Variations in pelvic orientation affect preoperative planning decisions, intraoperative navigation, and postoperative measurements. By providing the means to measure pelvic flexion at low cost and reporting pelvic flexion using the standard reference system, a lateral radiograph technique based on the pubic tubercles and anterior superior iliac spines may be useful for studying functional pelvic orientation and functional alignment and for improving accuracy of postoperative measurement. We evaluated the accuracy of this method by synthesizing 50 lateral pelvic radiographs. Six observers performed manual landmark-based pelvic flexion measurements on the resultant radiographs. Pelvic flexion measurement errors were small (0.004° ± 1.38°). Apart from one outlier with an error of 12.4°, the errors ranged from −4.0° to 3.0°. The data suggest that accurate measurements of pelvic flexion can be made from lateral radiographs with respect to the standard anatomic reference system. However, failure to correctly observe a landmark can introduce large errors. Therefore, the clarity of the relevant landmarks should be considered carefully before applying this technique. Lateral radiographs can be easily acquired and analyzed, making this technique convenient and inexpensive.

Variation of pelvic orientation has received renewed attention, especially with the introduction of computer-assisted tools for total hip arthroplasty (THA). Intraoperatively, surgeons try to identify pelvic orientation, and navigation techniques can be used to accurately localize and track the pelvis. Nonetheless, joint instability can still occur if the acetabular implant is optimally placed with respect to pelvic anatomy alone. Studies of variation in pelvic orientation have led some researchers to propose the concept of functional implant alignment, which amends implant placement by incorporating patient-specific functional pelvic orientation information. Similarly, uncertainty of pelvic orientation during imaging also contributes to errors in postoperative implant measurements. An accurate, convenient, and inexpensive method of assessing pelvic orientation would have clinical and research applications.

Measurements of pelvic orientation using computed tomography (CT) scans and CT/x-ray-matching techniques have shown large variations in pelvic orientation, especially in pelvic flexion. Similar variations have been measured using landmarks and lateral pelvic radiographs. Various landmarks have been used to assess pelvic flexion from lateral radiographs: the most anterior point of the greater sciatic notch and the anterior superior iliac spines (ASIS), the posterior superior iliac spine (PSIS) and the ASIS, and the pubic tubercles and the ASIS. However, these techniques have yet to be rigorously validated. Ideally, pelvic orientation measurements are made with respect to a single precise reference system to facilitate the execution of a preoperative plan and to provide meaningful preoperative, intraoperative, and postoperative measurement comparisons. However, only one of these lateral radiograph techniques uses the standard navigation reference system.

In conventional THA, surgeons try to establish a pelvic reference frame against which the acetabular implant is aligned. Navigation techniques emphasize the importance of a precisely measurable three-dimensional (3-D) pelvic reference system. The standard navigation reference system is constructed from the locations of the ASIS land-
marks and the midpoint of the pubic tubercles. These three points define the anterior pelvic plane (APP). In upright positions, pelvic flexion is then defined by the angle between a vertical line and the APP. Lateral radiographs can then be used to measure flexion with respect to the APP by comparing the lines between projections of the pubic tubercles and the ASIS landmarks with a vertical line. By providing the means to measure pelvic flexion at low cost and reporting pelvic flexion using a standard and precise reference system, this technique may be useful for studying functional pelvic orientation and functional alignment and for improving postoperative measurement accuracy. However, this is a new technique that has yet to be validated.

We evaluated the level of accuracy with which pelvic flexion can be measured by manually identifying the locations of the pubic tubercles and ASIS landmarks from lateral pelvic radiographs of the bony anatomy.

MATERIALS AND METHODS

Fifty lateral pelvic radiographs were synthesized from the preoperative CT scans of five patients. These scans were obtained previously for use in the clinical trial of a CT-based surgical navigation system for THA. A custom software program, Xalign, was used to synthesize the radiographs and to record the 3-D pelvic positions and orientations, which were used as control measurements in this study. Xalign has been used and validated

Fig 1. Pelvic flexion can be measured from the lateral projections of the ASIS and pubic tubercles.

Fig 2A–B. (A) Landmarks are localized on a pelvis in extension. Pelvic flexion is assessed by measuring the angles between a vertical line and the lines connecting the landmarks. (B) Landmarks are localized on a pelvis in flexion. In these images, as is generally the case, the pubic tubercles are effectively superimposed, while the ASIS landmarks have nonoverlapping projections.
as a postoperative radiograph measurement tool that improves measurement accuracy by coregistering a CT scan and a computer implant model with a standard radiograph. For each patient, 10 different radiographs were synthesized with unique pelvic orientations (flexion, version, and abduction) and x-ray source positions relative to the pelvic anatomy. The source-to-film distance was kept constant at 1016 mm. Pelvic flexion ranged from −22.6º to +13.0º. These angles represent true pelvic flexion as defined by the angle between the APP and a vertical line in 3-D space (angle $\alpha$, Fig 1). Fifty synthetic radiographs were produced, which was sufficient to cover the tested range with adequate density.

