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Open-face plane orientation of a BioMedtrix biologic fixation acetabular cup can be accurately determined from a lateral radiograph

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Objective
To develop and validate a method to calculate biologic fixation (BFX) acetabular cup open-face plane orientation based on measurements from a lateral radiograph.

Methods
The formulas describing the open-face plane orientation were derived using geometric arguments and trigonometry. To assess the method, an in vitro plastic model of a pelvis was implanted with a BFX acetabular cup. A lateral radiograph of the implanted model was obtained and used to calculate the cup open-face plane orientation using the derived method. Direct measurement of the open-face plane orientation was performed, and the calculated values were compared to the directly measured values. The procedure was repeated with the cup in a different orientation for each trial.

Results
52 trials were performed. The derived calculation method demonstrated high repeatability and reproducibility, with intra- and interobserver intraclass correlation coefficients > 0.94. The direct measurement method demonstrated high reproducibility, with interobserver intraclass correlation coefficients > 0.98. The mean absolute angular difference between the calculated and directly measured orientation vectors was 2.8 ± 1.3°, with 95% of trials within 4.7°.

Conclusions
The open-face plane orientation determined by the derived method agreed closely with the directly measured orientation.

Clinical Relevance
Knowledge of the BFX open-face plane orientation can inform decisions regarding cup revision, help identify complications associated with cup malpositioning, and allow the surgeon to improve their cup placement performance.

Keywords: total hip replacement, BFX, orientation, ALO, version

Accurate positioning of the acetabular cup is central to successful total hip replacement (THR). Knowledge of cup orientation informs decisions regarding cup revision, helps identify whether cup malpositioning contributed to postoperative complications, and allows the surgeon to improve their performance. The orientation of the open face of the cup is particularly critical in determining how the cup interacts with the femoral component. This orientation is traditionally described by the spherical coordinates angle of lateral opening (ALO) and open-face version (OFV).[1] Published recommendations for cup orientation include an ALO of 45° and an OFV of 15° to 25° retroversion.[1]

Intraoperatively, cup orientation is assessed via several methods. The acetabular reamer handle and cup impactor handle can be fitted with orientation bars that guide orientation during reaming and implantation. Cup orientation is also evaluated in relation to the local anatomy of the cranial and caudal acetabular pillars. Finally, the cup orientation relative to the femoral component can be assessed by comparing the plane of the open face of the cup to the flat surface of the back of the femoral head with the hip in reduction and the leg in a neutral position. According to the manufacturer, these planes should be parallel.[2]

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Postoperatively, assessment of implant positioning is typically performed using orthogonal radiographs of the pelvis. A cemented fixation (CFX) cup is radiolucent and contains an embedded circular metallic wire marker whose plane is parallel to the open face. On a ventrodorsal (VD) radiograph, the shape and orientation of this wire marker can be used to readily determine ALO and OFV.[1,3] For a biologic fixation (BFX) cup, it is challenging to determine the open-face plane orientation from radiographs. The shell of the cup is titanium and forms a relatively homogenous metal-opacity radiographic silhouette, making it difficult to discriminate the geometry that lies within this silhouette.

Several methods have been proposed for estimating aspects of BFX cup orientation from a lateral or VD radiograph.[4–7] Most estimate ALO alone rather than complete open-face plane orientation and tend to become less accurate when larger values of OFV combine with ALO to produce foreshortening of the cup silhouette. One study[6] assessed both ALO and version using an assistive device placed in the cup at the time of imaging. This device may improve ease of measurement when it is in place but has the disadvantages that it can only be used intraoperatively and only by using intraoperative radiography. Determining complete open-face plane orientation postoperatively from the cup radiographic silhouette alone remains challenging.

The objectives of this study were to develop a method to calculate BFX acetabular cup open-face plane orientation based on measurements from a lateral radiograph, derive the mathematical basis of the method, and assess its agreement with direct measurement. The proposed method uses the portion of the open face that is visible as the ventral margin of the cup silhouette on the lateral radiograph. It fits an ellipse to this profile, measures the shape and orientation of this ellipse, and then uses trigonometry to calculate the acetabular axis vector. This ellipse-based radiographic method bears similarities to methods for describing a CFX cup on a VD radiograph,[1,3] which in turn traces its origins to a method first described by Lewinnek et al[8] in human hip arthroplasty in 1978 that has been built upon in the decades since.[9]

Using this radiograph-based method and direct measurement of a plastic model implanted with a cup, we assessed agreement between the calculated orientation and the directly measured orientation.

Methods

Geometric derivation of the method to calculate ALO and OFV

The dorsal plane was defined as the plane containing the most dorsal points of the cranial iliac spines and the ischiatic tuberosities. On a lateral radiograph, this plane forms the ilioischial axis. The x-axis is the cranial-caudal axis that lies in the dorsal plane. The y-axis is the ventral-dorsal axis normal to the dorsal plane. The z-axis is the medial-lateral axis that lies in the dorsal plane.

