis, a laser indicator to the phantom was attached to the phantom. The
inherent asymmetricity of pelvic phantom and dubious spatial calibration may have attenuated the accuracy of
reference values in the previous study. Ghostine et al. assessed accuracy only in the neutral position and found
that it was less than 1° for pelvic parameters, using synthetic EOS images of a virtual pelvis67. All previous studies
assessed only the effect of axial rotation rather than 3D positional changes and addressed variation of rotation
in the horizontal plane only rather than all components of the 3D positional effect. Studies on clinical images
assessed the reliability of pelvic parameters and pelvic orientation measured with the EOS system43,44,53. Studies
using clinical images offer greater chances of acquiring study materials during clinical practice and provides
valuable information in terms of real-subject variability; however, their scope is limited in that the researcher
cannot assess accuracy, as these images lack reference value information.

To overcome the limitations of previous studies, we devised a positioning device to be able to visualize the
orientation of the pelvis using the standard coordinate system42–44. This allows assessment of measurement errors
with complicated pelvis positions, as the pelvis model can be oriented in any direction in 3D space by means of
the device (Fig. 6).

The measurement errors obtained with the EOS in the present study were smaller than those reported in
studies using radiography37–40, indicating that the EOS is one of the most accurate and reliable modalities cur-
cently available for the measurement of pelvic orientation and parameters of the pelvis in various functional
positions. However, the results of the present study still indicate that correct positioning of patients is required
to minimize measurement errors of pelvic parameters and orientation, even with the EOS.

As the EOS imaging system offers comparable accuracy to that of radiostereometric analysis in terms of
angular measurements59, it may be reasonable to assume that the major source of errors is manual registration
of anatomical landmarks60.

Even though the EOS uses biplanar stereoradiography to reflect the 3D coordinates of the pelvis, registration
of anatomical landmarks is guided on 2D projection images in the SterEOS software44.

Not all parameters demonstrated the same level of errors in this study, which agreed with the findings of
previous studies25,29,34,50. Among pelvic parameters, the measurement of SS was more error prone than that of
sPT in the present study. Pelvic flexion was more vulnerable to measurement error than obliquity and rotation
of the pelvis. Comparison of the methods of registration used for these measurements may yield insight into
the source of the errors.

Measurements of parameters are guided in different ways in SterEOS software44. Five anatomical landmarks
are involved: (1) the centers of both femoral heads, (2) the center of the upper endplate of S1, (3) the orientation
of the upper endplate of S1, (4) the center of both pubic tubercles, and (5) both ASISs. While the measurement
of sPT relies on the first two landmarks, measurement of the sacral slope is dependent only on the first and third
landmarks41. For pelvic orientation, rotation and obliquity only rely on the centers of both femoral heads, while
flexion is dependent on the last two landmarks.

Although all anatomical landmarks for registration have round contours, rather than pin-points, the SterEOS
uses a point-based registration onto projected 2D images. As the projected 2D images accentuate the tangen-
tial surface in the direction of projection, registration onto 2D images can lead to errors50,56. As a curve-based
method is used for marking the center of the femoral head, the registration was less vulnerable to errors of manual
registration52. However, registration of the remaining landmarks was guided using a point-based method, which
is a heavily error-prone method of registration57. Among the remaining measurements, the errors of sPT were
smaller than those of SS. To obtain the orientation of the upper endplate of S1, two points located as far as the
sacral endplate diameter must be selected, and even small variability in selecting these points may affect the
measurements of the S1 endplate orientation57. In contrast to the orientation of the upper endplate of S1, the
center of the upper endplate of S1 is located far from the midpoint of the centers of both femoral heads. Thus, the
measurements of sPT were less affected by variability in selecting the points. Improvement in SterEOS software
based on our observations, using 3D reconstructed models for registration and surface-based registration, may
further decrease measurement errors.

Our phantom study had several limitations. The present study used a phantom model of a symmetric pelvis.
A study of the validity of a specific imaging system requires repetitive acquisition of images; this is not ethically
acceptable unless such repeated imaging is clinically required, particularly if the imaging system requires the
use of radiation34. This issue can be addressed by using a phantom or synthesis of projection images from 3D
models22,23,29,39. The pelvis and sacral upper endplate demonstrate large morphometric variations35,58. To focus
on the effect of position, we used a single symmetric pelvis in the present study. However, similar to the effect
of each positional parameter, the shape of an anatomical structure may have complicated effects on the meas-
urements. Moreover, the phantom we constructed lacked soft tissues. In the EOS images acquired in clinical
practice, complex contours or markings of soft tissue can have confounding effects on measurements, causing
additional measurement errors. Constructing a phantom with a soft tissue is technically demanding, and it is rarely reported in the literature. However, constructing a phantom with a soft tissue mounted on the positional device implemented in the present study may overcome this limitation.