Six sets of synthetic radiographs were printed on ordinary paper stock. Because CT scans have a lower resolution than radiographs (especially between slices), the synthetic radiographs exhibited a lower resolution than conventional radiographs. However, the synthetic radiographs were clearer because of reduced soft tissue noise.

Six observers, three surgeons (YG, MH, MS) and three engineers (BJ, TL, PM), performed the pelvic flexion measurements. Each observer was assigned an alphabetical letter (A through F). Data collection and analysis were performed by an independent evaluator (KE) who was not one of the observers. The individual paper printouts enabled every observer to freely draw individual measurements without influencing others. The observers identified the locations of the ASIS ($I_1$ and $I_2$) and the pubic tubercles ($P_1'$ and $P_2'$) (Fig 1). In general, all landmarks were identifiable on the lateral radiographs. Because the distance between the pubic tubercles is short, they were effectively superimposed. This was not the case with the ASIS landmarks, which typically appeared as two distinct projections (Fig 2). After identifying the landmarks, lines were drawn between the center of the pubic tubercles and the two ASIS landmarks. Custom protractors, which were printed on transparency sheets, were used to measure the angles of these lines with respect to the vertical edge of the paper. The average of these two angles was recorded as pelvic flexion. When the ASIS landmarks were superimposed, only a single angle was measured.

Global and individual observer mean errors, standard deviations, confidence intervals, and Spearman correlations were calculated. Histograms and adaptive kernel probability density function estimates were calculated and plotted as well. The D’Agostino-Pearson test was used to measure the normality of the distributions. Intraclass correlations also were used to report reliability. The total number of measurement samples is more than adequate for the detection of subdegree errors (power of 0.99 with $\alpha = 0.05$ for differences of 0.5º).

**RESULTS**

The pelvic flexion measurement errors from lateral pelvic radiographs of the bony anatomy were small (0.004º ± 1.38º) (Table 1; Fig 3). The intraclass correlation coefficient was 0.986 with a 95% confidence interval of (0.981, 0.992). There was one outlier out of the 300 measurements with an error of 12.4º (Observer D, Fig 4). This outlier occurred because the observer failed to identify one of the two ASIS landmarks while measuring pelvic flexion. Apart from this outlier, the range of errors was −4.00º to 3.00º. Thus, 99.7% of all measurements fall into an error range of −4.00º to 3.00º. With the outlier excluded, the error measurements pass the D’Agostino-Pearson normality test ($X^2 > 0.05$). With the outlier included, the data fail

![](image)

**TABLE 1. Pelvic Flexion Measurement Errors**

<table>
<thead>
<tr>
<th>Measure</th>
<th>Total</th>
<th>Observer A</th>
<th>Observer B</th>
<th>Observer C</th>
<th>Observer D</th>
<th>Observer E</th>
<th>Observer F</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean</strong></td>
<td>0.004</td>
<td>0.20</td>
<td>0.03</td>
<td>−0.27</td>
<td>0.04</td>
<td>0.35</td>
<td>−0.38</td>
</tr>
<tr>
<td><strong>Standard deviation</strong></td>
<td>1.38</td>
<td>1.14</td>
<td>1.14</td>
<td>0.89</td>
<td>2.14</td>
<td>1.29</td>
<td>1.24</td>
</tr>
<tr>
<td><strong>Range</strong></td>
<td>3.00</td>
<td>2.61</td>
<td>2.25</td>
<td>1.50</td>
<td>2.11</td>
<td>3.00</td>
<td>2.00</td>
</tr>
<tr>
<td>95% Confidence</td>
<td>−12.36</td>
<td>−3.99</td>
<td>−3.77</td>
<td>−2.25</td>
<td>−12.36</td>
<td>−2.49</td>
<td>−4.00</td>
</tr>
<tr>
<td><strong>Interval range</strong></td>
<td>0.15</td>
<td>0.53</td>
<td>0.35</td>
<td>−0.02</td>
<td>0.65</td>
<td>0.72</td>
<td>−0.03</td>
</tr>
<tr>
<td><strong>Spearman’s rank</strong></td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
<td>0.97</td>
<td>0.99</td>
<td>0.99</td>
</tr>
</tbody>
</table>

**Fig 3.** The histogram, nonparametric probability density function estimate, and Gaussian fit illustrate small pelvic flexion measurement errors with a single outlier.
the normality test. There is a slightly bimodal distribution of errors among the surgeons’ measurements (Observers D, E, and F, Fig 4).

We observed a narrow spread of errors across the range of pelvic flexion, indicating that the amount of pelvic flexion had little influence on the accuracy of measurements (Fig 5). Combined with the small observed errors, the scatter plots of known pelvic flexion versus pelvic abduction, pelvic version, and source position indicate robustness to imaging variations (Figs 6, 7).

Fig 4. The histogram, nonparametric probability density function estimate, and Gaussian fit (shown for each observer, A through F) illustrate the individual observer’s small measurement errors. The single outlier, seen in the chart for Observer D, emphasizes the importance of correctly discerning every landmark.