The BFX acetabular cup approximates a hemisphere with a portion removed for the dorsolateral truncation. Thus, the ventrolateral open face of the BFX acetabular cup is a circle with a portion removed by the truncation. The acetabular axis was defined as the unit vector perpendicular to the open face.[3] The open-face plane orientation can be described by 2 angles: ALO and OFV. The ALO is the angle between the open-face plane and the dorsal plane.[1] The OFV is the angle formed between the z-axis and the projection onto the dorsal plane of the acetabular axis. In this study, OFV was 0° when this vector projection was parallel to the z-axis and positive when the vector angled caudally (retroversion). Because the projected acetabular axis is perpendicular to the ellipse major axis and the z-axis is perpendicular to the x-axis, this angle is equivalent to the angle that would be measured on a VD radiograph between the ellipse major axis and the x-axis as could be performed using the wire marker on a CFX cup.[1] The open-face plane orientation is therefore described by a spherical coordinate system, with ALO and OFV the spherical coordinates of the acetabular axis vector.

The derivation assumes that the lateral radiographic projection, with the beam centered on the acetabula, approximates an orthographic projection at the level of the cup, the laterality (left or right) of the implanted acetabulum is known, and the cup is implanted with the acetabular axis vector pointing in a generally ventrolateral direction.

On a lateral pelvis radiograph, the circle of the cup open face is seen obliquely, and its projection forms an ellipse minus the truncation. This ellipse has a shape, which can be described by the aspect ratio (R), the ratio of major axis (MA) to minor axis (mA), and an orientation, which can be described by the angle between the ellipse major axis and the ilioischial axis. We define this angle as major axis inclination (MAI). The 2 parameters, R and MAI, define the shape and orientation of the ellipse. Under these assumptions, the ellipse uniquely determines the 3-D open-face plane orientation.

ALO and OFV are expressed in terms of R and MAI according to the following 2 equations:

$$\mathrm{ALO} = \arcsin\left(\sqrt{\sin^2(\mathrm{MAI}) + \frac{\cos^2(\mathrm{MAI})}{R^2}}\right)$$

$$\mathrm{OFV} = \arctan\left(\sin(\mathrm{MAI}) * \sqrt{R^2 - 1}\right)$$

For the derivation of these equations, refer to "Derivation" in **Supplementary Material S1**.

To facilitate the radiographic measurements and trigonometric calculations, a public web-based interface was created (https://thr-tools.github.io/bfxcuporientation/). The interface is optional; the measurements and calculations can also be performed manually. For an explanation of how to measure R and MAI with high precision and how to compute the above equations, refer to "How to" in **Supplementary Material S2**.

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To confirm consistency between this approach and previously described methods,[1] an in silico model was created in which the open-face plane orientation could be evaluated both via the traditional VD wire ring method and the proposed lateral radiograph method. The 2 methods yielded identical values of ALO and OFV, supporting the consistency of the derived equations **(Figure 1)**.

Agreement between calculated angles and directly measured angles

To assess the radiograph-based method, the following experiment was performed. A CT scan of the pelvis of a normal mixed-breed dog was used to create a 3-D–printed plastic pelvis model. At the left acetabulum, a concave recess was modeled to accommodate a 30-mm BFX acetabular cup in any orientation. Supports were modeled to allow the pelvis to stand in true lateral recumbency or in dorsal recumbency with the ilioischial axis parallel to the table. A separate femur jig was made to hold a BFX femoral stem with head. The femur jig held the stem with its long axis parallel to the radiograph table and with the neck in mild anteversion.

For each trial of the experiment, the following steps were performed **(Figure 2)**:

1. A 30-mm BFX cup (22-mm internal diameter) was placed into the pelvic recess, secured to the plastic pelvis with a temporary adhesive. The stem with head was placed in the femur jig.
2. The model was positioned for a lateral radiograph. The cup side of the pelvis was toward the table. The femur jig was placed to locate the stem in a neutral femur position with the head reduced into the cup. The radiograph beam was centered on the acetabula. The lateral radiograph was acquired.
3. From this image, the measurements R and MAI were obtained.
4. Using the first and second equations, the angle of lateral opening was calculated ($ALO_{calculated}$) and the open-face version was calculated ($OFV_{calculated}$).
5. The pelvis model with implanted cup was placed in dorsal recumbency on a level surface, and ALO and OFV of the cup were directly measured:
   a. To measure ALO, a 3-D–printed "ALOmeter" was used. One end of the ALOmeter had a flat surface with a centered, 21-mm-diameter hemisphere. This was placed on the open face of the cup with the hemisphere in the cup and the flat periphery held in full contact with the open-face margin (like the THR cup impactor handle fitted with a central impactor). The other end of the ALOmeter had an angular scale plate and plumb line. With the proximal end of the jig maintained in complete contact with the cup open-face margin, the ALOmeter was rotated on the axis of its cylinder until the scale plate was just in contact with the plumb line. The angular measurement was recorded (to the nearest whole degree) as the measured angle of lateral opening ($ALO_{measured}$). **Figure 3** shows the geometric logic and implementation of this method.

