EOS Low-Dose Radiography: A Reliable and Accurate Upright Assessment of Lower-Limb Lengths

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Background: Children with lower-limb-length discrepancy require repeated radiographic assessment for monitoring and as a guide for management. The need for accurate assessment of length and alignment is balanced by the need to minimize radiation exposure. We compared the accuracy, reliability, and radiation dose of EOS, a novel low-dose upright biplanar radiographic imaging system, at two different settings, with that of conventional radiographs (teleorotgenograms) and computed tomography (CT) scanograms, for the assessment of limb length.

Methods: A phantom limb in a standardized position was assessed ten times with each of four different imaging modalities (conventional radiographs, CT scanograms, EOS-Slow, EOS-Fast). A radiation dosimeter was placed on the phantom limb, on a portion closest to the radiation source for each modality, in order to measure skin-entrance radiation dose. Standardized measurements of bone lengths were made on each image by consultant orthopaedic surgeons and residents and then were assessed for accuracy and reliability.

Results: The mean absolute difference from the true length of the femur was significantly lower (most accurate) for the EOS-Slow (2.6 mm; 0.5%) and EOS-Fast (3.6 mm; 0.8%) protocols as compared with CT scanograms (6.3 mm; 1.3%) (p < 0.0001), and conventional radiographs (42.2 mm; 8.8%) (p < 0.0001). There was no significant difference in accuracy between the EOS-Slow and EOS-Fast protocols (p = 0.48). The mean radiation dose was significantly lower for the EOS-Fast protocol (0.68 mrad; 95% confidence interval [CI], 0.60 to 0.75 mrad) compared with the EOS-Slow protocol (13.52 mrad; 95% CI, 13.45 to 13.60 mrad) (p < 0.0001), CT scanograms (3.74 mrad; 95% CI, 3.67 to 3.82 mrad) (p < 0.0001), and conventional radiographs (29.01 mrad; 95% CI, 28.94 to 29.09 mrad) (p < 0.0001). Intraclass correlation coefficients showed excellent (>0.90) agreement for conventional radiographs, the EOS-Slow protocol, and the EOS-Fast protocol.

Conclusions: Upright EOS protocols that utilize a faster speed and lower current are more accurate than CT scanograms and conventional radiographs for the assessment of length and also are associated with a significantly lower radiation exposure. In addition, the ability of this technology to obtain images while subjects are standing upright makes this the ideal modality with which to assess limb alignment in the weight-bearing position. This method has the potential to become the new standard for repeated assessment of lower-limb lengths and alignment in growing children.

Clinical Relevance: This study assesses the reliability and accuracy of a diagnostic test used for clinical decision-making.

Lower-limb-length inequality is common in the general population, with small differences noted in 36% to 77% of military recruits. Clinically important differences are less common, with approximately one in every 1000 individuals having a limb-length discrepancy of >2 cm. The impact of limb-length discrepancy on long-term function and health-related quality of life is not fully understood, but limb-length discrepancy has been implicated as a cause of low-back pain.

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There is a general consensus that a limb-length discrepancy of 2 cm is an appropriate threshold for intervention\textsuperscript{8, 17}.

Children who have, or are at risk for, a clinically relevant limb-length discrepancy often require multiple radiographs throughout childhood to plan for treatment and to monitor outcomes. Radiographic evaluation must provide a sufficiently reliable and accurate assessment of limb length and alignment while minimizing radiation exposure, particularly for younger children, who are estimated to be two to five times more radiosensitive than adults\textsuperscript{14}. A guiding principle in pediatric imaging (the ALARA principle) is to keep radiation exposure "as low as reasonably achievable,"\textsuperscript{15} without compromising the image quality for diagnosis and clinical decision-making.