Conclusion
The EOS imaging and measuring system rendered accurate and reliable information regarding pelvic orientation and pelvic parameters, irrespective of positional variation. However, positional variation can differently affect the measurements of pelvic flexion and the sacral slope.

Methods
This was an experimental study, utilizing a custom-made pelvic phantom. A phantom is a surrogate object that simulates body parts of patients for medical research or calibration of medical devices; the phantom was mounted on a positioning device. The study was approved by the Ajou University Institutional Review Board of our hospital (AJIRB-MED-DEV-19-471). In the present experiment, no human participant other than CT scan images were involved. The requirement for informed consent was waived by the Institutional Review Board of our hospital as performing CT was part of patient’s healthcare and the use of these data posed minimal risk to the patient. All methods were performed in accordance with the relevant guidelines and regulations.

Pelvic orientation. A globographic coordinate system was used to describe the 3D orientation of the pelvis.

In brief, the pelvic rotation angle was defined as the angle between the frontal radiographic plane and the projection of the bicoxofemoral axis to the horizontal plane. Positive rotation corresponded to displacement of the symphysis in the left acetabular direction (clockwise rotation from the distal view). The pelvic obliquity angle was defined in the pelvic frontal plane as the angle between the bicoxofemoral axis and the horizontal plane. A positive value indicated that rotation had occurred in the clockwise direction when observed from the front. The pelvic flexion angle was defined in the pelvic sagittal plane as the angle between the pelvic frontal plane and the anterior pelvic plane, which is a plane formed by both anterior superior iliac spines and the center of the pubic tubercles. Positive flexion corresponded to displacement of the symphysis in the caudal direction (Figs. 3 and 4). The angles of these three gyrations defined the 3D orientation of pelvis.

Pelvic parameters. The three pelvic parameters generally investigated include sacral slope (SS), spinopelvic tilt (sPT), and pelvic incidence (PI). The SS was defined as the angle in the hip sagittal plane between the sacral upper endplate and the hip axial axis. The sPT was defined as the angle in the hip sagittal plane between the hip frontal plane and the line connecting the midpoint of the sacral plate and the bicoxofemoral axis. The sPT was considered positive when the sacral endplate moved forward. The PI was defined as the angle in the hip sagittal plane between the line perpendicular to the sacral plate at its midpoint, and the line connecting the midpoint of the sacral plate and the bicoxofemoral axis (Fig. 5).

Pelvic phantom. According to the description of pelvic orientation, an independent researcher (JTK), who was not one of the observers, devised a positional device that visualized the position of a symmetric pelvic model.
Symmetric pelvis model. A set of CT images of the hip of a 22-year-old man with suspected osteoid osteoma on the left femur neck was used to design a completely symmetric hip model containing the pelvis and proximal femur.

The CT scan of the pelvis and proximal femur was reconstructed into a 3D model using MIMICS 20.0 (Materialise, Leuven, Belgium). The right hemipelvis, containing the proximal femur, was mirrored to the pelvic sagittal plane and fused to the right hemipelvis itself to form a symmetric hip model. The distance from the center of the femoral head to the sagittal plane was measured using 3-matic modeling software (Materialise, Leuven, Belgium) at 80.23 mm.

The 3D image was 3D printed (Projet360, 3D Systems Inc., Rock Hill, CA, USA) using plaster material that absorbs radiation (Visijet PXL, 3D Systems Inc.). The accuracy of the output was within 100 μm, according to the information provided by the manufacturer.

Positioning device. A positioning device (Yes-protec, Dong-Tan, Korea) was designed to control the orientation of the symmetric pelvis model according to the defined sequence of rotation, according to the globographic coordinate system. It was made from radiolucent material to not interrupt the projection of the pelvic model.

The margins of error for positioning the device were 0.138° for flexion, 0.225° for obliquity, and 0.191° for rotation, as the thickness of marking was 0.6 mm, 1 mm, and 0.5 mm, and the radius of the positioning device was 250 mm, 255 mm, and 150 mm, respectively.

Imaging and measurements. Biplanar radiographic acquisitions were performed using the EOS (EOS Imaging, Paris, France), which was equipped with aluminum and copper beam filters. The pedestal of the EOS was confirmed to be flat using a levelling machine.
Acquisitions. The image acquisition protocol of ‘pelvis morphotype 1’ adopts an aluminum spectral filter for both frontal and lateral tubes to reproduce the real imaging context of the pelvis. The center of rotation was placed at the midpoint of the bicoxofemoral axis for the center of the detectors to be in perfect alignment with the center of rotation.

Variation in orientation consisted of 3 variations in obliquity, 7 variations in flexion, and 5 variations in rotation, resulting in 105 pairs of anteroposterior and lateral scanograms. The range and interval were from −10° to 10° of obliquity, with increments of 10°; from −45° to 45° of flexion, with increments of 15°; and from −20° to 20° of rotation, with increments of 10° (Fig. 6).