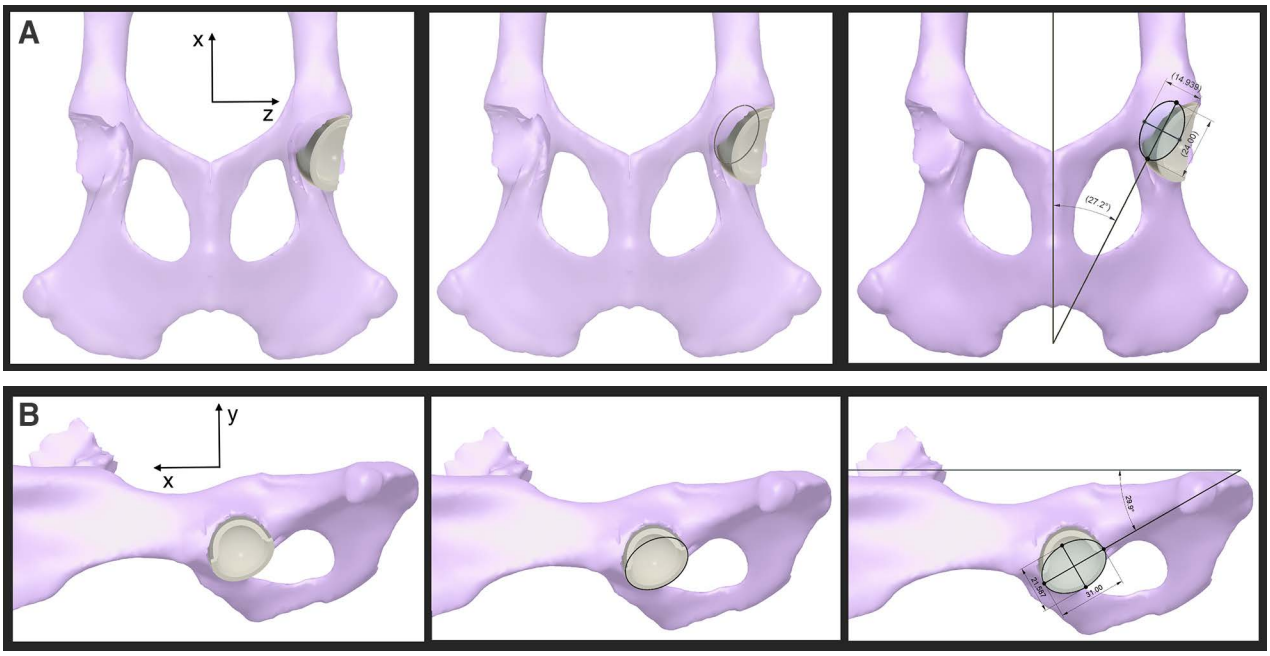


Figure 1—A—In silico, a ventrodorsal projection is used to measure the angle of lateral opening (ALO) and open-face version (OFV) from the wire marker ellipse as would traditionally be performed on a cemented fixation (CFX) cup using the ellipse major axis (MA) and minor axis (mA): $ALO = \arccos(\frac{mA}{MA})$ = 51.5°, OFV = 27.2°. B—The same pelvis and cup viewed from a lateral projection. The projected ellipse of the open face is measured to determine the ratio of major axis to minor axis (*R*) and major axis inclination (MAI). The 2 equations shown in the Methods section are used to calculate ALO = 51.5° and OFV = 27.2°.