**DISCUSSION**

Variations in pelvic orientation affect preoperative planning decisions,\(^2\,5\,6\,8\) intraoperative navigation,\(^3\) and postoperative measurements.\(^1\,6\) A need exists for an accurate, convenient, and inexpensive method of assessing pelvic orientation outside the surgical theater. Ideally, pelvic orientation measurements would be made with respect to one precise reference system. Because the anterior pelvic reference system is the standard used in surgical navigation,
the ability to relate functional orientation and postoperative implant measurements to this reference is desirable. Unfortunately, the majority of landmark-based techniques requiring only one radiograph have yet to be rigorously validated, and most do not use the standard navigation reference system. Although CT scans and CT/x-ray-matching techniques have been used to measure pelvic orientation,\textsuperscript{1,3,6} obtaining a CT scan involves increased cost and is often impractical.

We note some limitations. Synthetic radiographs of the bony anatomy were used rather than radiographic films. The soft tissue noise in radiographic films makes landmark localization more difficult. However, the main purpose of this study was to validate the suitability of measuring pel-

**Fig 5.** The scatter plot of measurement errors versus control pelvic flexion shows a narrow spread of errors, indicating that the amount of pelvic flexion had little influence on the accuracy of the measurements.

**Fig 6.** The scatter plot of source position versus flexion illustrates the variety of imaging parameters used to synthesize the images.
vic flexion from lateral radiographs, assuming the pubic tubercles and ASIS landmarks are clearly visible. Also, these landmarks were confidently assessed by one observer from the radiographic films of 84 patients in a related study. To determine measurement errors, 3-D control measurements were required. These control measurements were best achieved through direct radiograph synthesis. Because these synthetic radiographs were generated from CT scans of real patients, the resolution of the synthetic radiographs is actually lower than radiographic film. The study is also limited by the degree of anatomic variation found in the scans.

Studies of variation in natural pelvic orientation have indicated a need for knowledge of pelvic flexion for preoperative planning, intraoperative alignment, and postoperative measurements. McCollum and Gray suggested adjusting cup placement based on a patient’s standing pelvic flexion as a means of reducing dislocation after THA. A large range (−12° to 40°) in preoperative standing flexion was reported, supporting this idea. A similar range has been found using lateral pelvic radiographs. Pelvic orientation is unique to each patient and changes with patient position. Placing the acetabular component without considering the natural orientation of a patient’s pelvis can lead to dislocations, even though the cup may have been placed ideally relative to the bony anatomy. Planning for THA ought to take this into account. Also, it is important to know pelvic orientation when measuring cup alignment from postoperative radiographs.

Various techniques have been used to measure adult pelvic orientation outside the surgical theater. Although CT scans have been used to measure full 3-D pelvic orientation, the physical constraints of the CT scanner restrict patient-positioning options. Thus, CT scans alone can provide only limited information about functional pelvic orientation. Image-based CT/x-ray-matching techniques have been used to determine full 3-D pelvic orientation as well, and geometric-ratio-based CT/x-ray-matching techniques have been used to assess the flexion component of orientation. In general, CT/x-ray-registration techniques can be used to measure the full 3-D orientation of the pelvis and implants from an entire series of radiographs using only a single scan. Nonetheless, the need for even one CT scan increases cost and is often impractical. Several low-cost, landmark-based techniques for measuring adult pelvic flexion have been explored. On lateral radiographs, the most anterior point of the greater sciatic notch and the ASIS have been used. The PSIS and the ASIS also have been investigated. However, when compared with the sciatic notch and ASIS method, a wider range of pelvic flexion measurements is observed with the PSIS and ASIS method. Recently, the pubic tubercles and the ASIS were used to measure pelvic flexion. Inspired by methods proposed for use with children, measurements of the distance between the sacrococcygeal joint and the pubis symphysis from the AP radiographs of four cadavers were correlated with pelvic flexion. However, the accuracy of these techniques has not been rigorously validated, and few refer to the APP.

The data suggest that accurate measurements of pelvic flexion can be made from lateral radiographs with respect
to the standard navigation reference system. The errors are small compared with the range of pelvic flexion found in previous studies. The ability to measure pelvic flexion may provide a better understanding of variations in pelvic orientation. Incorporating patient-specific knowledge into the planning of functional alignment for THA may decrease the risk of dislocation. However, failure to correctly observe a landmark can introduce large errors. Therefore, the clarity of the relevant landmarks should be considered carefully before using this technique. By using the standard navigation reference system, these pelvic flexion measurements can be incorporated easily into a navigation-based preoperative plan and can enable meaningful preoperative, intraoperative, and postoperative measurement comparisons. Lateral radiographs can be easily acquired and analyzed, making this technique convenient and inexpensive.

Acknowledgments

We thank John Scott, MA, and Laura D. Cassidy, PhD, from the University of Pittsburgh. We also thank David Davidson, BS, Andrew B. Mor, PhD, Michael J. Seel, MD, Yram J. Groff, MD, and Patricia Murtha, PhD, and the entire staff of ICAOS and Renaissance Orthopaedics at The Western Pennsylvania Hospital.

References