Several imaging modalities, each with advantages and disadvantages, are currently used to evaluate limb-length discrepancy\textsuperscript{16, 17}. Conventional computed or digital radiographs or teleoroentgenograms are widely available, and, because they involve a single brief exposure, are less prone to motion artifact. They provide a more accurate assessment of limb alignment when the patient is in the weight-bearing position of standing and can take into account the contributions of the foot and pelvis to overall limb lengths. However, conventional radiographs are associated with magnification error (the so-called "parallax" effect)\textsuperscript{16, 18}. The magnitude of this error is influenced by the distance of the cassette from the x-ray source, the divergence of the x-ray beam, and the size (length and girth) of the object being evaluated (see Appendix). This differential magnification is typically addressed with the use of a radiolucent ruler that is placed upright along the cassette, with measurements being made from the ruler markings. The radiation exposure associated with this technique is higher than that of other modalities, such as computed tomography (CT) scanograms\textsuperscript{16, 19}. Conventional full-length teleoroentgenograms require a specialized long cassette, which may not be available at all institutions, to capture the full length of the limb in a single exposure. More recent advances in digital-image acquisition and processing allow for the creation of similar full-length images from multiple smaller images that are digitally "stitched" together. The use of multiple smaller images may reduce the parallax effect, but these images are prone to motion artifact during repositioning. These digital images are associated with relatively less radiation exposure than other radiographic methods such as scanograms and orthoroentgenograms. Those older methods, which involve making multiple images centered on the hip, knee, and ankle with the patient in the supine position, also reduce the parallax effect. For the conventional scanogram method, a standard-length radiographic cassette is moved for the three exposures and therefore provides only partial visualization of each limb segment. This partial visualization precludes any reliable assessment of the alignment of the entire limb or each bone segment. For the orthoroentgenogram method, a single long cassette is placed under the patient, who remains lying still between the three exposures at the hip.

### TABLE I Femoral Length Measurements to Assess Accuracy

<table>
<thead>
<tr>
<th>Modality</th>
<th>Measured length* (mm)</th>
<th>Difference from true length of phantom limb\textsuperscript{†} (mm)</th>
<th>Relative magnification\textsuperscript{†}</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional Radiographs</td>
<td>522.2 ± 2.3</td>
<td>(519.4 to 526.3)</td>
<td>8.8%</td>
<td></td>
</tr>
<tr>
<td>CT Scanograms</td>
<td>473.7 ± 0.7</td>
<td>(472.7 to 474.9)</td>
<td>-1.3%</td>
<td></td>
</tr>
<tr>
<td>EOS-Slow</td>
<td>477.4 ± 1.5</td>
<td>(476.0 to 481.0)</td>
<td>-0.5%</td>
<td></td>
</tr>
<tr>
<td>EOS-Fast</td>
<td>476.4 ± 0.6</td>
<td>(475.0 to 477.1)</td>
<td>-0.8%</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

\*The values are expressed as the mean and the standard deviation, with the range in parentheses. \textsuperscript{†}The values indicate the difference from true length of the phantom limb (480.0 mm) as provided by the manufacturer and are expressed as the mean, with the range in parentheses. The relative magnification was derived by dividing the difference between the measured length and the true length by the true length.

### TABLE II Comparison of Accuracy Among Modalities

<table>
<thead>
<tr>
<th>Modality</th>
<th>Mean Absolute Difference (mm)</th>
<th>95% CI (mm)</th>
<th>Difference from Conventional Radiographs</th>
<th>Difference from CT</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional radiographs</td>
<td>42.2</td>
<td>41.4 to 43.1</td>
<td>-</td>
<td>&lt;0.0001</td>
<td></td>
</tr>
<tr>
<td>CT scanograms</td>
<td>6.3</td>
<td>5.5 to 7.1</td>
<td>&lt;0.0001</td>
<td>-0.0001</td>
<td></td>
</tr>
<tr>
<td>EOS-Slow</td>
<td>2.6</td>
<td>1.9 to 3.6</td>
<td>&lt;0.0001</td>
<td>-0.0001</td>
<td></td>
</tr>
<tr>
<td>EOS-Fast</td>
<td>3.6</td>
<td>2.8 to 4.5</td>
<td>&lt;0.0001</td>
<td>-0.0001</td>
<td></td>
</tr>
</tbody>
</table>
To our knowledge, no study has compared the EOS imaging system with CT scanograms or conventional radiographs (teleoroentgenograms) with regard to the accuracy of assessment of length or the radiation dose per image. The purpose of the present study was to compare the relative reliability and accuracy of upright EOS low-dose radiographic evaluation with that of conventional teleoroentgenograms and CT scanograms.

**Materials and Methods**

**Phantom Limb**

Limb-length measurements were performed with use of a phantom limb composed of a plastic left-sided hemipelvis, leg, and foot bones (modeled from an adult skeleton) that were covered in radiopaque paint, connected with latex bands, and encased in simulated soft tissue (Sawbones; Pacific Research Laboratories, Vashon, Washington). The phantom limb was evaluated with use of conventional computed radiographs (teleoroentgenograms), CT scanograms (CT), and two protocols of EOS low-dose radiographic imaging: a slow protocol (EOS-Slow) and a fast protocol (EOS-Fast). For each modality, the limb

| TABLE III Inter-Rater Reliability of Phantom Limb Femoral Segment Measurements |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| Raters*                         | Conventional Radiographs | CT Scanograms   | EOS-Slow        | EOS-Fast        |
|                                 | Variation† (mm)       | 6.8 ± 0.7 (6.2 to 7.6) | 1.5 ± 0.6 (0.9 to 2.0) | 6.0 ± 0.4 (5.5 to 6.5) | 1.9 ± 0.3 (1.6 to 2.1) |
| Intraclss correlation coefficient| 0.95               | NA†             | 0.99            | 0.93            |