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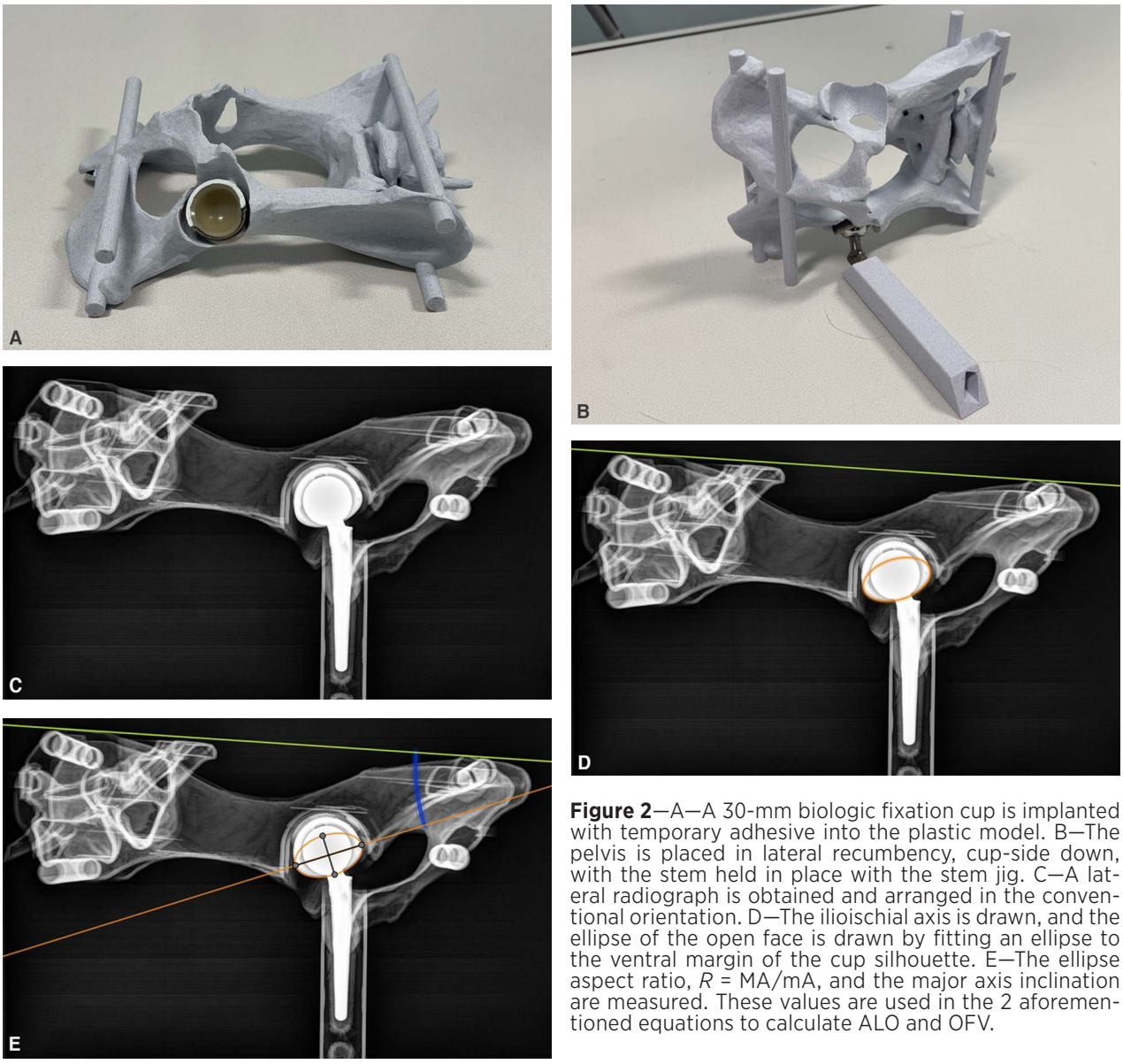


Figure 2—A—A 30-mm biologic fixation cup is implanted with temporary adhesive into the plastic model. B—The pelvis is placed in lateral recumbency, cup-side down, with the stem held in place with the stem jig. C—A lateral radiograph is obtained and arranged in the conventional orientation. D—The ilioischial axis is drawn, and the ellipse of the open face is drawn by fitting an ellipse to the ventral margin of the cup silhouette. E—The ellipse aspect ratio, *R* = MA/mA, and the major axis inclination are measured. These values are used in the 2 aforementioned equations to calculate ALO and OFV.

b. To measure OFV, a horizontal laser line was projected onto the open face of the cup. A photograph was taken from directly above the model. This image was used to measure the angle between midline and the laser line projected on the open face. This angle was recorded (to the nearest 0.1°) as the measured open-face version ($OFV_{measured}$). **Figure 4** shows the geometric logic and implementation of this method.

Statistical analysis

The procedure was repeated with the cup placed in a different orientation for each trial. The cup orientations were selected without a specific target orientation for each trial. No a priori sample size calculation was performed because the study was structured to characterize method agreement rather than to test a specific hypothesis. The number of trials was chosen to include a broad distribution of measured ALO and OFV values across the clinically relevant range and to obtain stable estimates of agreement and repeatability.

Interobserver reproducibility for the direct measurements was assessed using a subset of the first 21 consecutive trials independently measured by a second observer. Agreement between observers was evaluated using intraclass correlation coefficients (2-way random effects for single measurements) and Bland-Altman analyses. Following confirmation of acceptable agreement, the direct measurements for the remaining trials were performed by a single observer.

Intraobserver repeatability for the radiograph-based calculations was assessed by having 1 observer repeat each radiographic calculation twice several days apart. Interobserver reproducibility was assessed by having a second observer perform the