Measurements. With the use of SterEOS software (version 1.5.3.7947, EOS Imaging), the manual registration of anatomical landmarks, such as both femoral heads, upper endplate of the sacrum, both sacroiliac joints, both anterior superior iliac spines (ASISs), and the midpoint of both pubic tubercles on the biplanar radiographic images enabled the semiautomated measurement of pelvic parameters and the orientation of the pelvis. Three different observers, including an orthopedic surgeon, with 7 years of experience, and two musculoskeletal radiologists, with a minimum of 7 years of experience, underwent a 1-day training session with 20 samples provided by the study designer. In the training session, the methods of measurements were standardized as below. The midpoint of both pubic tubercles was used to represent both these structures; the points on both ASISs, which met a line tangential to both these structures and the midpoint of both pubic tubercles, were used to represent both ASISs.

No numerical feedback was provided during manual registration, as inherent to the SterEOS system design. Thus, the raters could only adjust the registration before acquisition of numerical results. Once the result was obtained at the final step of each measurement, no adjustment of registration or remeasuring was allowed. The measurements of the 105 pairs of images were made by the three raters, separately.

Statistical analysis. Trueness, which is defined as the closeness of agreement between the average of repeated measurements and the reference value, refers to a systematic error. It is quantified using the measurement bias (δ)\(^{46}\).

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Figure 6. Image acquisition of the pelvic phantom performed for 105 position variations. SterEOS software (version 1.5.3.7947, EOS Imaging, Paris, France) was used to create the image. (a) The biplanar images depict the neutrally positioned phantom in the EOS system. (b) The biplanar images reveal the phantom with +10° rotation and −10° obliquity, and 45° flexion.
\[ \delta = \text{reference value} - \text{measurements} \]

However, as negative measurement errors cannot offset positive measurement errors, the arithmetic mean partially reflects the trueness of measurements. Thus, the standard deviations of bias were used as the representative values of trueness.

The rates of measurement errors outside of the positioning error margin (RMEPEM) of the pelvic position were evaluated based on the error margins of the positioning device.

\[
\text{RMEPEM} = \frac{\text{Number of measurements out of positioning error margin}}{\text{Number of all the measurements}}
\]

Precision, which is defined as the closeness of the results obtained by replicate measurements made by multiple operators, refers to a random error. It is often assessed by calculating the intraclass correlation coefficient (ICC). Thus, the ICC (3, k) model for consistency was calculated for each parameter, at each position, for the whole data set.

However, the ICC is highly dependent on the distribution of subjects, and it does not provide results directly related to the quantified uncertainty of measurement. A single pelvic phantom, which restricts morphometric parameters such as PI to single values, was used in the present study; thus, the reliability of PI could not be measured using ICC values.

Therefore, precision was also assessed according to the guidelines of the ISO 5725-2 standard, using the root-mean square average of the standard deviations of each case (RMS\textsubscript{SD})\textsuperscript{47,50}.

\[
\text{RMS}_{\text{SD}} : \sqrt{\frac{\sum (\text{SD case})}{\text{Number of cases}}} = \sqrt{\frac{\sum (\text{Reference value} - \text{measurements})^2}{\text{Number of cases} - 1}}
\]

This approach allows estimation of a 95% confidence interval for the position precision provided by \( \pm 2 \) \( \text{RMS}_{\text{SD}} \).

The global uncertainty value (\( \pm \varepsilon \)) includes both trueness and precision. It was calculated as the sum of the standard deviation of bias (SD\textsubscript{b}) and 95% confidence interval (2 \( \text{RMS}_{\text{SD}} \)).

\[
\text{Global uncertainty} (\varepsilon) = \text{SD}_b + 2\text{RMS}_{\text{SD}}
\]

The relationship between pelvic orientation variation, which was represented as the sum of flexion, obliquity, and rotation of the pelvis, and the sum of the differences between the reference value and measured values was analyzed using non-parametric locally estimated regression (local polynomial regression [LOESS]) analysis\textsuperscript{51}.

As these data contain 4-dimensional information, the pattern of measurement errors was depicted on multiple heat maps.

The effect model of pelvic orientation on the measurement error was established based on the heat maps; the model was analyzed using Spearman’s correlation.

All statistical analyses were performed with R software (www.r-project.org), version 3.6.1, and Microsoft Excel (Microsoft Corp., Redmond, WA, USA). \( p < 0.05 \) was considered to indicate statistical significance.

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**Author contributions**

J.T.K.: conception of the work, Writing—original draft and revision. D.H.L.: acquisition, analysis of data. H.D.L.: acquisition, analysis of data. H.B.S.: interpretation of data. B.H.P.: interpretation of data. S.H.P.: Writing—original draft, review and editing, design of the work, acquisition of data. H.K.S.: Writing—original draft, analysis of data, design of the work. All authors reviewed the manuscript.

**Competing interests**

The authors declare no competing interests.

**Additional information**

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