*Comparison of measurements of ten images (for each modality) by two raters. †The values are given as the mean and the standard deviation, with the range in parentheses. ‡Not available.

| TABLE IV Inter-Rater Reliability of Phantom Limb Tibial Segment Measurements |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| Raters*                         | Conventional Radiographs | CT Scanograms   | EOS-Slow        | EOS-Fast        |
|                                 | Variation† (mm)   | 10.7 ± 0.5 (10.0 to 11.3) | 2.0 ± 0.8 (1.0 to 2.9) | 4.1 ± 0.3 (3.6 to 4.4) | 2.8 ± 0.5 (2.3 to 3.4) |
| Intraclss correlation coefficient| 0.97              | NA†             | 0.98            | 0.91            |

*Comparison of measurements of ten images (for each modality) by two raters. †The values are given as the mean and the standard deviation, with the range in parentheses. ‡Not available.

knee, and ankle. These methods are prone to motion artifact, deliver higher radiation doses, and cannot be reliably used to measure weight-bearing mechanical axis alignment. For these reasons, conventional scanograms and orthoroentgenograms commonly have been replaced by other techniques.

CT scanograms provide digitized images that are made with the subject lying supine on a standard CT scanner gantry, which then moves as a collimated x-ray beam is transmitted to the patient from a stationary source. Compared with conventional computerized radiographs, CT scanograms provide superior accuracy for the measurement of length discrepancies in the coronal plane and also can provide more accurate measurements of length in the presence of flexion contractures because of the ability to produce orthogonal projections, provided that such contractures are recognized at the time of imaging. The accuracy and interobserver reliability of CT scanograms are quite high. CT scanograms also typically have a lower radiation dose per use in comparison with conventional computerized radiographs. CT scanograms provide less accurate assessment of limb alignment. Furthermore, subjects often tend to lie with the lower limbs externally rotated, which can affect the accuracy of assessment of coronal alignment. These factors limit the clinical utility of CT scanograms to only the assessment of limb lengths.

EOS (EOS Imaging, Paris, France) is a novel low-dose biplanar digital radiographic imaging system that involves the use of highly sensitive gaseous photon detectors without loss of image quality. For the assessment of limb lengths alone, biplanar imaging is not necessary and only anteroposterior images can be made, further reducing the radiation dose.

For the assessment of length or the radiation dose per image. The purpose of the present study was to compare the relative reliability and accuracy of upright EOS low-dose radiographic evaluation with that of conventional teleoroentgenograms and CT scanograms.

**Materials and Methods**

**Phantom Limb**

Limb-length measurements were performed with use of a phantom limb composed of a plastic left-sided hemipelvis, leg, and foot bones (modeled from an adult skeleton) that were covered in radiopaque paint, connected with latex bands, and encased in simulated soft tissue (Sawbones; Pacific Research Laboratories, Vashon, Washington). The phantom limb was evaluated with use of conventional computed radiographs (teleoroentgenograms), CT scanograms (CT), and two protocols of EOS low-dose radiographic imaging: a slow protocol (EOS-Slow) and a fast protocol (EOS-Fast). For each modality, the limb
was positioned such that the patella was oriented anteriorly. After each image was made, the phantom limb was removed and repositioned and then the subsequent image was made. This process was repeated until ten images were made with each modality. Two sets of ten images were made with use of EOS: one with use of the slow protocol and one with use of the fast protocol.

Conventional Radiographs
Full-length long radiographs of the phantom limbs were made with use of a Siemens x-ray machine (Siemens AG, Erlangen, Germany) and a Fuji imaging plate long-view computed radiology cassette (FujiFilm, Stamford, Connecticut) (35.4 x 124.5 cm) behind a standard Bucky grid (see Appendix). The phantom limb was secured to an Octostop immobilizer (Octostop, Quebec, Canada) with Velcro straps in a vertical orientation and was positioned directly in front of the grid and cassette with the patella directed anteriorly toward the x-ray source. The x-ray parameters were set to 75 kV and 32 mA. A total of ten separate anteroposterior radiographs of the phantom limb were made, with the limb being removed and repositioned after each image.