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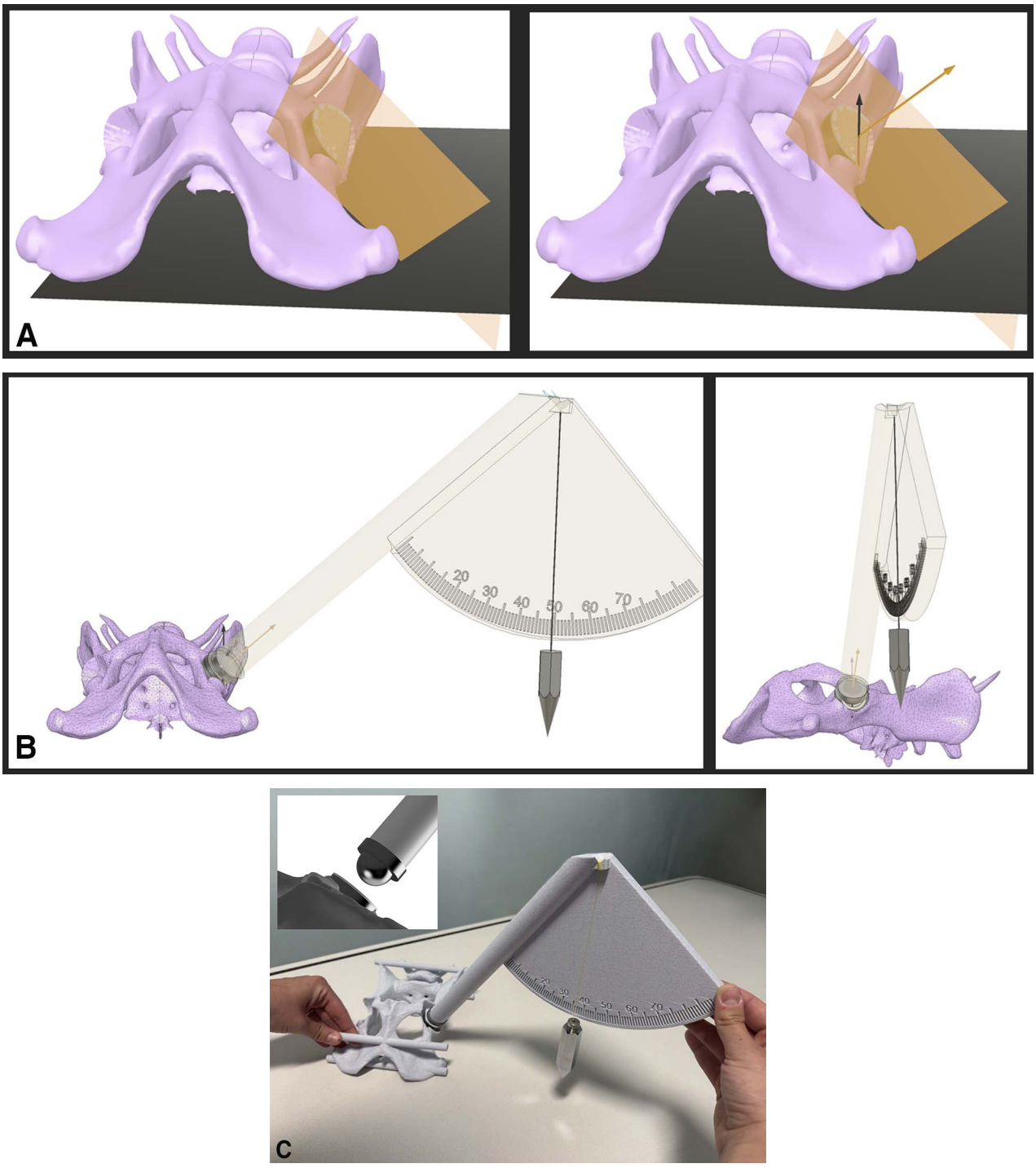


Figure 3—A—The angle of lateral opening (ALO) is defined as the angle between the open-face plane and the dorsal plane, which can be calculated as the angle between the vectors normal to each plane. The vector normal to the open-face plane is the acetabular axis, and the vector normal to the dorsal plane is the y-axis. B—The ALOmeter end registers flush on the cup open face so that the cylindrical portion aligns with the acetabular axis. The plumb line is parallel to the y-axis. The ALOmeter is rotated along the axis of the cylinder until the scale plate is just in contact with the plumb line. The value on the scale is the angle between the cylinder axis (acetabular axis) and the plumb line (y-axis). Thus, this value is the ALO. C—Implementation of the ALOmeter to directly measure the angle of lateral opening ($ALO_{measured}$); the inset image illustrates the end of the ALOmeter about to interface into the cup.

calculations once for all trials. Intraobserver and interobserver effects were evaluated using intraclass correlation coefficients (2-way random effects for single measurements) and Bland-Altman analyses.

For assessment of agreement between calculated and directly measured values, the values used were those from a single observer to reflect typical clinical application.

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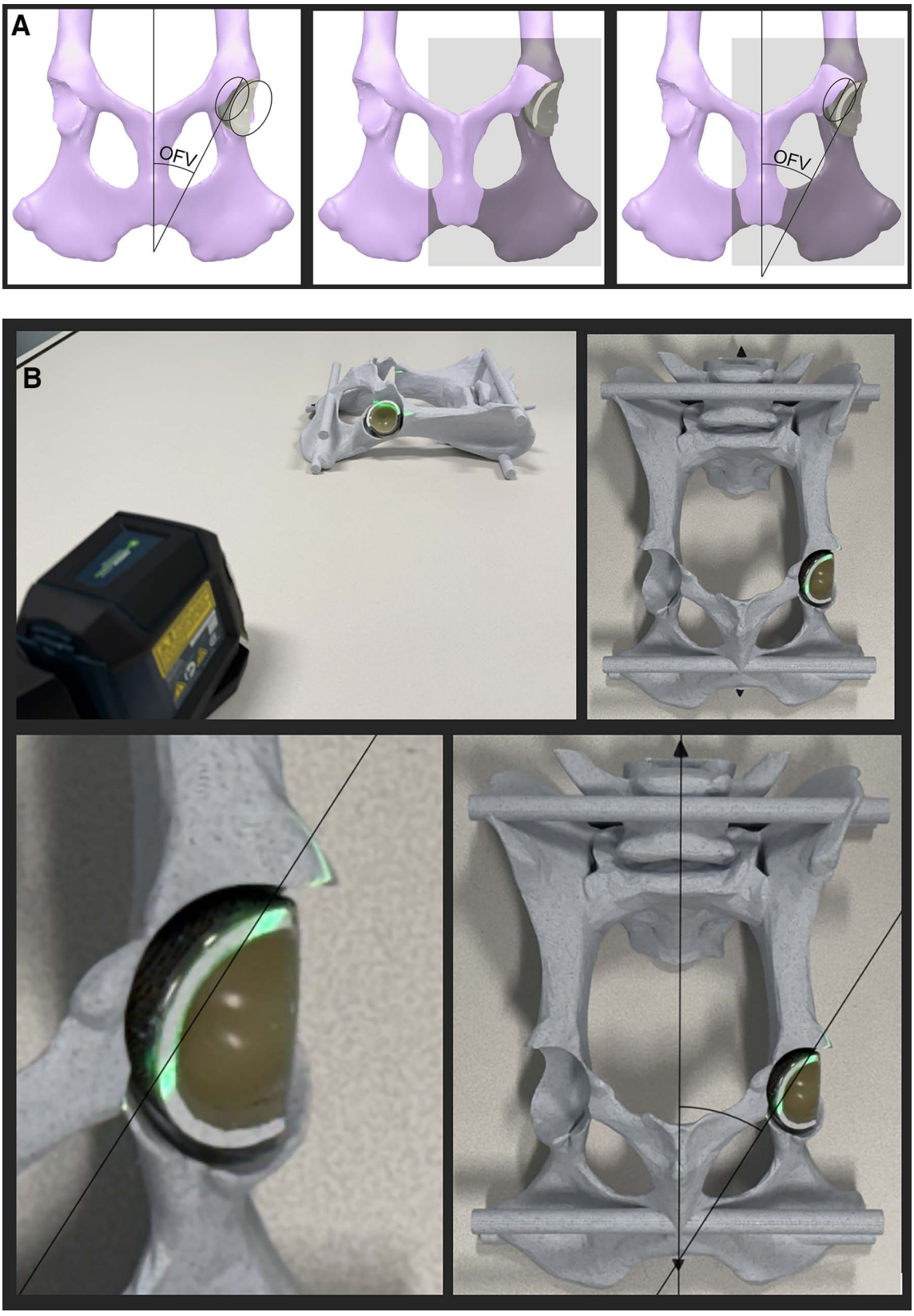


Figure 4—A—The wire marker that is present on a cemented fixation cup is parallel to the open face and is traditionally used to measure OFV. A plane parallel to the dorsal plane that intersects the open-face plane of the cup creates a line of intersection, and this line is parallel to the major axis of the wire ellipse. Thus, OFV can be measured using this line of intersection. B—A horizontal laser creates a plane parallel to the dorsal plane that intersects with the open face of the cup to form a line. From a ventrodorsal view, the angle between this line and midline is OFV.

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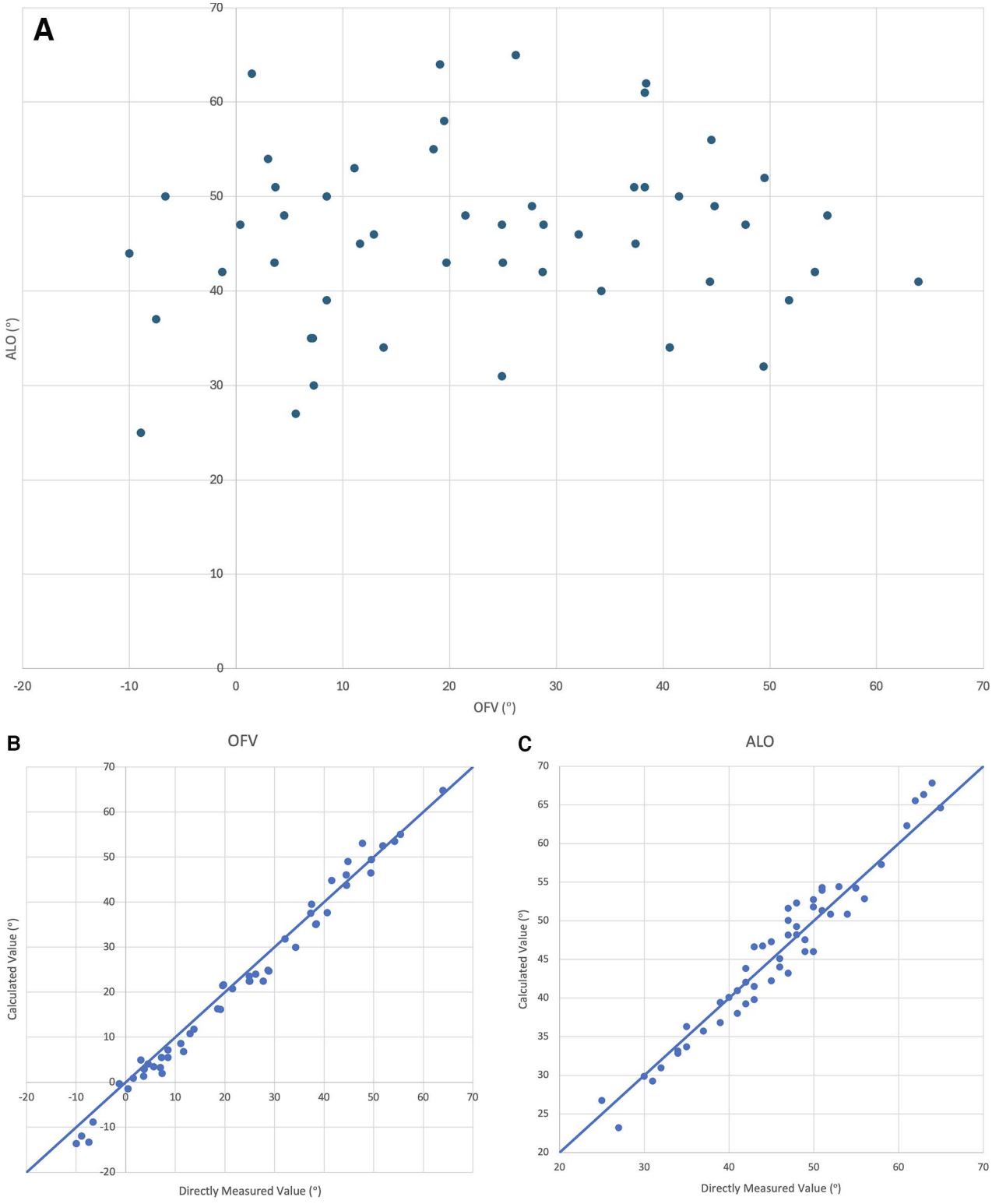