Computed Tomography Scans
The phantom limb was positioned with the patella oriented anteriorly in the center of a Philips Gemini GXI 16 CT scanner (Philips Healthcare, Best, The Netherlands) (see Appendix), and a single posteroanterior scout image was made with the parameters set to 90 kV and 20 mA. The limb was then removed and repositioned until a total of ten images had been made.

EOS
Two different sets of radiographs were made with the EOS scanner with use of different settings for current (mA) and scanning speed. The phantom limb was fixed with Velcro straps to an Octostop immobilizer and was placed with a vertical orientation in the scanning chamber (see Appendix). The phantom limb was aligned with laser-light markings to ensure that the patella was oriented anteriorly and in the center of the scanning field. Two sets of imaging parameters were used: (1) a “slow” setting (85 kV and 20 mA; speed setting, 4), which was the initial standard setting at our institution, and (2) a “fast” ultra-low-dose setting (85 kV and 20 mA; speed setting, 2), which is currently undergoing testing at our institution specifically for lower-limb imaging. A total of twenty separate anteroposterior images of the phantom were made (ten on the slow setting and ten on the fast setting), with the limb being removed and repositioned after each image was made. The biplanar mode of EOS was not utilized because the lateral image is not routinely required for limb-length assessment. The biplanar images are useful when a sagittal plane deformity is present.

Radiation Dose Measurements
Peak entrance exposure was recorded for each modality with use of a calibrated Unfors Xi skin-entrance dosimeter (Unfors Instruments AB, Billdal, Sweden). For each modality, the dosimeter was positioned on the skin surface closest to the radiation source. For the conventional radiographic and EOS evaluations, the dosimeter was placed on the anterior portion of the hip. For the CT evaluations, the dosimeter was placed on the posterior region of the hip because the x-ray tube is located below the table in this setup. Five separate exposures were made with each modality. The dosimeter was placed on the posterior region of the hip because the lateral image is not routinely required for lower-limb imaging. A total of ten separate anteroposterior scout images were made with each modality. Two sets of ten images were made with use of EOS: one with use of the slow protocol and one with use of the fast protocol.

Length Measurements and Analysis
All images were downloaded to a picture archiving and communication system (PACS), and subsequent measurements were made on PACS monitors with use of standard viewing software (General Electric Centricity PACS; GE Healthcare, Westborough, Massachusetts) by four investigators. To assess the accuracy of the different modalities, a consultant pediatric orthopaedic surgeon (U.G.N.) measured the femoral length from the superior aspect of the femoral head to the intercondylar notch (line A); the vertical length of the femur was defined as the perpendicular distance between a horizontal line tangential to the superior aspect of the femoral head and a horizontal line placed at the most distal aspect of the femoral condyles, that is, at the point of the most distal (inferior) part of whichever femoral condyle is lower (most often the medial femoral condyle) (line B), and the vertical length of the tibia was defined as the distance between a horizontal line at the most distal aspect of the femoral condyles and a horizontal line at the superior midpoint of the talus (line C). This individual was blinded to the actual femoral length as reported by the manufacturer. Accuracy was expressed as the difference between the true length of the phantom femur provided by the manufacturer and the measured lengths of the phantom femur.

To assess the inter-rater reliability of each modality, two orthopaedic surgery residents (B.G.E., B.R.) measured the vertical lengths of the femur and tibia on each image for each modality. The vertical length of the femur was defined as the perpendicular distance between a horizontal line tangential to the superior aspect of the femoral head and a horizontal line placed at the most distal aspect of the femoral condyles (Fig. 1, line B). The vertical length of the tibia was defined as the distance between a horizontal line at the most distal aspect of the femoral condyles and a horizontal line at the superior midpoint of the talus (line C). Measurements of accuracy and radiation doses were compared among the four modalities (conventional radiographs, CT scans, EOS-Slow, and EOS-Fast) with use of a fixed-effects analysis of variance with adjustment for multiple comparisons with use of the Tukey variation. The inter-rater reliability of the femoral and tibial segment measurements was determined for all four modalities with use of an intraclass correlation coefficient.
There was no external funding source for this study.