Figure 5—A—The measured values of ALO and OFV for the 52 trials. Scatter plots of the calculated values versus the directly measured values for OFV (B) and ALO (C). The solid lines represent equality between the calculated and directly measured values.

For each trial, the calculated and measured values of ALO and OFV were used to create calculated and measured acetabular axis vectors, $v_{calculated}$ and $v_{measured}$. The absolute angular difference between the 2 was calculated as the inverse cosine of the dot product of the 2 vectors. The mean ± SD, median, and IQR of the absolute angular difference were reported. For each trial, $ALO_{calculated}$ was compared

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to $ALO_{measured}$, and $OFV_{calculated}$ was compared to $OFV_{measured}$. For both ALO and OFV, the mean ± SD signed difference between the calculated and measured values was reported. Bland-Altman analysis was performed to assess for bias. The mean ± SD absolute difference between the calculated and measured values was reported. Because the goal of the study was to assess agreement between the 2 measurement methods, statistical analysis centered on bias, variability, and limits of agreement rather than on hypothesis-based significance testing.

Results

Interobserver reproducibility for the directly measured ALO was 0.985 (ICC; 95% CI, 0.947 to 0.995) with a mean signed difference of −0.9° and 95% limits of agreement from −3.7° to 1.9°. Interobserver reproducibility for the directly measured OFV was 0.996 (ICC, 95% CI, 0.987 to 0.999) with a mean signed difference of −0.9° and 95% limits of agreement from −3.7° to 2.0°. The mean absolute angular difference between the directly measured orientation vectors for the 2 observers was 1.8 ± 1.0°.

Intraobserver repeatability for the calculated ALO was 0.961 (ICC; 95% CI, 0.933 to 0.978) with a mean signed difference of 0.18° and 95% limits of agreement from −5.3° to 5.7°. Intraobserver repeatability for the calculated OFV was 0.987 (ICC; 95% CI, 0.978 to 0.993) with a mean signed difference of 0.02° and 95% limits of agreement from −6.4° to 6.4°. The mean absolute angular difference between the calculated orientation vectors from the 2 repetitions was 2.9 ± 2.1°.

Interobserver reproducibility for calculated ALO was 0.947 (ICC; 95% CI, 0.909 to 0.969) with a mean signed difference of −0.1° and 95% limits of agreement from −6.6° to 6.4°. Interobserver reproducibility for calculated OFV was 0.987 (ICC; 95% CI, 0.978 to 0.993) with a mean signed difference of −0.2° with 95% limits of agreement from −6.1° to 6.5°. The mean absolute angular difference between the calculated orientation vectors from the 2 observers was 3.5 ± 1.9°.

The 52 trials covered a wide range of clinically relevant cup orientations, with directly measured ALO values from 24° to 65° and OFV values from −10° to 63.9° **(Figure 5)**.

The mean absolute angular difference between the calculated and directly measured orientation vectors was 2.8 ± 1.3°. The median absolute angular difference was 3.2° (IQR, 1.9° to 3.8°). Ninety-five percent of trials had differences ≤ 4.7°. **Figure 6** illustrates the measured acetabular axis together with cones representing the mean and 95th percentile absolute angular differences.

For OFV in isolation, the mean signed difference between the calculated and directly measured values was −1.4 ± 2.4°. The mean absolute difference was 2.4 ± 1.5°. For ALO in isolation, the mean signed difference between the calculated and directly measured values was 0.01 ± 2.4°. The mean absolute difference was 2.0 ± 1.3°.

Figure 5 shows scatter plots of the calculated values versus the directly measured values.



Figure 6—The directly measured acetabular axis (black). Comparing the calculated and directly measured acetabular axis vectors, there was a mean absolute angular difference of 2.8° (narrow cone half angle) and a 95th percentile absolute angular difference of 4.7° (wide cone half angle).

Discussion

In this study, a lateral pelvis radiograph–based calculation method demonstrated close agreement with directly measured cup open-face plane orientations across a wide range of clinically relevant orientations.

The equations were derived from geometric arguments and trigonometry, and an in silico comparison was made to the established VD radiograph–based method of measurement of a CFX cup to verify consistency of the derived equations.[1]

The calculation method was assessed by in vitro comparison to a reference standard, direct measurement of ALO and OFV from an implanted pelvis model. This reference standard was not a true ground truth because direct measurement itself is subject to error. The direct measurement method demonstrated high interobserver reproducibility.

Previous studies[1,4] estimating ALO have considered accuracy within 5° to be ideal, whereas accuracy within 10° has been described as clinically useful. In this study, the mean absolute difference between calculated and directly measured ALO was 2.0 ± 1.3°, and the mean absolute difference between calculated and directly measured OFV was 2.4 ± 1.5°. The observed agreement indicates that the method can provide useful estimates of cup orientation under the experimental conditions of this study. Additionally, knowing both ALO and OFV is more clinically valuable than highly accurate knowledge of either angle alone because it allows calculation of the acetabular axis. The mean absolute angular difference between the calculated and the directly measured acetabular axis vector was 2.8 ± 1.3°, with 95% of the trials having a difference ≤ 4.7°.

The mean absolute angular difference between the calculated and directly measured vectors was similar in magnitude to the inter- and intraobserver variability for both the calculation method and the

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direct measurement method. This finding suggests that the difference between methods likely reflects, at least in part, the intrinsic variability in the measurement methods rather than systematic bias. The technique demonstrated a level of agreement with the direct measurement method that approached the repeatability limits of either method alone.

The calculated ALO values showed minimal bias relative to the directly measured values, with a mean signed difference of 0.01°. The calculated OFV values demonstrated a mean signed difference of −1.4° relative to the directly measured values. With no ground truth orientation, it is not possible to know if this bias originated from the radiographic calculation method, the direct measurement, or a combination.

The method has several advantages. By determining both ALO and OFV, it allows calculation of the acetabular axis vector. This allows comparison of this vector to a target cup vector or to the vector of the implanted femoral component neck, valuable information in both clinical and research settings. The method is valid across a wide range of clinically relevant orientations and does not suffer from systematic error that progressively worsens in wider angle domains. Being based on a lateral radiograph, this method is less susceptible to pelvic malpositioning artifact than VD methods. Malpositioning of the pelvis is readily identified on a lateral radiograph, and patient positioning can be corrected.[1,3,10] This method can be adapted to the intraoperative setting where a sagittal plane fluoroscopic image is readily obtained. The web-based interface makes the calculations rapid and straightforward to perform.

The method also has limitations. It requires a correctly aligned lateral radiograph, and it cannot be used if there is a contralateral metallic acetabular implant. This method provides no information about the truncated face. This method requires precise measurement of *R* and MAI from the lateral radiograph. The web-based interface may improve measurement precision, but regardless, small user inaccuracies can affect the calculated results.

The validation experiment has limitations. The radiographic method was compared to measurements on an in vitro construct rather than in vivo. In a clinical patient, the cup appearance on a lateral radiograph is affected by summation with bone and soft tissues, making the cup silhouette margin less crisp than in the in vitro construct. Additionally, obtaining a properly aligned, centered radiograph is more difficult in the clinical patient than in the in vitro construct. These factors may reduce measurement accuracy in the clinical setting. Future studies should evaluate the method in vivo, although doing so would require establishing an appropriate in vivo reference standard. Second, the in vitro construct used a pelvis model from a single clinically normal dog. It employed a single size of the BioMedtrix BFX cup and used the same femoral component size and orientation for each trial. This consistency in pelvis morphology, implant size, and stem orientation was chosen to minimize variables during the validation process but does not reflect clinical use. For each trial, the reference standards for ALO and OFV were obtained by direct measurement, which itself contains error. For the radiograph-based calculations, the 2 observers were board-certified surgeons with extensive experience performing BioMedtrix BFX THRs and were also involved in developing the method. Users with less experience may not achieve similar accuracy.

In conclusion, we derived and assessed a method to calculate the open-face plane orientation of a BFX cup based on measurements from a lateral radiograph. In this experimental construct, the calculation method provided estimates of open-face plane orientation that agreed closely with those determined from direct measurement. Because the method estimates both ALO and OFV, it allows evaluation of the functional orientation of the cup open face. This method provides a practical means of assessing whether an implanted cup approaches a target orientation.

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Disclosures

Dr. Lotsikas is a paid consultant for BioMedtrix.

Assistive AI (ChatGPT, version 5.5; Open AI) was used to recommend statistical methodology and to review content for coherence and style. No generative AI was used. The authors take responsibility for the integrity of the content generated.

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