## Results

Table I shows the femoral length measurements for each modality and how these measurements compare with the true length as provided by the manufacturer. Conventional radiographs overestimated the length by an average of 42.2 mm (8.8%). In contrast, CT scans, EOS-Fast, and EOS-Slow underestimated the true length of the femur by 6.3 mm (1.3%), 3.6 mm (0.8%), and 2.6 mm (0.5%), respectively. The comparisons of the mean absolute differences between the measurements for each of the modalities and the true length can be found in Table II. The mean absolute differences for CT, EOS-Slow, and EOS-Fast were all significantly different from that of conventional radiographs ($p < 0.0001$). The mean absolute differences from the true length were the smallest for the EOS-Slow and EOS-Fast protocols; the mean absolute differences for these two protocols were not significantly different from one another ($p = 0.48$) but were significantly differently from that for CT ($p < 0.0001$). The EOS-Slow and EOS-Fast protocols were significantly more accurate for the assessment of length than conventional radiographs and CT ($p < 0.0001$).

The mean radiation dose was significantly lower for EOS-Fast (0.68 mrad; 95% confidence interval [CI], 0.60 to 0.75 mrad) compared with EOS-Slow (13.52 mrad; 95% CI, 13.45 to 13.60 mrad) ($p < 0.0001$), CT scanograms (3.74 mrad; 95% CI, 3.67 to 3.82 mrad) ($p < 0.0001$), and conventional radiographs (29.01 mrad; 95% CI, 28.94 to 29.09 mrad) ($p < 0.0001$) (Fig. 2).

Inter-rater reliability, quantified with intraclass correlation coefficients, showed excellent ($>0.90$) agreement for conventional radiographs, the EOS-Slow protocol, and the EOS-Fast protocol. The intraclass correlation coefficient estimates for the reliability of CT were paradoxically unstable (low) because the intra-rater and inter-rater measurements showed very limited variation (the least of all four modalities) because of the use of the same phantom limb for each image. The intraclass correlation coefficients for the vertical lengths of the femur and tibia can be found in Tables III and IV, respectively, along with the mean and range of variation between the measurements made by two raters for ten separate observations for each imaging modality.

## Discussion

Radiographic assessment of limb-length discrepancy must balance the need for accurate assessment of limb length with the risks associated with repeated exposure to radiation. Accurate assessment of limb-length discrepancy is important for surgical decision-making. Repeated exposure to radiation is a particular concern when assessing children, who are estimated to be two to five times more radiosensitive than adults. According to the ALARA principle, it is the clinician’s responsibility to obtain the information required to make clinical decisions while utilizing radiation doses that are “as low as reasonably achievable.”

Our results indicated that EOS was the most accurate modality for the assessment of limb length in the coronal plane at both the fast and slow settings. Whereas the mean differences on both EOS settings were significantly different from those on CT scanograms, these were not clinically important. For instance, the mean absolute difference between EOS-Fast and CT was only 2.7 mm. However, the EOS system provides upright weight-bearing images, which allows for more valid assessments of limb alignment. This is a particularly important advantage because many lower-limb-length discrepancies are either associated with, or a direct consequence of, malalignment.

We also found that the inter-rater reliabilities of conventional radiographs, the EOS-Slow protocol, and the EOS-Fast protocol were excellent.

The present study demonstrated that changes to the image-acquisition parameters of the EOS system will greatly impact the radiation dose while still capturing the clinical features of interest. For example, radiation dose is inversely related to scanning speed. Doubling the speed will halve the...
that the use of the same limb for multiple images made with the same modality limited the amount of variability that we could expect between measurements. As a result, we were unable to calculate an intraclass correlation coefficient for our measurements of length on CT scanograms because the differences between measurements made by each rater were so miniscule that even small differences between raters produced very low intraclass correlation coefficient values. To avoid this limitation, we would have needed a number of phantom limbs of different lengths to introduce some variability, but phantom limbs of different lengths are not readily available. Because only one phantom limb was used, an inherent measurement bias was introduced with each subsequent measurement as a result of the investigator's knowledge of prior measurements. However, this bias applied equally to all three techniques being compared. In order to minimize bias related to repeated measurement of the same phantom limb, for each set of measurements, the anchor lines representing the top of the femoral head, the most distal aspect of the femur, the top of the talar dome, and the vertical distance between each of these lines were first traced out on the PACS for all images, before the specific lengths were read off the monitor, so that the investigator was “blinded” to the prior measurements.

Our results indicate that upright ultra-low-dose digital radiographic evaluation with the EOS imaging system set on a “fast” scanning speed with a current of 20 mA provides accurate and reliable assessments of length with minimal radiation doses. These properties, in addition to the ability to make weight-bearing images, make the EOS imaging system an attractive imaging method for the repeated assessment of lower-limb-length discrepancy and limb alignment.

Appendix

An illustration depicting the conventional teleorientoentrogram setup, a photograph of the EOS scanner, and photographs showing the phantom-limb setups for the various imaging methods are available with the online version of this article as a data supplement at jbjs.org.

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